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# Simulation study of an electrically read- and writable magnetic logic gate

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ABSTRACT

In order to keep up with economic growth and competitiveness the performance of microelectronic components will continuously increase, thanks to the introduction of new device types and materials. Spin based technologies are promising candidates because of their fast switching capability, high endurance, and non-volatility. Furthermore, the use of spin as a degree of freedom permits the combination of information storage and processing in a single device creating a fully non-volatile information processing system and thus allowing an even denser layout of simplified building blocks. Recently a fully electrical read–write 1 bit demonstrator memory device out of a ferromagnetic semiconductor has been shown and it has been proposed to extend this device to a logic XOR gate. However, up to now neither the feasibility of this gate nor the extendability to further logic gates has been shown. In this work we carried out a rigorous simulation study of the proposed logic gate. We are able to show that firstly the magnetization can be switched diagonally. Secondly, by changing the relative angle between the current flow path and the magnetization, not only a XOR gate is feasible but also (N)AND and (N)OR gates can be realized.

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## 1. Introduction

Diluted magnetic semiconductors (DMS) belong to the group of extensively studied (prototype) materials for future devices [1]. Especially one member of this group – $(Ga, Mn)As$ – is of interest due to its compatibility with established semiconductor technology, carrier mediated ferromagnetism caused by *sp—d* exchange [2], and its cubic anisotropy which can be modified to an in-plane bi-axial anisotropy ([1 0 0], [0 1 0]) for compressively strained thin films or an easy axis out of plane ([0 0 1]) for tensile strained thin films [3]. Hümpfner et al. [4] showed that by lithographical means local stress relaxation can be used to taylor the local anisotropy type. It was demonstrated that due to anisotropic stress relaxation, leads along [1 0 0] and [0 1 0] exhibit uni-axial anisotropies along these axes, respectively. Mark et al. [5] connected two pairs of such leads (along [1 0 0] and [0 1 0]) with a disk exhibiting a bi-axial anisotropy and thus enabled a realization of an electrically writable 1 bit demonstrator device. They also proposed an electrically read- and writable XOR gate consisting of two disks connected by a small constriction. Pappert et al. [6] connected two orthogonal and uni-axially relaxed leads by a small constriction and showed that the overall electrical resistance of the structure depends on the angle between the current flow $\vec{j}$ and the local magnetization $\vec{m}$ at the constriction. For a small constriction (~tens of nanometers) and $\vec{j} \| \vec{m}$ the structure exhibited a several times bigger resistance (up to more than 5 times) compared to $\vec{j} \perp \vec{m}$. Therefore, combining two disks with bi-axial anisotropies, uni-axial leads, and a constriction connecting the disks, allows to combine memory and logic in one structure. Additionally this device allows an even denser layout on top of the density gain by scaling due to the merging of logic and memory units. We show that the disks can be switched by horizontal and diagonal current flow, scaling leads to smaller switching times, and the possibility of further logic gates by changing the angle between the current density $\vec{j}$ and the magnetization $\vec{m}$ at the constriction.

## 2. Methods

For the simulation study of the proposed structure disk radii of 160, 80, and 40 nm were used. Furthermore, a fixed constriction length and width of 15 nm, a saturation magnetization $M_S$ of 32000 A/m [2], a cubic anisotropy with its easy axis oriented parallel to the leads and a cubic anisotropy constant $K_C$ of 2000 J/m$^3$ [3] for the $(Ga, Mn)As$ film were assumed. It was further supposed

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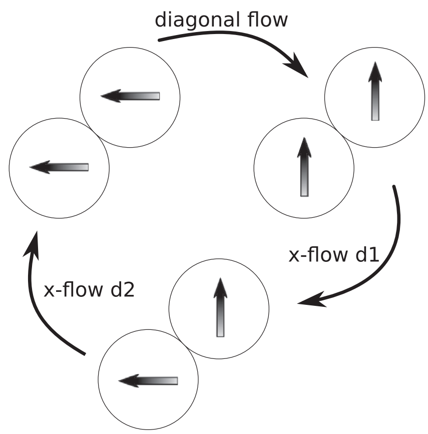


**Fig. 1.** The different initial and ending states and the current paths needed for transition between these states are depicted. The cycle begins with both disks exhibiting a magnetization along 90° and applying a horizontal current flow through disk $d1$ to reach the state, where the magnetization in $d1$ is flipped to 180°, while in disk $d2$ the magnetization is still oriented along 90° (x-flow $d1$). From there a horizontal current flow is applied through $d2$ to orient the disk in the same direction as $d1$ (x-flow $d2$). In order to reset the two disks to their initial state a diagonally flowing and through the constriction passing current is applied (diagonal flow).

