

## Magnetologic with $\alpha$ -MnAs Thin Films

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Taking advantage of the spin information in present day computing is expected to yield an enormous increase in efficiency. A promising ferromagnetic material compatible with semiconductors for room temperature applications is MnAs. By sensitive cantilever beam magnetometry, we discovered that  $\alpha$ -MnAs films on GaAs(001) exhibit an additional small out-of-plane component of the magnetization which is magnetically coupled with the dominant in-plane magnetization. We demonstrate that by regarding the two components as independent inputs, the  $\alpha$ -MnAs layer can be utilized as a logic gate with nonvolatile output. The logic functionality of the layer can be preselected to be AND or OR at run time, thus offering the perspective for programmable magnetologic devices.

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Magnetic thin films, which are without competition in data storage, are increasingly gaining importance for the computational process [1]. In spintronics—a new research field combining semiconductor technology and magnetics—the spin information of the electron is intended to be utilized for extending the functionalities of the common transistor [2,3]. Even newer developments, going beyond transistor-based circuits, are initiating a paradigm shift from the electrically to a purely magnetically controlled digital logic. The first design concepts for magnetic logic AND and OR gates [4–6] were introduced recently and are based on magnetoresistive elements [7], the building blocks of the magnetic random-access memory (MRAM) [8]. An enormous advantage, among others, compared to conventional technology is the nonvolatile logic output of magnetic elements which is expected to reduce the power consumption by several orders of magnitude [9].

Here we report on a novel magnetic switching behavior of heteroepitaxial  $\alpha$ -MnAs/GaAs(001) films [10].  $\alpha$ -MnAs films are promising candidates for spin injection at room temperature [11], particularly since on both technologically leading semiconductor substrates, Si(001) and GaAs(001), high-quality epitaxial growth [12–15] and the formation of sharp interfaces [14,16] are routinely achieved. Our study reveals that the magnetization of  $\alpha$ -MnAs/GaAs(001) can be reversed also by a small out-of-plane magnetic field and not only by a magnetic field along the easy axis, as usual. This unexpected magnetization reversal by two independent magnetic input lines opens a new field of applications for  $\alpha$ -MnAs films. We will demonstrate that by a proper choice of in-plane and out-of-plane magnetic fields the basic logic functionalities AND and OR can be realized. By offering a nonvolatile output together with a logic functionality that is programmable at run time,  $\alpha$ -MnAs films are designated for application in future magnetologic devices.

The MnAs films were deposited by molecular beam epitaxy on commercial, 100  $\mu$ m thick, epi-ready

GaAs(001) wafers, which were coated with a 100 nm GaAs(001) buffer layer after removal of the oxide [17]. The deposition rate was 20 nm/h at an  $As_4/Mn$  beam equivalent pressure ratio of 250 and a substrate temperature of 250 °C. Under these conditions MnAs grows predominantly (95%) in its  $A$  orientation with MnAs( $\bar{1}100$ ) || GaAs(001) and MnAs[0001] || GaAs[ $1\bar{1}0$ ] [18]; in addition, a small amount of MnAs in the  $B$  orientation (rotated by 90° in plane) was detected previously [18] as well as a tiny fraction with an out-of-plane magnetization (see below). The easy axis of magnetization lies in the film plane along MnAs[ $11\bar{2}0$ ] [12,15] as in the bulk [19] with the anisotropy fields being large (2.0 T in plane along MnAs[0001] and 1.0 T out of plane, i.e., along MnAs[ $\bar{1}100$ ], in accordance with Ref. [15]).

The key instrument for this study is a sensitive cantilever beam magnetometer (CBM) [20], which enables quantitative magnetic measurements in thin films. ( $25 \times 5$ ) mm<sup>2</sup> sized cantilevers cleaved from 110  $\mu$ m thick GaAs(001) wafers are used as substrates with MnAs[ $11\bar{2}0$ ], i.e., the easy magnetization axis of MnAs [13,15,19], directed along their length. The measurements are based on the well-known fact that magnetic dipoles experience a torque  $\vec{T}$  in external magnetic fields  $\vec{B} = \mu_0 \vec{H}$ , which is related to the magnetization  $\vec{M}$  by  $\vec{T} = V_F \vec{M} \times \vec{B}$ ;  $V_F$  is the involved film volume. With the easy axis of magnetization ( $M_{||}$ ) lying in the film plane along the length of our cantilever beam ( $x$  axis), a magnetic field perpendicular to the film plane ( $B_{\perp}$ ;  $z$  axis) gives rise to a torque, the bending moment ( $T_B$ ) only along the width of the cantilever beam ( $y$  axis).  $T_B$  is related to the beam deflection  $\Delta z$  by [20]:

$$T_B = -V_F M_{||} B_{\perp} = \frac{Ywt^3}{6l^2} \Delta z. \quad (1)$$

Here  $w$ ,  $t$ ,  $l$ , and  $Y$  are the width (5 mm), thickness (110  $\mu$ m), length, and the corresponding Young's modulus of the substrate, respectively. The length  $l$  involved in

bending (19.5 mm) is shorter than the cantilever itself due to clamping and the width of the capacitor needed for measuring the substrate deflection. The Young's modulus in Eq. (1) is canceled upon calibrating the CBM by measuring the substrate deflection due to its own weight after rotation by  $180^\circ$  (for details, see Ref. [20]).

As shown previously [20], magnetic hysteresis loops of thin films can be determined quantitatively with torque measurements by ramping an additional magnetic field ( $B_{\parallel}$ ) along the cantilever beam axis. For the hysteresis measurement of a 60 nm  $\alpha$ -MnAs film, displayed in Fig. 1(a), the magnetizing field  $B_{\parallel}$  is oriented in plane along MnAs[11 $\bar{2}$ 0]. The torque of all data points plotted on the left scale was generated by shortly applying an out-of-plane field  $B_{\perp} = 7$  mT. The scale on the right gives the magnetization  $M_{\parallel}$  calculated from  $T_B$  by Eq. (1). The almost perfectly squarelike hysteresis loop confirms that the easy axis of magnetization lies along MnAs[11 $\bar{2}$ 0]. We obtain a saturation magnetization of  $0.65 \pm 0.05$  MA/m

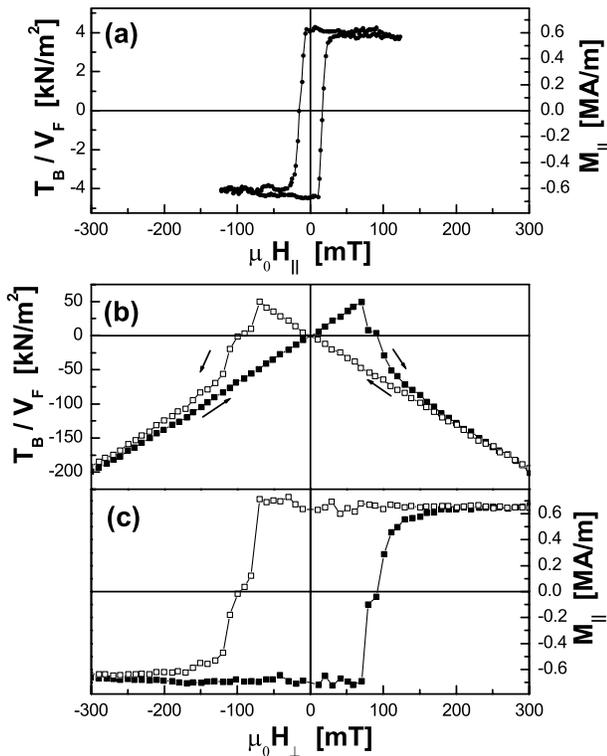


FIG. 1. Torque measurements by CBM of a 60 nm  $\alpha$ -MnAs film on GaAs(001) performed at 5–10 °C: (a) Torque  $T_B$  per film volume  $V_F$  arising from an out-of-plane field  $B_{\perp} = 7$  mT, while ramping the magnetic field along MnAs[11 $\bar{2}$ 0], the easy axis of  $\alpha$ -MnAs; right scale gives the magnetization  $M_{\parallel}$  calculated from  $T_B$  by Eq. (1). (b)  $T_B/V_F$  as a function of the vertical field  $B_{\perp}$ ; note that, in contrast to (a), the magnitude of  $B_{\perp}$  is varied and no in-plane field  $B_{\parallel}$  is applied. (c)  $M_{\parallel}$  calculated by Eq. (1) from the torque in (b); note that the saturation magnetizations in (a) and (c) are identical within experimental error.

which is in good agreement with the bulk value of 0.67 MA/m reported for  $\alpha$ -MnAs at 5–10 °C [21], thus demonstrating that the film is in the ferromagnetic  $\alpha$  phase. The coercive field  $B_c^{\parallel}$  for magnetization reversal is 17 mT.

