Lateral spin transfer torque induced magnetic switching at room temperature demonstrated by x-ray microscopy

M. Buhl1,2, A. Erbe1, J. Grebing1, S. Wintz1,2, J. Raabe3 & J. Fassbender1,2

1Helmholtz-Zentrum Dresden-Rossendorf, 2 Technische Universität Dresden, 3Paul Scherrer Institut.

Changing and detecting the orientation of nanomagnetic structures, which can be used for durable information storage, needs to be developed towards true nanoscale dimensions for keeping up the miniaturization speed of modern nanoelectronic components. Therefore, new concepts for controlling the state of nanomagnets are currently in the focus of research in the field of nanoelectronics. Here, we demonstrate reproducible switching of a purely metallic nanopillar placed on a lead that conducts a spin-polarized current at room temperature. Spin diffusion across the metal-metal (Cu to CoFe) interface between the pillar and the lead causes spin accumulation in the pillar, which may then be used to set the magnetic orientation of the pillar. In our experiments, the detection of the magnetic state of the nanopillar is performed by direct imaging via scanning transmission x-ray microscopy (STXM).

The state of small magnetic entities has been used for data storage for some decades. Developments, e.g. based on giant magnetoresistance (GMR)1,2 or tunnelmagnetoresistance (TMR)3,4 effects, have enabled the nanoscale integration of these entities into large area devices such as hard disk drives. The state of these structures is usually set by the application of external magnetic fields. The generation of these fields at the location of the nanoscale magnetic memory requires the very precise positioning of a magnetic write head with respect to the element. This process, however, has not only the drawback of being time-consuming and technologically involved, but is also accompanied by parasitic stray fields that may limit the achievable storage density. Therefore, techniques allowing for magnetic switching without the necessity of applying an external field have been investigated extensively during the past years in the field of spintronics5, a terminus which stands for the concept of using the electron spin for information storage and manipulation. The torque which is exerted by a spin polarized current on the electrons in a conductor depends on the relative orientation of the corresponding spin moments. A spin polarized current entering a ferromagnetic element thus may change the magnetization orientation of this element and by this information can be stored inside it. The underlying effect, called spin transfer torque (STT)6,7, has been studied intensively in several magnetization switching experiments using time-resolved STXM8–10. However, most of the structures investigated so far have in common that they require vertical integration of the memory cell in the so-called current perpendicular to the plane (CPP) configuration, making the circuit design and fabrication rather complicated. In contrast, demonstration of STT induced switching of magnetic nanostructures with a purely horizontal contact layout would open various efficient possibilities for large scale integration of STT magnetic memories. In our layout, the number of necessary lithography steps is reduced to 2 as opposed to at least 3 steps in the case of vertical magnetic nanostructures. In addition, the technologically challenging side-wall isolation of the magnetic pillars is not necessary in our design.

We have developed a layout consisting of a nanoscale, elliptic magnetic structure (“nanopillar”) and two micronscaled, rectangular magnetic elements (“polarizers”) as shown in figure 1. Both, the central pillar and the surrounding polarizers are fabricated from CoFe at a thickness of 8 nm. The magnetic anisotropy at this thickness enforces the magnetization to be oriented in the plane of the film. In addition, the elliptical shape of the central pillar leads to anisotropy energy in the plane of the pillar, which is minimized for a magnetization along the long axis of the ellipse. Thus, two energetically equivalent magnetic configurations arise as ground states for the pillar.

The electrical connection between the polarizers and the pillar is provided by a Cu line of 5 nm thickness and 100 nm width that also extends to underneath the polarizers. The total length of the Cu line between the polarizers is 280 nm, which is of the order of the typical spin coherence length in pure Cu at room temperature11. Our circuit thus allows us to generate a spin-polarized current below one of the polarizers, which flows...
underneath the pillar into the direction of the second polarizer. This kind of design is called a current in plane (CIP) configuration. Theoretical calculations have shown that in such CIP configuration the efficiency for STT induced magnetization switching due to spin diffusion is of similar order as in CPP configurations, i.e. configurations in which the charge current passes directly through the pillar. Recent experiments have indeed demonstrated electrical measurements for the switching of magnetic nanostructures in CIP configurations at low temperatures (between 10 K and 77 K). Here, we show the first experimental realization of directly imaging the magnetic state of a nanostructure in CIP configuration before and after switching events by using STXM and exploiting x-ray magnetic circular dichroism (XMCD) effects. Corresponding micrographs and the construction of the magnetic contrast images are demonstrated in figure 2. Furthermore, the size scale and the layout of our sample even allow for the operation and detection of CIP STT switching at room temperature. This opens the way for a fundamental characterization of the switching mechanisms in static and dynamic experiments as well as for the development of possible applications incorporating CIP configurations in this area.

