

Optimization of nanostructured permalloy electrodes for a lateral hybrid spin-valve structure

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Ferromagnetic electrodes of a lateral semiconductor-based spin-valve structure are designed to provide a maximum of spin-polarized injection current. A single-domain state in remanence is a prerequisite obtained by nanostructuring Permalloy thin film electrodes. Three regimes of aspect ratios $m$ are identified by room temperature magnetic force microscopy: (i) high-aspect ratios of $m \geq 20$ provide the favored remanent single-domain magnetization states, (ii) medium-aspect ratios $m \sim 3$ to $m \sim 20$ yield highly remanent states with closure domains and (iii) low-aspect ratios of $m \leq 3$ lead to multi-domain structures. Lateral kinks, introduced to bridge the gap between micro- and macroscale, disturb the uniform magnetization of electrodes with high- and medium-aspect ratios. However, vertical flanks help to maintain a uniformly magnetized state at the ferromagnet-semiconductor contact by domain wall pinning.

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I. INTRODUCTION

Lateral ferromagnet-semiconductor (FM-SC) devices have attracted much interest for future all-electrical spintronics applications such as spin valves or spin transistors. Hereby, ferromagnetic electrodes are sought to spin polarize a current which is subsequently injected into a semiconductor allowing spin manipulation by purely electrical means. While other materials such as half-metals or ferromagnetic semiconductors are strongly favorable because of high spin polarization and high spin injection rates they suffer major drawbacks due to difficult technological processing and the lack of stable long range ferromagnetism at room temperature. Until today, only ferromagnetic metals provide high enough Curie temperatures for reliable room temperature operation. Unfortunately, ferromagnetic transition metals (Fe, Ni, Co) and the technological relevant alloys (e.g. Permalloy) only allow a moderate spin polarization up to 45 % [1]. Therefore we aim at the maximum spin polarization possible by realizing a uniform magnetization at the FM-SC contact. For zero-field operation a magnetic single domain state in remanence of the ferromagnetic electrodes is essential. The magnetization configuration of soft ferromagnetic thin film elements are dominantly determined by geometry. This permits tailoring of the remanent domain configuration and coercive fields by variation of the length-to-width aspect ratio in rectangular elements. However, in recent works on lateral FM-SC spin valves multi-domain states at remanence prevail or magnetic domain states and stray field contributions were not characterized. A multi-domain configuration of low aspect ratio Py structures as discussed by G. Meier et al. leads to a reduction of the stray field, but an application for zero-field operation is limited as a maximum degree of spin-polarization cannot be achieved. Furthermore, for low-aspect ratio Py platelets a variety of different metastable remanent magnetic states can be found, although a well defined remanent domain state is favorable.

In this work, we propose a lateral FM-SC spin-valve layout for a maximum possible spin polarization in remanence (zero-field operation) and a minimum of well-controlled stray fields. Single-domain rectangular Py electrodes are tailored by nanostructuring high-aspect ratios and characterized in detail by magnetic force microscopy (MFM). For application in a lateral hybrid device additional lateral kinks and vertical flanks may have to be considered. Lateral kinks may bridge the gap between the micro- or nanoscale electrodes and macroscale bond pads, and vertical flanks may arise from the transition of a thick field oxide to a thin tunneling oxide at the edge of the FM-SC contact area. We show that lateral kinks lead to domain wall formation and vertical flanks act as domain wall pinning centers. Our MFM study comprises three steps. First, we map the multidomain to single-domain transition for rectangular Py micro- and nanostructures over a wide range of aspect ratios. Second, a reliable maintenance of the highly remanent state in high-aspect ratio Py wires is proven by application of magnetic fields prior to imaging. Third, the influence of lateral kinks and vertical flanks on the formation of domain walls is studied for a lateral Py-InAs spin-valve structure.

II. PREPARATION AND EXPERIMENT

In order to prepare the multi- to single-domain transition rectangular polycrystalline Py micro- and nanostructures are prepared on p-Si (111) and undoped n-type InAs (100) by electron-beam lithography (EBL), electron-beam evaporation (EBV) and lift-off. The length $l$ varies...
from 200 nm up to 60 μm and the width w from 200 nm up to 30 μm, covering aspect ratios m = l/w from 1 to 105 (Py thickness t = 38 nm and 50 nm).

