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GaMnAs-based hybrid multiferroic memory device

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We report a nonvolatile hybrid multiferroic memory cell with electrostatic control of magnetization based on strain-coupled GaMnAs ferromagnetic semiconductor and a piezoelectric material. We use the crystalline anisotropy of GaMnAs to store information in the orientation of the magnetization along one of the two easy axes, which is monitored via transverse anisotropic magnetoresistance. The magnetization orientation is switched by applying voltage to the piezoelectric material and tuning magnetic anisotropy of GaMnAs via the resulting stress field.

A rapidly developing field of spintronics is based on the premise that substituting charge with spin as a carrier of information can lead to devices with lower power consumption, nonvolatility, and high operational speed.1–3 Despite efficient magnetization detection,4–6 magnetization manipulation is primarily performed by current-generated local switching8 can completely solve the problem.

Molecular beam epitaxy at 265 °C was employed to grow 15 nm thick epilayers of Ga0.92Mn0.08As on semi-insulating (001) GaAs substrates. The wafers were subsequently annealed for 1 h at 280 °C in a nitrogen atmosphere, increasing the Curie temperature to TC~80 K and reducing the cubic anisotropy. The GaMnAs layer was patterned into 2 μm wide Hall bars oriented along the [110] axis by combination of e-beam lithography and wet etching, see Fig. 1. After lithography, 3 × 3 mm2 samples were mechanically thinned to ~100 μm and attached to a multilayer piezoelectric lead zirconium titanate (PZT) ceramic with epoxy, aligning the [010] axis with the axis of polarization of the PZT. Application of positive (negative) voltage VPZT across the piezoelectric introduces tensile (compressive) strain in the sample along the [010] direction, and strain with the opposite sign along the [100] direction proportional to the piezoelectric strain coefficients d33=−2d11. Both coefficients decrease by a factor of 15 between room temperature and 4.2 K. The induced strain ε=ΔL/L for both the [010] and the [100] directions was monitored with a biaxial strain gauge glued to the bottom of the piezoelectric measured in the Wheatstone bridge configuration: Δε=ε[010]−ε[100] = (ΔL/L)[010]−(ΔL/L)[100]=α(R[010]−R[100])/R, where α is the gauge sensitivity coefficient and R is the resistance of the

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FIG. 1. (Color online) (a) Atomic force microscope image of a 2 μm wide Hall bar attached to a piezoelectric. Strain is applied along the [100] and the [010] directions, red dashed lines on the sketch. (b) Hall bar with relative orientation of electrical current I, magnetic field H, and magnetization M.
unstrained gauge. It has been shown before that the strain gradient across the piezoelectric and the sample is negligible: i.e., gauges glued on top of the sample and on the opposite side of the piezoelectric measure similar strain.

Direction of the in-plane magnetization $M$ is measured via transverse anisotropic magnetoresistance (TrAMR), also known as giant planar Hall effect, e.g., a 1° change shifts the center of the loop by ±100 V.

We model the strain along the [010] direction and magnetization aligns itself with [010]. As additional tensile strain is applied along the [010] direction, the [100] direction becomes the easy axis and polarization switches by 90°. The switching occurs in a few steps, indicating a few-domain composition of our device. At $V_{PZT}=0$, the magnetization has two stable orientations, $M∥[100]$ and $M∥[010]$, and the orientation can be switched by applying a negative or a positive voltage on the piezoelectric. Thus, the device performs as a bistable nonvolatile magnetic memory cell with electrostatic control of the state.

The center of the loop can be shifted by adjusting $\varphi_H$, e.g., a 1° change shifts the center of the loop by $\Delta e = 3.5\times10^{-3}$. As $H$ increases, the size of the hysteresis loop decreases, and the hysteresis vanishes for $H > 100$ mT; see inset in Fig. 3. At $H < 40$ mT, the loop increases beyond ±200 V.

We model the strain along the [100] and the [010] directions as an extra magnetostatic energy density term $2\epsilon_{[100]}K_e\sin^2(\varphi_m+45°) + 2\epsilon_{[010]}K_e\sin^2(\varphi_m-45°) = \Delta e K_e \sin(2\varphi_m) + \text{const.}$ Then, for a single domain magnet, the free energy density can be written as

$$E = K_u \sin^2(\varphi_m) + K_I/4 \cos^2(2\varphi_m) + HM \cos(\varphi_m - \varphi_H) + \Delta e K_e \sin(2\varphi_m),$$

omitting constant offset, where $K_I$, $K_u$ and $K_e$, are cubic, uniaxial, and strain anisotropy constants; $H$ is the applied in-plane magnetic field; and $\varphi_m$ and $\varphi_H$ are the angles between the [110] direction and magnetization and magnetic field respectively; see schematic in Fig. 1. We assume that $K_u$ is the same for the [100] and the [010] directions.

In equilibrium, the magnetization orientation $\varphi_m$ minimizes the free energy, $dE/d\varphi_m = 0$ and $d^2E/d\varphi_m^2 > 0$. The TrAMR can be calculated from Eq. (1) for a given angle $\varphi_H$ of the external field $H$. From the fits to the experimental TrAMR data, we can extract the anisotropy constants $K_I$, $K_u$, and $K_e$. The model captures all the essential features of the
data, and corresponding fits are shown in Fig. 2 for the strained and unstrained devices. For the unstrained device anisotropy fields $2K_u/M=40 \text{ mT}$ and $2K_u/M=6 \text{ mT}$. These values are significantly smaller than the previously reported values for as-grown (not annealed) wafers.\cite{2,21} For the sample attached to the piezoelectric the crystalline anisotropy field remains the same, but the uniaxial anisotropy increases to $2K_u/M=50 \text{ mT}$. The strain-induced anisotropy field $\Delta\varepsilon K_u/M$ varies between 13 and 19 mT for different $V_{\text{PZT}}$ between $-200$ and $200 \text{ V}$, the coefficient $K_u/M=17 \text{ T}$. To illustrate the mechanism of magnetization switching, we plot magnetic energy density normalized by magnetization $E/M$ [Eq. (2)] as a function of $\varphi_m$ in Fig. 4. At $H=0$, there are only two minima along the $[100]$ axis due to the large uniaxial strain [see Figs. 4(a) and 4(e)], caused by anisotropic thermal expansion coefficient of the piezoelectric. With $H=50 \text{ mT}$ applied at $\varphi_m=62^\circ E/M$ has two minima: at $\varphi_m=32^\circ$ and at $123^\circ$, i.e., close to the $[010]$ and the $[100]$ crystallographic directions. For the strain field $\Delta\varepsilon K_u/M=13 \text{ mT}$ the global minimum is at $\varphi_m=32^\circ$, and in equilibrium the magnetization is oriented along the $[010]$ direction. As the strain field increases to $19 \text{ mT}$, the two minima switch, and $\varphi_m=123^\circ$ becomes the global minimum. It is interesting to note that there is always a small barrier between the two minima. Unless the barrier is an artifact of our model, the switching of magnetization should be either temperature activated or should occur via macroscopic quantum tunneling.

In our experiments, the magnetic field balances the residual strain due to anisotropic thermal expansion of the PZT. Alternatively, intrinsic piezoelectric properties of GaAs can be utilized. In this case, there will be no thermally induced strain and electrostatic switching of the magnetization direction can be realized without applying an external compensating magnetic field. Scaling of the piezoelectric element from 0.5 mm down to $\sim 1 \mu m$ will compensate for a small strain coefficient in GaAs ($\varepsilon_{33}^{\text{GaAs}}=10\varepsilon_{14}^{\text{GaAs}}$ at 30 K), reduce operating voltage to a few volts, and allow electrostatic control of individual memory cells.

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\begin{figure}[h]
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\includegraphics[width=\textwidth]{fig4.eps}
\caption{(Color online) (a) Polar plot of magnetostatic energy $E/M$ as a function of magnetization angle $\varphi_m$ for $H=0$ (black), 50 mT (blue) and 100 mT (red) for $\varphi_m=62^\circ$ and $V_{\text{PZT}}=0$ ($\Delta\varepsilon K_u=16 \text{ mT}$). (b) Angular dependence of $E/M$ for $\Delta\varepsilon K_u=13–19 \text{ mT}$ (black to magenta) for $H=0$ (c), $H=50 \text{ mT}$ (d) and $H=100 \text{ mT}$ (e). Blue line and arrow mark $\varphi_m=62^\circ$; dashed red lines indicate two stable orientations of magnetization.}
\end{figure}

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