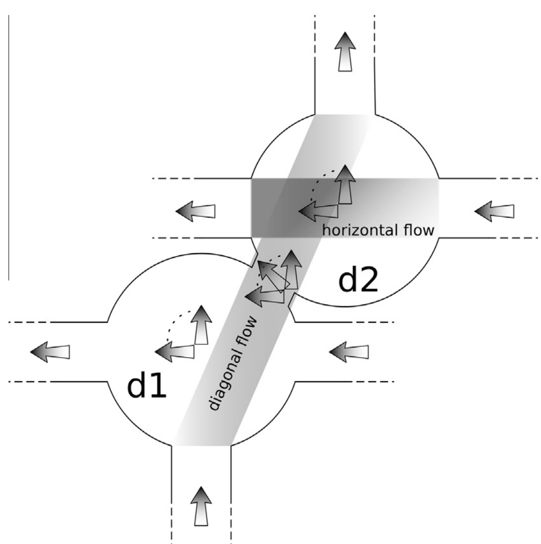


**Fig. 2.** The magnetization in the leads is fixed and oriented along 180° for horizontal leads and along 90° for vertical leads. The disks can be switched between the two states by either applying a horizontal or a diagonal current. At the constriction the resulting magnetization is a superposition of the magnetizations in $d1$ and $d2$ and, therefore, the magnetization at the constriction is switched in multiples of 45° between 90° and 180°.

that the magnetization of the leads is fixed, Gilbert damping $\alpha = 0.02$, current polarization $P = 0.7$, a dimensionless parameter $\beta = \alpha$ for the non-adiabatic spin-transfer torque (STT) contribution [7], and a uniform exchange constant $A_{exch}$ of $4 \times 10^{-14}$ J/m [8]. In a first step current density profiles for the different radii and current paths from self-consistent transport simulations [9] were gained (see Figs. 6–8). These profiles were used in a STT model, which was extended to enable arbitrary 2D current density profiles. The model is based on a STT model from IBM research Zürich [10] and takes advantage of an Object Oriented Micromagnetic Framework [11]. Current densities between $1 \times 10^{10}$ and $5 \times 10^{11}$ A/m² and a pulse time of 20 ns were used.

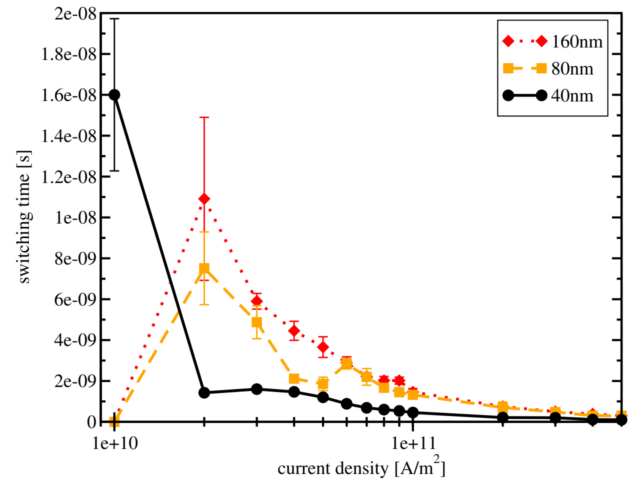


**Fig. 3.** Switching times for x-flow $d1$ at 40, 80, and 160 nm, respectively.

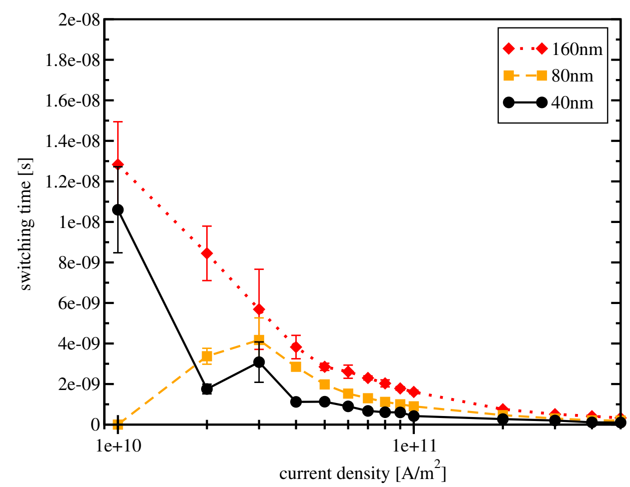


**Fig. 4.** Switching times for x-flow $d2$ at 40, 80, and 160 nm, respectively.

Out of all possible switching combinations a representative path that switches between three different logic states was studied (see Fig. 1), taking care that every disk is at least switched once and at the end of the cycle the initial state is regained. Switching is realized by either switching a single disk with a horizontal current flow (x-flow $d1/d2$) or by a diagonal current flowing through the constriction (cf. Figs. 2,6,7,8).

## 3. Results

### 3.1. Switching times

In order to get a relation between the switching times, applied current densities, and scaling, the switching times as function of applied current density and disk size were extracted. The switching time has been defined as the difference between the start of the current pulse and when the magnetization reaches 80% of its equilibrium state (for a successful switching). Furthermore, to improve the accuracy of the results, all data points shown are an average over several simulations (in the range of ±5% of the corresponding current density) and the error bars depicted in Figs. 3–5 state the respective standard deviation $\pm\sigma$. In cases without switching events the corresponding switching times were set to 0 s. The switching probabilities (number of successful outcomes over all simulations) are in the range of ≈ 30% to ≈ 90% and a total aver-

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