Lateral Py-oxide-InAs spin-valve structures are prepared by high-resolution EBL and lift-off patterning. InAs exhibits a strong spin-orbit interaction which makes it an interesting candidate for spintronic applications. First, a 200 nm thick electrically isolating SiO2 film is sputtered on the InAs substrate. Then a 20 μm thick contact area is reopened to the InAs substrate by means of optical lithography and wet chemical etching. A thin tunneling oxide is thermally grown at T = 140 °C in dry O2 for 120 min. Finally, the 30 nm thin film Py electrodes are prepared by patterning a 80 nm PMMA (polymethylmethacrylate) film using EBL at 5 kV, EBV and lift-off in acetone. The electrodes with overall lengths of 150 μm are placed across a 20 μm wide tunneling contact area. Electrical access to the electrodes is achieved by bond pads on the thick field oxide outside the FM-SC contact area. The electrodes 2 μm and 0.4 μm wide are separated by 0.2 μm.

MFM is performed with a Nanoscope MultiMode scanning-probe microscope (DI) operating in the TappingMode/LiftMode. A commercially available probe (MESP, DI) is used and pre-magnetized along its vertical axis. Lift scan heights of about 120 nm are applied to minimize the probe-induced perturbations.

Two-dimensional micromagnetic simulation were performed by NIST package OOMMF.

### III. RESULTS AND DISCUSSION

#### A. Multidomain to single-domain transition

Fabrication of single-domain ferromagnetic electrodes for a zero-field operation in FM-SC hybrid devices requires a precise knowledge of the influence of electrode geometry on remanant magnetization. The remanant domain configuration of a rectangular thin film Py structure can accurately be controlled by its aspect ratio m because the magnetocrystalline anisotropy is negligible at room temperature and the resulting magnetization arrangement is determined by the competition between the exchange energy and the stray field energy. Here, we map the multi- to single domain transition for the range of aspect ratios m from 1 to 70. We find, in accordance with Gomez et al. [13], that Py microstructures of low-aspect ratio (m from 1 to 3) invoke five principle multidomain patterns. As an example, the multidomain MFM image of a low-aspect ratio (m = 2.5) rectangular Py structure is shown in Fig. I(a), micrograph (I). Dark and light contrasts indicate perpendicular stray field components of the tilted diamond pattern consisting of seven domains in flux closure configuration. Aspect ratios m of about 3 denote a transition from multidomain states to highly remanent magnetization states which originate for m ≥ 4. MFM images of highly remanent domain states consist of a featureless central region which indicates a uniform magnetization parallel to the long axis of the microstructures and dark or light stray field contrast from fan-type closure domains at both ends. The extension of the closure domains diminish and the regions of homogeneous magnetization increase with increasing aspect ratio. An example of a MFM image exhibiting highly remanent magnetization states is given for two Py stripes with medium aspect ratios m = 14 in Fig. I(a), micrograph (II). Finally, single domain states are observed for high-aspect ratios of m ≥ 20. By MFM imaging closure domains are not anymore resolved and perpendicular components of stray fields at the wire ends are marked as structureless black and white spots as shown in Fig. I(a), micrograph (III) for two Py stripes with high-aspect ratios of m = 57 (top) and m = 43 (bottom).

The transition from a multi- to a single-domain state is summarized in Fig. I(b). The plot establishes validity regions of (I) multidomain patterns, (II) highly remanent magnetization states and (III) single domain states for the investigated structure sizes l and corresponding aspect ratios m. A transition line from single-domain state to highly remanent state is included from a phenomenological model developed by A. Aharoni [17] for ellipsoidal particles. Below a lower bound, namely the minor semi-axis a, ellipsoidal particles are found to be in a single-domain state in remanence. The lower bound depends on the exchange interaction, on the saturation magnetization, and on the aspect ratio between the particle’s major and minor axis m’.

According to Seynaeve et al. [19] a critical length Lc = 2m’a0 separates the multidomain states (above Lc) from the single-domain states (below Lc). For the calculation of Lc the bulk saturation magnetization of Py, 800 kA/m, is taken and an exchange constant of 1.3·10−9 J/m is required, 2 orders of magnitude higher than the reported bulk value of Py [15]. A comparable deviation was found in the analogue evaluation of domain structures for Co microstructures [19]. While the model is based on ellipsoidal particles, we investigate rectangular Py microstructures, and this profoundly changes the calculation of the stray field. Furthermore, the prepared structures exhibit finite surface and edge roughness due to vapor deposition and lift-off, which introduces magnetization inhomogeneities at the edges. Finally, experimental MFM data exhibit a resolution limit of the order of the probe lift-scan height, which is approximately 120 nm. Therefore, the phenomenological model [17] cannot be expected to match quantitatively, however, the observed qualitative agreement of the multi- to single-domain transition indicates the same underlying fundamentals of scaling behavior.