In contrast to the hysteresis measurement of Fig. 1(a), the torque  $T_B$  plotted in Fig. 1(b) is measured as a function of the out-of-plane field  $B_{\perp}$  (note that different from the preceding experiment  $B_{\perp}$  is varied and no in-plane field  $B_{\parallel}$  is applied). As follows from Eq. (1),  $T_B$  depends linearly on  $B_{\perp}$ , when the film magnetization  $M_{\parallel}$  is constant. A linear increase of  $T_B$  is indeed observed when sweeping  $B_{\perp}$  from  $-300$  to  $+80$  mT (full squares) with a change of sign when the direction of  $B_{\perp}$  is reversed. The magnetization  $M_{\parallel} = 0.68 \pm 0.05$  MA/m calculated from the slope  $\Delta T_B/\Delta B_{\perp}$  is in good agreement with the saturation value derived from Fig. 1(a). We remark that magnetostrictive effects, which also may give rise to a torque [20], depend on  $M^2$ , thus not altering the sign of  $T_B$ , and they are small for  $B_{\perp} < 200$  mT. At  $B_{\perp} \approx 80$  mT, there is an abrupt jump in the curve to negative torque values, which on further increase of  $B_{\perp}$  gradually approach the initial slope of the curve but with opposite sign. An analogous behavior is observed when sweeping the field back (open squares). In Fig. 1(c), the corresponding film magnetization  $M_{\parallel}$ —calculated for the torque experiment of Fig. 1(b) by Eq. (1)—is plotted. Surprisingly again a hysteretic behavior, similar to Fig. 1(a), is obtained. Note, however, that  $M_{\parallel}$  vs  $B_{\perp}$  is plotted and not  $M_{\perp}$  vs  $B_{\perp}$  as in conventional hysteresis loops. The “coercive” field  $B_c^{\perp}$  is about 80 mT, i.e., approximately 4 times larger compared with the magnetization reversal by the  $B_{\parallel}$  field [Fig. 1(a)].

The experiments of Fig. 1—all essentially measuring  $M_{\parallel}$  in excellent agreement with the bulk value—reveal the unexpected result that the magnetization of the  $\alpha$ -MnAs film along the easy axis can be reversed by both in-plane and out-of-plane magnetic fields. We remark that misalignment of the cantilever beam in the out-of-plane field can be definitely ruled out as an explanation of the magnetization reversal. A tilt of  $\sim 10^\circ$  is necessary to yield an in-plane component of  $B_{\perp}$  equal to  $B_c^{\parallel}$  at  $B_{\perp} = 80$  mT, which is far beyond the experimental accuracy of  $1^\circ$ – $2^\circ$ . The peculiar magnetic switching behavior of  $\alpha$ -MnAs/GaAs(001) points to a small MnAs fraction which exhibits an easy magnetization direction that is tilted against the easy axis of the majority of the film (MnAs[11 $\bar{2}$ 0]). In order to comply with the experimental observations, this fraction needs to have both, (i) an out-of-plane component along MnAs[1 $\bar{1}$ 00] ( $M_{\perp}$ ) to be sensitive to a vertical magnetic field and (ii) a component along MnAs[11 $\bar{2}$ 0], which ensures the magnetic coupling with the rest of the film. Its concentration is indeed very small (less than 2%–3%), confirmed by the tiny out-of-plane hysteresis loop measured by SQUID magnetometry [22]. Since the MnAs film is purely in the  $\alpha$  phase at 5–10 °C, inhomogeneous strain effects as discussed in the

$\alpha/\beta$ -phase coexistence region [23] cannot account for the observed out-of-plane anisotropy. Also the small fraction of the  $B$  orientation cannot be held responsible since for that orientation the easy axis ( $\text{MnAs}[11\bar{2}0]$ ) lies in the film plane as well. In principle, such a switching behavior is feasible if the magnetic layer possesses a strong uniaxial anisotropy axis which is slightly tilted against the film plane (canted magnetization).