Discussion

In order to prove the significance of the STT effect for the switching processes observed we will discuss and subsequently exclude other possible switching mechanisms, such as induced by stray fields, Oerstedt fields, or device heating, in the following.

In order to confirm that the magnetic field in the center of our structure is indeed zero, micromagnetic simulations of the stray field originating from the polarizers in the configuration shown in figure 3 were carried out (details of the simulation can be found in the SI). As expected, the polarizer induced stray fields at the location of the pillar are negligible ($\mu_0 H < 0.1$ mT). We have further tested the influence of magnetic fields on the magnetization of the pillar by performing measurements at externally applied, supporting fields $H_{ext}$ (shown in the SI). The values of the current density needed to perform switching, $j_{sw}$ in the nanopillars are similar for all elements, regardless of the value of $H_{ext}$. We can thus conclude that application of $H_{ext}$ does not alter the switching for the majority of the structures. It is, however, remarkable that a small number of samples can be switched with applied $H_{ext}$ only. This supporting field then needs to be close to the switching field without additional spin transfer torque. In most cases, however, the values of $j_{sw}$ are symmetric around 0 T. This indicates that the influence of stray fields originating from the polarizers is...
**Figure 2** | (a) STXM image of the central area of the spin torque device including the two polarizers and the magnetic pillar in the center. The upper image shows the direct absorption contrast caused by the metallic layers. The images are recorded at the absorption maximum of Co, i.e. $E = 780 \text{ eV}$. The lower image shows the contrast given by different absorption of the transmitted x-rays due to XMCD indicating the magnetization directions of the two polarizers. In our images black structures correspond to the magnetization pointing to the right side (positive values of $H$), and white structures to the magnetization pointing to the left side (negative $H$). This contrast is achieved by depicting the normalized intensity difference $c_{\text{XMCD}} = \frac{I^+ - I^-}{I^+ + I^-}$ of the two images taken at different polarizations. (b) Zoom on the central pillar and construction of the magnetic contrast images. The central region containing the nanopillar (highlighted by the dashed circle) is scanned with circularly polarized x-rays. The contrast of spin-polarized regions depends on the polarization, thus subtraction of the images shows the magnetic contrast in the structure. It can be seen in (a) that the Au leads connecting the polarizers to the current pulser disappear in the magnetic contrast image.

**Figure 3** | Switching of the pillar without supporting magnetic field. It is shown that switching in both directions can be performed at identical absolute values of the current density using 5 and 2 consecutive pulses, as well as single pulses.
passing underneath the pillar during each current pulse cannot be
mental values for these quantities, an estimate of the spin current
diffusion length in the Cu stripe or the degree of spin polarization of
nanopillar can be performed in order to obtain values for the spin
STXM. Therefore, no electrical transport measurements through the
Curie temperature are relevant here. As even for elevated tempera-
ture of the wire, we obtain a planar shape anisotropy
of the bulk Co (TCurie(Co) = 1400 K), as well. The
superparamagnetic limit for Co nanostructures, which exceed
volumes of \(1 \times 10^{-15}\) m\(^3\), lies above 1000 K, therefore bulk values for
Curie temperature are relevant here. As even for elevated tempera-
tures the ratio of thermal and anisotropy energy is \(\ll 1\), thermal
effects can be neglected as mechanism significantly supporting the
magnetization switching in our case.

We now turn to the discussion, whether our results can be
explained by pure spin transfer torque switching. The geometry
shown in figure 1 is optimized for the experiments performed using
STXM. Therefore, no electrical transport measurements through the
nanopillar can be performed in order to obtain values for the spin
diffusion length in the Cu stripe or the degree of spin polarization of
the conduction electrons of the CoFe elements. Without experi-
mental values for these quantities, an estimate of the spin current
passing underneath the pillar during each current pulse cannot be
achieved. We therefore have to limit our discussion to a qualitutive
comparison between our structure and the structure reported by
Yang et al.\(^{12}\). In both structures, a Cu line connects two magnetic
structures, one of which is used as a polarizer, the other one as a
detector for the spin polarized current. Our data are recorded on
pillars consisting of CoFe, while the nanostructures in\(^{12}\) are made from permalloy. The distance between the pillar and the polarizer is
90 nm in our structures as opposed to 270 nm reported in\(^{12}\) or
400 nm in\(^{11}\). This explains, why we are able to observe spin transfer
torque in our structures at room temperature in a CIP configuration.
We have shown that elliptical nanopillars can be switched between
their two preferred magnetic states by passing a spin-polarized
current underneath the pillars, and we can image the different states
before and after the switching using STXM. For our structures
(elliptical pillars with dimensions of 100 nm \(\times\) 120 nm) we can
exclude all other switching sources as, for example stray fields,
Oersted fields or heating. This study, therefore, provides an unam-
biguous demonstration of the switching by spin transfer torque
(STT) in a current in plane (CIP) geometry and paves the way for
future developments of such structures aiming at integration of these
structures into fully planar device architectures. Furthermore, time-
resolved studies of the dynamics of this switching mechanism will be
possible in the future.

Methods

The devices were fabricated on Si\(_3\)N\(_4\)membranes with a thickness of 100 nm. The
metallic multilayers were deposited by magnetron sputtering before patterning the
nanostructures in order to ensure optimal layer quality and interface integrity.
The layer consists of 2 nm Ta for a barrier, 5 nm Cu for the conductive part of the spin-

diffuse electrons, 8 nm of CoFe, and a Ru capping layer of 3 nm. By varying the
Fe content of the CoFe layer we can adjust the magnetic softness of the pillar\(^{14}\) and,
thus, the coercive field needed to switch the magnetization. Addition of Fe to the stack
reduces, however, the imaging contrast of our structure in the STXM experiments (see
below).

The metallized membranes were subsequently structured using electron beam
lithography and dry etching using both positive and negative lithography steps. The
metallic layers are removed using argon ion beam etching. In a first step, the polar-
zers and their connection including the pillar are defined by removing the stack at all
other positions of the sample. The remaining lithography steps are performed on a
metal-cored coil providing a static magnetic field parallel to the magnetization
in a lift-off process. The samples are contacted on a circuit board with high-frequency
source-drain connections.

The switching of the magnetic state of the nanopillar is performed by driving a
pulse of spin-polarized current underneath and through the pillar. In order to gen-
rate an in-plane pulse we apply a positive current across the pillar, and then stop the


current passing the polarizers and the Cu connection under the pillar. Depending on the
resistance ratio between the Cu connection and the CoFe pillar, a fraction of the
current flows through the pillar directly, as well. For the geometry and material
composition in our experiment, we estimate that a fraction of 1/5 flows through the
pillar and a fraction of 4/5 is spin-polarized in the Cu stripe. The different aspect ratios
of the polarizers (shown in figure 1) lead to different coercive fields\(^{14}\); the magnet-
ization points along the long axis of the polarizers and parallel to the surface of the
sample. As a consequence the polarizers can be set in either one of the two available
states with magnetization pointing to the left or to the right (see figure 1 for details)
and in an antiparallel configuration, as well. The magnetization of the polarizers
defines the majority charge carriers injected into the Cu lead connecting the two
polarizers. Therefore we have the possibility to pass a spin-polarized current through the
Cu connector, which is polarized in either one of the two directions, left or right.
When the magnetization of the pillar at the center of the structure is antiparallel to the
polarizers, the current, spin transfer torque (STT)\(^{20}\) acts on the spins in the pillar
because of spin diffusion through the Cu/CoFe interface. The goal of our experiments
is twofold: to demonstrate that STT is strong enough to switch the direction of
magnetization of the pillar at nondestructive current levels, and to image the magnetic
state of the pillar before and after switching.

In order to characterize the magnetic state of our structures, we perform magnetic
imaging in a scanning transmission x-ray microscope (STXM) at the swiss light
source (SLS) beamline X07DA (Pilatus). Using circularly polarized x-rays we image the
spin density of the unoccupied d-band exploiting the effect of x-ray magnetic
circular dichroism (XMCD)\(^{13}\) effect. The x-rays are focused by passing through a
metal-core coil providing a static magnetic field parallel to the magnetization
direction of the polarizers. This external field is used to define the magnetization of the
polarizers and, in some of the experiments, as a supporting field aiding the
switching of the pillar.

We perform measurements of the magnetic behavior of the pillar and the polarizers
by changing the static magnetic field \(H_{app}\) step by step and recording STXM images at
each value of \(H_{app}\). A STXM overview of the whole configuration in antiparallel
alignment can be seen in figure 2. Here, the magnetization of the pillar in the center
always points parallel to one and anti-parallel to the other of the two polarizers. Thus,
passing a current underneath the device in one direction can switch the magnetization
of the pillar. Driving the current in the opposite direction provides spin polarization
of the magnetization of the pillar at the interface and, therefore, does not lead to changes in
the magnetization. Switching without a supporting magnetic
field can be performed in both directions by varying the direction of the current as
long as the magnetization directions of the polarizers do not change.
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Author contributions M.B. and J.G. carried out the device fabrication. M.B., A.E., J.G., S.W. and J.R. performed the STXM experiments. A.E., M.B., S.W. and J.G. interpreted the data. J.F. and A.E. designed the experiment, M.B. and J.G. prepared the figures. All authors discussed the results and contributed to the manuscript preparation.

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