#### B. Lateral spin-valve configuration in remanence

A lateral FM-SC hybrid spin valve consist of two spin-polarizing and -detecting ferromagnetic electrodes placed on top of a semiconductor substrate (spin transport chan-
nel). For a spin-valve effect distinctly different switching fields of the ferromagnetic electrodes are required. As shown above, a single domain state in remanence is provided by elongated rectangular Py electrodes of high aspect ratios. The switching field of elongated Py wires are essentially determined by their widths and our magnetoresistance effects on behalf of spin injection. First, a reproducible, stable remanent magnetic domain configuration after magnetic field sweeps is required. Second, side effects as stray field contributions have to be kept to a minimum.

Below, we demonstrate two prerequisites for magnetoresistance experiments in order to resolve subtle magnetoresistance effects on behalf of spin injection. First, a reproducible, stable remanent magnetic domain configuration after magnetic field sweeps is required. Second, side effects as stray field contributions have to be kept to a minimum.

Prior to MFM imaging Py wires of aspect ratios 14 to 33 were magnetized by applying longitudinal magnetic fields of different amplitude and polarity. MFM images of single domain and highly remanent Py wires are shown in Fig. 2. Wire lengths of 20 µm resemble the electrode sections within the FM-SC contact area in the lateral FM-SC spin-valve structure discussed in section D. The two wires labelled as (I) and (II) exhibit typical widths for lateral spin-valve devices of 0.5 µm and 1.4 µm, respectively. After applying a magnetic field of +60 mT (Fig. 2 (a)) all wires are magnetically saturated. In a reversed field of -20 mT (Fig. 2 (b)) the broad wire II is switched. At fields of -60 mT all wire magnetizations are reversed. This subsequent switching occurs all the same in a reversed magnetic-field sweep. Hence, for parallel Py wires of different aspect ratios magnetic field induced parallel and antiparallel magnetization configuration are stable in remanence. Furthermore, for wires such as (I) and (II) an antiparallel magnetization configuration exists over a field range of several ten mT which is suitable for spin blockade experiments.

The lateral extension Δl over which perpendicular stray fields arise from magnetic inhomogeneities at the wire ends can be roughly quantified from MFM images. Due to the finite radius of the MFM tip as well as the distinct scan height the ratio of Δl/l of Fig. 2 gives an upper bound, which is given in Fig. 3. As a lower limit, we have also inserted in Fig. 3 the values of the lateral extension of magnetic inhomogeneities in simulated two-dimensional structures with corresponding aspect ratios but lower total length (2 µm). For higher aspect ratios Δl is clearly reduced. It is noteworthy that the electrodes of the lateral spin-valve structure proposed in section D have much larger aspect ratios of 375 and 75. The FM-SC contact area exhibits no wire ends. Hence, the lateral extension of magnetic inhomogeneities at the edges of the FM-SC contact area is expected to be strongly reduced or even nil.

C. Lateral kinks in medium aspect ratio wires

The influence of lateral kinks on the highly remanent domain configuration of elongated Py microstructures is outlined for medium aspect ratios \( m \geq 4 \). The domain configuration is strongly perturbed by kink angles between 10° and 90°, as can be seen from MFM images of Py wires with an aspect ratio of 10 \( (w = 2 \mu m, l = 10 \mu m) \) in Fig. 4. An undisturbed, straight wire (Fig. 4(a)) features the highly remanent domain configuration with significant closure domains at both ends and a uniformly magnetized mid-part. However, a 10° kink changes the domain configuration drastically (Fig. 4(b)). Here, cross-tie walls separate two main domains. With increasing kink angle the domain configuration transforms back to highly remanent states, but a significant magnetization inhomogeneity at the centre of the structure is observable (Fig. 4(c), (d)). For kink angles larger than 70° domain walls are clearly visible at the kink. Micromagnetic two-dimensional simulation of the magnetization distribution of similar elongated Py wires with aspect ratio \( m = 10 \) show equally that small lateral kink angles of 10 degree suffice to introduce magnetic inhomogeneity (Fig. 5). For the simulation the structure length had to be reduced to 2 µm, and a discrete cell size of 10 nm were chosen.