In the following, we will demonstrate that the strong magnetic coupling between the two  $\alpha$ -MnAs fractions can be advantageously utilized for magnetologic gates made of  $\alpha$ -MnAs. In Fig. 2, we show “hysteresis” loops obtained analogous to Fig. 1(c), but with different in-plane field  $B_{\parallel}$  along  $\text{MnAs}[11\bar{2}0]$  applied, while ramping the torque-generating field  $B_{\perp}$ . At  $B_{\parallel} = -3$  mT and  $B_{\parallel} = +3$  mT, the entire loop is shifted by about  $+50$  and  $-50$  mT along the  $B_{\perp}$  axis, respectively. Obviously, the additional in-plane field  $B_{\parallel}$  either counteracts the magnetization reversal or makes it more feasible, depending on its orientation. These results therefore suggest that the respective coercive fields for the magnetic switching can be controlled on purpose by applying in-plane and out-of-plane fields simultaneously.

To employ the  $\alpha$ -MnAs film as a novel type of magnetologic gate, the two coupled magnetization components  $B_{\perp}$  and  $B_{\parallel}$  are considered as logic inputs  $A$  and  $B$ , respectively. We define  $B_{\perp} = +100$  mT and  $B_{\parallel} = +3$  mT as logic 1 and  $B_{\perp} = -100$  mT and  $B_{\parallel} = -3$  mT as logic 0. The output is determined by the direction of the in-plane magnetization in real space with  $+M_{\parallel}$  and  $-M_{\parallel}$  corresponding to logic 1 and 0, respectively. The input fields may be generated—similar to the existing MRAM technology—by a current through

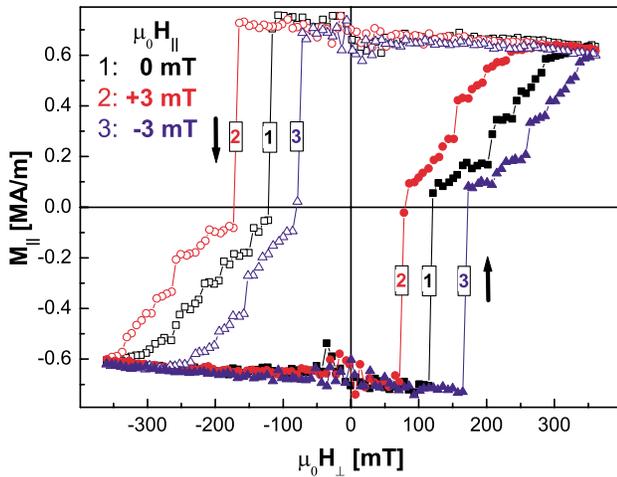


FIG. 2 (color online). Torque measurements, analogous to Fig. 1(c), of a 60 nm  $\alpha$ -MnAs film on GaAs(001) performed at 15°C and with different in-plane fields  $B_{\parallel}$  along  $\text{MnAs}[11\bar{2}0]$  applied. Note that depending on the direction of  $B_{\parallel}$  the entire hysteresis loop is shifted to lower or higher values of  $B_{\perp}$ .

conducting lines in close proximity above or below the magnetic layer for  $B_{\parallel}$ . To generate  $B_{\perp}$ , we suggest placing two additional, parallel lines on either sides of the layer and sending a current of opposite sense through both simultaneously. The output can be read, e.g., via magneto-optic effects or by the giant magnetoresistance effect (GMR) by adding a second magnetic layer with fixed magnetization. Note that the output value is maintained without external power source, i.e., it is nonvolatile, since the direction of the magnetization does not change when the magnetic fields are turned off.

To realize the AND functionality, the  $\alpha$ -MnAs film is set to a well-defined magnetic initial state by an out-of-plane field  $B_{\perp} = -300$  mT and/or an in-plane field  $B_{\parallel} = -50$  mT, which switches the in-plane magnetization to  $-M_{\parallel}$  corresponding to output 0. In a next step, the logical operation is executed by applying both inputs separately. Four different combinations can be distinguished: Applying at both inputs  $A$  and  $B$  a logic 0 ( $B_{\perp} = -100$  mT and  $B_{\parallel} = -3$  mT), the magnetization stays at  $-M_{\parallel}$  corresponding to output 0. When changing only  $B_{\perp}$  to  $+100$  mT, i.e., input  $A = 1$  and input  $B = 0$ , no flip occurs (the output is still 0). If input  $B$  is 1 ( $B_{\parallel} = +3$  mT) and input  $A$  is 0 ( $B_{\perp} = -100$  mT), the field configuration is again not sufficient to rotate  $-M_{\parallel}$ . Only when both inputs  $A$  and  $B$  are set to 1 ( $B_{\perp} = +100$  mT and  $B_{\parallel} = +3$  mT) a flip from  $-M_{\parallel}$  to  $+M_{\parallel}$  occurs. However, the switching is not complete and needs optimization of the film properties and/or the field configuration. The switching behavior is summarized in Table I(a) and obviously corresponds to a logical AND function, where the output is stored.

The logic OR function can be realized by setting the  $\alpha$ -MnAs film to the second well-defined magnetic initial state by an out-of-plane field  $B_{\perp} = +300$  mT and/or an in-plane field  $B_{\parallel} = +50$  mT, which switches the in-plane

TABLE I. (a) AND functionality realized by setting the  $\alpha$ -MnAs film to  $-M_{\parallel}$  prior to the logic operation. (b) OR functionality realized by presetting the film to  $+M_{\parallel}$ .

	Input A ( $B_{\perp}$ /mT)	Input B ( $B_{\parallel}$ /mT)	Output (AND)
(a)	0 (−100)	0 (−3)	0 (− $M_{\parallel}$ )
	0 (−100)	1 (+3)	0 (− $M_{\parallel}$ )
	1 (+100)	0 (−3)	0 (− $M_{\parallel}$ )
	1 (+100)	1 (+3)	1 (+ $M_{\parallel}$ )
	Input A ( $B_{\perp}$ /mT)	Input B ( $B_{\parallel}$ /mT)	Output (OR)
(b)	0 (−100)	0 (−3)	0 (− $M_{\parallel}$ )
	0 (−100)	1 (+3)	1 (+ $M_{\parallel}$ )
	1 (+100)	0 (−3)	1 (+ $M_{\parallel}$ )
	1 (+100)	1 (+3)	1 (+ $M_{\parallel}$ )

magnetization to  $+M_{\parallel}$  corresponding to output 1. In analogy to the discussion above, the only field configuration, which switches  $+M_{\parallel}$  to  $-M_{\parallel}$  (i.e., to output 0), is  $B_{\perp} = -100$  mT and  $B_{\parallel} = -3$  mT, i.e., setting both inputs simultaneously to 0. All other field combinations are not able to flip the magnetization  $M_{\parallel}$ , thus the output being kept at 1 [see Table I(b)].

Note that the logical operation proceeds in two steps: the set step, where the logic functionality of the  $\alpha$ -MnAs film is selected by setting its magnetization to  $-M_{\parallel}$  for AND or  $+M_{\parallel}$  for OR, followed by the logic step. The corresponding NAND and NOR functionalities using the GMR as detection mode is achieved by reversing the magnetization of the analyzer layer.

In conclusion,  $\alpha$ -MnAs/GaAs(001) with two coupled magnetization components is capable of performing magnetism-based logic operations. This novel approach offers several advantages compared to conventional, i.e., charge-based, logic gates: (i) The logic functionality can be preselected to be (N)AND or (N)OR on demand, thus providing magnetologic gates that are programmable at run time. (ii) The output is nonvolatile (such as in MRAMs); therefore a time- and energy-consuming transfer to an external storage is not required. (iii) The magnetization reversal process can be performed by short field pulses, thus minimizing the energy consumption of the device. (iv) MnAs can be easily integrated into nowadays semiconductor technology. (v) The proposed magnetologic device is close to realization since the spin-valve effect has already been demonstrated for MnAs/GaAs/MnAs trilayers [24].

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