In summary, horizontal kink angles introduced in a Py wire of medium aspect ratio disturb the highly remanent domain state. Fortunately, as shown in section D vertical flanks prevent the originated magnetic inhomogeneities from extending into the FM-SC contact of a lateral spin-valve.

D. Lateral kinks and vertical flanks in high aspect ratio wires: optimized spin-valve geometry

Following the above domain investigations an optimized electrode geometry of a lateral spin-valve structure can be set up to study spin-dependent transport phenomena in low- or zero-field operation. In order to unambiguously identify electrical spin-injection in magnetotransport the lateral spin-valve structure must fulfill the following requirements: stable single-domain states in remanence at the FM-SC contact, distinctly different switching fields of two electrodes, minimized perpendicular stray field components and multi-terminal measurement geometries to identify all magnetoresistance contributions.

A top view of a complete device structure is given by the scanning electron micrograph (SEM) in Fig. 6. Two broad and one narrow high-aspect ratio Py electrodes of 30 nm thickness are spaced by 200 nm in the FM-SC contact area. The inset of Fig. 6 enlarges the high-quality nanostructured Py electrodes. For the broad electrodes lateral kinks lead to macroscopic bond pads (not shown). As the narrow electrode dominates the magnetoresistance, it is kept straight in order to avoid any mag-
netization inhomogeneity in the FM-SC contact area. All three electrodes approach the FM-SC contact window via inclined planes of the etched 200 nm thick sputtered SiO$_2$ which are depicted in the following as vertical flanks. A schematic cross-section of the device is shown in Fig. 7. An upper bound for the inclination angle of 30 to 40 degree is found from a cross-sectional SEM of thermally grown and subsequently wet-etched SiO$_2$, giving an upper estimate of the lateral width of the flank of about 100 nm.

Due to the overall length of 150 µm and the height difference of 200 nm the complete electrodes structure cannot be captured in one single MFM image. However, decisive parts of the domain configuration in the Py electrodes are detailed in MFM images in Fig. 8. The narrow electrode has an overall aspect ratio of 375 ($l = 150$ µm, $w = 0.4$ µm) and solely black and white contrasts (Fig. 8 (4),(5)) at the ends of the wire are visible. The steep flanks which lead to the 20 µm long FM-SC contact area do not introduce domain walls in this straight high-aspect ratio electrode. The narrow electrode is in a single-domain state in remanence. In consequence, vertical flanks do not impose a multidomain state with domain walls in straight high-aspect ratio wires.

Contrary, the domain configuration of high-aspect ratio electrodes with lateral kinks is more complex. The broad electrodes with an overall aspect ratio of 73 ($l = 145$ µm, $w = 2$ µm) are composed of several parts: the 45 µm long wire ends ($m=21$) which are connected to a straight mid-part by a lateral kink angle of 45 degree. The mid-part consists of three 20 µm long straight wire sections ($m=10$). MFM images of these wire sections are depicted in Fig. 8(b) by images 1, 2, 5 and 6, which show a uniform magnetization parallel to the length of the wire sections and strong stray field contrasts at the wire ends. At the lateral kink either a magnetization inhomogeneity (Fig. 8(b) 1, 5) or a domain wall occurs (Fig. 8(b) 2, 6). However, at the edge of the FM-SC contact area the vertical flanks pin domain walls so that also the broad electrodes are uniformly magnetized within the region of the FM-SC contact. A MFM image of the decisive section of the FM-SC contact area is displayed in Fig. 8(c), 10, showing uniform remanent magnetization for all three electrodes. From the topography, Fig. 8(c), image 11, it is evident that the lift-off edges with a roughness less than the wire thickness ($\leq 30$ nm) invoke minimal magnetic contrasts due to fringe fields, as visible in Fig. 8(c), image 10.

In magnetotransport experiments perpendicular stray field components, visible by dark and light contrast in the MFM images, may induce local Hall voltages in the semiconductor $[9]$. Such side effects complicate the study of spin-dependent transport considerably. However, in the lateral spin-valve structure presented, stray field contributions are minimized and well-controllable. First, strong perpendicular stray fields occur only at the vertical flanks because the electrodes sections in the FM-SC contact area are in a single-domain state. Furthermore, the remaining stray fields occur at the vertical flanks for which a tunneling injection current is exponentially reduced with increasing oxide thickness. Any remaining contribution of fringe fields to the magnetoresistance can be precisely characterized and subtracted by complementary four-terminal measurements.

### IV. CONCLUSION

A lateral ferromagnet-semiconductor device structure is optimized for spin-valve operation by nanostructuring high-aspect ratio ($m \geq 20$) Py electrodes. A combination of lateral kinks and vertical flanks necessary in hybrid devices provides the favored single-domain state of the spin-injection and -detection electrodes in remanence. The advantages of the presented lateral spin-valve layout will apply similarly to future spin-polarizing materials that exhibit long range ferromagnetism.

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Figure 1 (a) Magnetic force microscopy images of Py structures in remanence with (I) low (m = 2.5, with l = 10 \( \mu \text{m} \), t = 38 nm), (II) medium (m = 14, l = 20.9 \( \mu \text{m} \), t = 38 nm) and (III) high aspect ratios (m = 57 (top wire), m = 43 (bottom wire), t = 50 nm). (b) Experimentally observed domain states of Py micro-and nanostructures for varied length l versus aspect ratios m. Open squares indicate multdomain states (I), grey squares denote high remanent states (II) and closed squares indicate a single-domain state (III). The black solid line depicts the transition line between multi- and single-domain configuration from a phenomenological model [17]. The dotted lines are guides to the eye.

Figure 2 MFM images of an array of Py wires (l = 16.7 \( \mu \text{m} \), 20.9 \( \mu \text{m} \)) with aspect ratios from 14.2 to 32.7. Reliable maintenance of highly remanent state after applying longitudinal magnetic fields: (a) +60 mT and (b) -20 mT are observed.

Figure 3 Ratio of the lateral extension of magnetic inhomogeneities to the structure length \( \Delta l/l \) versus the aspect ratio m of Py wires. (a) Upper estimates of \( \Delta l/l \) from MFM images in 2 of an array of Py wires with medium and high-aspect ratios. (b) Lower limit for \( \Delta l/l \) from two-dimensional micromagnetic simulation (wire length: 2 \( \mu \text{m} \)). Aspect ratio regions are denoted as (I) low, (II) medium and (III) high.

Figure 4 MFM images of medium-aspect ratio Py wires (w = 2 \( \mu \text{m} \), length, l = 10 \( \mu \text{m} \), m = 10) with lateral kinks of (a) 0°, (b) 10°, (c) 40°, (d) 50°, (e) 70° and 90° (f). Arrows in (e) and (f) depict the insertion of domain walls.

Figure 5 Micromagnetic two-dimensional simulation of the magnetization distribution in elongated Py wires of medium aspect ratios (m = 10) with lateral kinks (a) 0°, (b) 10°, (c) 50°. Structure length: 2 \( \mu \text{m} \), cell size: 10 nm.

Figure 6 Scanning-electron-microscope image of a lateral Py-oxide-InAs spin-valve structure with electrodes of widths 2 \( \mu \text{m} \) and 0.4 \( \mu \text{m} \) separated by 0.2 \( \mu \text{m} \) in the contact area (electrode length: 150 \( \mu \text{m} \)). Inset: Enlargement of the Py electrodes at the FM-SC contact.

Figure 7 Schematic cross-section of the lateral spin-valve structure. The etched vertical SiO\(_2\) flanks at the edges of the ferromagnet-semiconductor contact area have inclination angles of 30° to 40°.

Figure 8 MFM images of a lateral Py-oxide-InAs spin-valve configuration. High-aspect ratio Py electrodes of 50 nm thickness are separated by 200 nm in the region of the contact area. (a) Schematic view...
of the complete structure, 150 µm in length, with section numbering of MFM images displayed in (b) and (c).

(b) Stray field contrast at the ends of the broad wires (images 1, 2, 5, 6) result from a multidomain configuration which originates from lateral kinks (images 7 and 8). The pair of strong black/white contrasts at the closures of the straight narrow wire (images 3 and 4) indicates a single domain magnetization configuration.

T. Last et al., Figure 1
FIG. 2:

FIG. 3:
FIG. 4: T. Last et al., Figure 4

FIG. 5: T. Last et al., Figure 5
FIG. 6:

FIG. 7:
