Spin-Structured Multilayers: A New Class of Materials for Precision Spintronics

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Magnetoelectronic multilayer devices are widely used in today’s information and sensor technology. Their functionality, however, is limited by the inherent properties of magnetic exchange or dipolar coupling which constrain possible spin configurations to collinear or perpendicular alignments of adjacent layers. Here, a deposition procedure is introduced that allows for a new class of layered materials in which complex spin structures can be accurately designed to result in a multitude of new and precisely adjustable spintronic and magnetoresistive properties. The magnetization direction and coercivity of each individual layer are determined by the deposition process in oblique incidence geometry and can be completely decoupled from neighboring layers. This applies for layers of any ferromagnetic material down to layer thicknesses of a few nm and lateral dimensions of a few 100 nm, enabling the design of efficient and compact magnetoelectronic devices, encompassing precision magnetoresistive sensors as well as layer systems with multiple addressable remanent states for magnetic memory applications.

1. Introduction

Magnetoresistive multilayer devices with their unique spintronic functionality, nanoscale dimensions, and ease of preparation have transformed data storage and sensor technology in the past decades.[1–4] The generic building blocks of spintronic devices are thin-film trilayers consisting of two ferromagnetic layers separated by a nonmagnetic spacer layer[5–8] often referred to as spin valves.[9] The hysteresis and magnetic saturation behavior of such trilayers defines the functionality of devices, e.g., as magnetic field sensors for a multitude of applications.[10] Typically, the giant magnetoresistance (GMR)[6,7] or tunnel magnetoresistance (TMR)[11,12] are employed in these devices to obtain large magnetoresistive effects. Various approaches were extensively explored to maximize the magnitude of the magnetoresistive signal, which is defined as the normalized difference of the electrical resistance in the antiparallel and parallel magnetic configuration of the trilayer. The basic GMR and TMR characteristics of spintronic devices and thus their functionalities, however, did not significantly change during the last decade. This is due to conventional magnetic multilayer design and its limitations based on the interplay of accessible magnetic anisotropy contributions. Here, we show that oblique incidence deposition (OID) can be used in an elegant way to achieve full control on the magnetic anisotropy in every individual layer of such magnetoresistive multilayer stacks for the first time. The additional shape anisotropy component introduced via OID allows for arbitrarily crossed magnetic easy axes with adjustable switching fields and opens a path for customized spintronic devices with conceptually new functionalities.

So far, two major approaches have been pursued to engineer field-dependent relative magnetic configurations of two ferromagnetic layers. In the first case, one of the ferromagnetic layers either exhibits an enhanced coercive field or is magnetically pinned (exchange biased) by an additional antiferromagnetic layer of high magnetic anisotropy. Thus, only the magnetically uncoupled free layer follows small external fields, causing a change of the magnetic configuration and the magnetoresistance.[13] In the second approach, an interlayer exchange coupling, the Ruderman–Kittel–Kasuya–Yoshida (RKKY) interaction, is used to align both layers relative to each other.[14] The interlayer coupling defines the magnetic saturation behavior and hence the functionality of the trilayer. In conventional systems, only parallel or antiparallel orientations of the ferromagnetic layers are reliably achieved. Efficient RKKY coupling is observed for particular material combinations only and depends very sensitively on the layer thickness.[15,16] Therefore, conventional magnetic multilayer design is restricted to a limited number of magnetic configurations in the trilayers which constrains the design and control of magnetic spin structures that are available for realizing particular magnetoelectronic responses.

Our approach enables one to realize and tune magnetic and magnetoresistive properties in spintronic multilayer systems that exceed the potential of conventional approaches by far. The technique is not based on exchange-bias or interlayer coupling and is not affected by their limitations. Every ferromagnetic layer of arbitrary chemical composition, as a constituent either of a simple trilayer or of a large multilayer stack,

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can be magnetically freely engineered. Magnetoresistive sensor technology thus will profit from layer structures with customizable, remarkably sharp switching fields and high thermal stability, resulting in a multitude of new and precisely adjustable functionalities, producible in a greatly simplified fabrication process.

2. Magnetic Anisotropy Control in Single Films via Oblique Incidence Deposition

This new path to spin engineering relies on the established technique of oblique incidence deposition.\[17–19\] OID is highly suitable for fabrication of customized arrays of 3D nano-objects with high aspect ratio. Based on particle beam shadowing, nanorods, nanospirals or zig-zag structures can be prepared by a proper sequence of deposition steps.\[20,21\] OID is also well applicable for adjustment of the magnetic anisotropy in films with a thickness of a few nm.\[19\] Here, we show that OID can be applied in an elegant way to arbitrarily stack custom-made magnetic layers to form new magnetic materials by design. This constitutes a qualitatively new feature with a huge impact for engineering of spintronic systems and magnetic multilayers in general.

In OID the direction of the atoms impinging on the substrate can be described via the polar angle \(\theta\) and the azimuthal angle \(\alpha\), as sketched in Figure 1. While polycrystalline ferromagnetic films deposited at normal incidence are soft magnetic and behave isotropic in-plane, for polar angles \(\theta > 45^\circ\) they exhibit an increased coercive field and an easy axis perpendicular to the projection of the deposition direction onto the sample plane. The microscopic origin of this effect is a wavy surface topography with a highly anisotropic correlation function.\[18\] Dipolar stray fields originating from this rough surface cause a preferred orientation of the magnetic moments and define an uniaxial magnetic anisotropy. The amplitude of the surface profile increases with growing film thickness as well as with increasing polar angle \(\theta\), and likewise does the strength of this magnetic shape anisotropy. A minor additional anisotropy contribution arises from the change in the crystalline structure in ultrathin OID films. For films with a thickness significantly above 10 nm the growth of crystalline nanocolumns can be observed. The contribution of the shape anisotropy introduced by the wavy surface profile becomes less pronounced and that of the nanocolumns starts to dominate.

Figure 1C shows the dependence of the coercivity on the polar angle of deposition for polycrystalline iron films of 5 nm thickness. All films are sputter deposited onto sapphire substrates and sandwiched between thin platinum layers to avoid oxidation. The coercive field along the easy axis can be precisely adjusted from 1 to 40 mT. The saturation field along the hard axis can be set in a range of around 1 to 120 mT. An advantage of high technological importance is that in this way hard-magnetic films can be prepared from any magnetic material independent of the substrate and buffer layer.

Using permalloy (Ni\(_80\)Fe\(_{20}\)) with its very small magnetocrystalline anisotropy the accessible range of coercive fields can be extended to cover a range of 0.1–40 mT.\[22\]

3. Spin-Structured Multilayers: Sequential Layer Switching and Crossed Magnetic Easy Axes

Remarkably, this tuning procedure can be employed to fabricate not only single layers but also multilayered materials with precisely adjusted switching fields and arbitrarily aligned magnetic easy axes. Both magnetization characteristics cannot be realized via conventional approaches. Thus, they open a huge phase space for engineering of novel magnetic multilayers and will stimulate the development of new custom-made magnetoresistive devices.

Figure 2A shows a sketch of a magnetic multilayer consisting of three iron layers of identical thickness of 5 nm deposited at identical azimuthal orientation exhibiting a common easy axis. The polar angle of deposition \(\theta\) is 0°, 55°, and 73°, respectively, resulting in a stepwise increase of the coercive field of the ferromagnetic layers. To magnetically decouple the ferromagnetic films in the layer stack and to exclude a RKKY interlayer coupling, thin carbon films with a thickness of 2.5 nm are used as spacers. The magnetic reversal of the multilayer is detected via the magneto-optical Kerr effect and is shown in Figure 2B. It confirms a three-step sequence of magnetic reversal with switching fields which can be precisely adjusted via OID. While the upper two iron layers in the stack are characterized by switching fields very similar to those found for magnetically isolated single layers, a small increase of the coercive field of the bottom iron layer deposited at normal incidence can be recognized. We expect that this increase is due to an Orange Peel coupling through the ultrathin carbon spacer layer.\[23\]
The structural basis for the magnetic anisotropy in ultrathin films resulting from the OID process is the crystalline and surface structure of the corresponding layers. Cross-sectional high-resolution transmission electron microscopy images of the sample along the magnetic hard and easy axes are depicted in Figure 2C. The correlation of microstructural properties with the switching properties of the individual layers can clearly be seen. A very sharp iron–carbon interface is identified for the bottom iron layer deposited at normal incidence. In contrast, both iron layers deposited at oblique incidence are characterized by a corrugated surface morphology with larger amplitude for the top iron layer deposited at larger polar angle \( \theta \), exhibiting the largest coercive field. Thus, we can conclude that the magnetic tuning possibilities via OID for single layers can be transferred unrestrictedly to multilayer stacks even with ultrathin non-magnetic spacer layers.

To prove that these tuning possibilities via OID are not restricted to simple multilayer structures with parallel easy axes we investigate the magnetization profile of a complex \([\text{Fe} (3.5 \text{ nm})/\text{C} (2.5 \text{ nm})]_{13}\) multilayer in which the preferred magnetization axes are crossed due to deposition at different azimuthal orientations (Figure 3A). The sequence of azimuthal deposition angles for subsequent Fe layers is \( \alpha = (+40^\circ, 0^\circ, 0^\circ, 0^\circ) \). The polar angle is \( \theta = 80^\circ \) for all iron layers. This fabrication procedure should result in a multilayer with two iron sublattices enclosing an angle of \( \Delta \alpha = 40^\circ \) exhibiting a magnetic ground state in which the vertical magnetic correlation length (\( \Lambda_{\text{mag}} \)) is four times the structural one (\( \Lambda_{\text{struc}} \), see Figure 3c).

To identify the remanent magnetization profile in the multilayer we employ nuclear resonant reflectometry of synchrotron radiation at the 14.4 keV nuclear resonance of the Mössbauer isotope \( ^{57}\text{Fe} \). The technique is highly suited to accurately

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**Figure 2.** Custom-made sequential magnetic switching in an iron/carbon multilayer. A) Schematic drawing of a \([\text{Fe}(5 \text{ nm})/\text{C}(2.5 \text{ nm})]_3\) multilayer with a common magnetic easy axis, in which the anisotropy of the iron layers is stepwise increased by increase of the polar angle of deposition \( \theta \). B) MOKE magnetization curve shows a sequential switching of the individual magnetic layers along the easy axis at selected switching fields (\( B_{73^\circ} = 3.5 \text{ mT} \), \( B_{55^\circ} = 7 \text{ mT} \), and \( B_{0^\circ} = 21.5 \text{ mT} \)). C) Cross-sectional transmission electron micrographs of the layer system, taken for sections along the easy (left) and hard (right) axes. A uniaxial corrugated surface morphology is identified as the origin of the pronounced imprinted magnetic anisotropy.

**Figure 3.** \([\text{Fe}(3.5 \text{ nm})/\text{C}(2.5 \text{ nm})]_{13}\) multilayer with crossed magnetic easy axes demonstrating the versatile tuning possibilities of OID in large layer stacks. A) The sequence of azimuthal deposition angles for subsequent Fe layers (\( \alpha = (+40^\circ, 0^\circ, 0^\circ, 0^\circ) \)) results in two magnetic sublattices enclosing an angle of \( \Delta \alpha = 40^\circ \). An external magnetic field \( B_{\text{ind}} = 100 \text{ mT} \) is used to induce a canted antiparallel configuration of the sublattices in which the vertical magnetic correlation length (\( \Lambda_{\text{mag}} \)) is four times the structural one (\( \Lambda_{\text{struc}} \)). B) The intended magnetization profile is confirmed by nuclear resonant reflectometry of synchrotron radiation. The gray curves are simulations assuming the structural and magnetic layer profile shown in (A) and (C).
determine the vertical spin profile in the multilayer due to a large penetration depth of the X-rays and a very high sensitivity of the reflected signal to the magnetic moment orientation in the layer stack. The accuracy of the magnetization orientation determined with this method is \( \approx 2^\circ \) for the individual ferromagnetic layers.

The experiment was performed at the High Resolution Dynamics Beamline P01\(^{[27]} \) at the synchrotron radiation source PETRA III (DESY, Hamburg), with the X-ray beam oriented parallel to the effective easy axis. A nonresonant reflectivity curve, which is sensitive to the electron density depth profile only, and the nuclear resonant one are shown in Figure 3B. After the regime of total external reflection, i.e., for incidence angles \( > 0.18^\circ \), the X-rays start to penetrate into the layer structure. At an incidence angle of 0.45° a Bragg peak is observed in the nonresonant signal, reflecting the 6.0 nm Fe/C bilayer period of the multilayer structure. In the resonant reflectivity curve, however, four magnetic Bragg peaks can be identified. The red curves in Figure 3B are simulations of both reflectivity curves using a layer matrix formalism\(^{[28–30]} \) and finally prove that the desired spin profile is realized with a precision better than 2° throughout the whole layer stack as determined by the parameters of the deposition process.

**4. Magnetoresistive Multilayers for Sensing of Axial Fields**

So far, the results have shown that OID can be used in an elegant way to achieve full control over remanent and field dependent multilayer magnetization profiles even with ultrathin nonmagnetic spacer layers. In this section we apply OID to magnetoresistive layer structures. The increased interface roughness compared to normal incidence deposition, the basis of magnetic tuning via OID, does not significantly reduce the magnitude of the magnetoresistive signal. Thus, versatile low and high-field GMR devices and spin-valve systems with tailor-made magnetoresistive functionality can be fabricated in a simple fashion from the same type of multilayer systems (identical layer structure and chemical composition) by adjusting the magnetic properties of the individual layers as described above.

Magnetoresistive trilayers are presented in the following with custom-made new functionalities. These trilayers can be used as building blocks and easily be stacked to design magnetic materials with further increased complexity and advanced functionality. Here, we focus on GMR functionalities connected to linear field sweeps and rotary fields as they are most relevant for a multitude of sensor applications. All GMR layer structures were deposited onto silicon substrates and sandwiched in between two tantalum layers (5 nm) to decouple the layer structures from the surface structure of the substrate and to avoid oxidation. The electrical resistance of all GMR structures in this study was measured at room temperature in current-in-plane geometry. At this stage no microstructuring or optimization of the Cu spacer layer or Co layer thicknesses was performed to maximize the GMR signal.

**Figure 4A** shows the most simple GMR system, a pseudo spin valve\(^{[31]} \). Two ferromagnetic Co layers with different strength of magnetic anisotropy are separated by a Cu spacer layer with a thickness of 4 nm, which is not expected to cause a significant RKKY interlayer coupling of the ferromagnetic layers\(^{[32]} \). An external field applied along the easy axis results in a sequential layer switching and antiparallel magnetic configuration in a certain field range with increased electrical resistance. While in conventional systems two different ferromagnetic materials are used and the accessible switching fields are strongly limited, here two cobalt layers of identical thickness \( d = 5 \) nm are used and the switching fields can be freely set over a wide range via the polar angle \( \theta \) of deposition.
Remarkably, the imprinted easy axes realized via OID cause very sharp step-function-like GMR switching characteristics which are atypical for polycrystalline layer systems but highly desirable for sensor applications. The relative magnitude of the GMR signal in this Co$_{45\°}$/Cu (4 nm)/Co$_{45\°}$ (5 nm) trilayer is close to 4\% and similar to that found in conventional polycrystalline trilayers at room temperature.\textsuperscript{[33]} The increased interface roughness thus does not cause a significantly reduction of the GMR signal.

The sequential layer switching can be easily extended and freely adjusted. Three cobalt layers deposited at polar angles of 45\°, 80\°, and 55\° result in a three-plateau GMR signal with a step-like increase at 2, 12, and 30 mT during axial magnetic field sweeps (see Figure 4B). While the polar angle $\theta$ determines the multilayer switching fields, the sequence of layer stacking can be used to define the sequence of spin configurations (and corresponding resistive states) upon field cycling.

Due to this functionality, such layer systems are interesting candidates for the realization of multilevel magnetic memory devices.

The possibility to realize multilayers with noncollinear magnetic easy axes offers an additional degree of freedom to adjust GMR characteristic and to generate new functionalities. In the following, two GMR systems with crossed easy axes of $\Delta \alpha = 90$\° and 20\° are discussed. Iron is used as ferromagnetic material in both cases as it has a smaller magnetic anisotropy than polycrystalline cobalt. This favors magnetic reversals out of the easy axis with very small hysteresis. Cu is kept as spacer layer material.

A striking example with two magnetic easy axes oriented perpendicular to each other is shown in Figure 4C. For a field sweep along one of the easy axes with a magnitude below its coercive field, the magnetization of the second layer will coherently and reversibly rotate away from its easy axis and cause a linear change of magnetoresistance. This GMR characteristic can be used to precisely determine the strength and orientation of axial external field variations as they are generated by Oersted fields of electrical currents for example. The sensitivity and field range can be precisely set via the polar deposition angle of the multilayer. Once the external field exceeds the switching field of the easy axis oriented parallel to it, a sharp jump in the GMR signal is observed, and the slope of the GMR curve inverts its sign.

In the next example we decrease the canting angle $\Delta \alpha$ of the easy axes in the Fe/Cu GMR structure from 90\° to 20\°, as illustrated in Figure 4D. The ferromagnetic layers were deposited at a polar angle of $\theta = 80$\°. Once this multilayer is saturated along the hard axis and the external field is removed, the magnetizations of the iron layers rotate back into their easy axes to form an almost antiferromagnetically ordered configuration in remanence which is not based on interlayer coupling. The GMR signal of this layer stack along the hard axis shows indeed a high-field characteristic that is very similar to that found for antiferromagnetically coupled Fe/Co superlattices,\textsuperscript{[33]} the archetype of GMR multilayer systems. However, since the functionality in the present system is not based on the RKKY interlayer coupling, its GMR characteristic is not limited to certain material combinations and interlayer thicknesses. More importantly, the slope of the GMR curve (shape and saturation field) can be freely adjusted via the arrangement of the easy axes and a possible anisotropy gradient within an extended layer stack.

These four examples for axial field sweeps indicate the versatile and elegant tuning possibilities for GMR characteristics opened up by the OID method.

## 5. Magneto resistive Multilayers for Sensing of Rotary Fields

The impact of the new deposition method for sensor technology is further emphasized by their unique capability of sensing rotary fields. Four basic GMR building blocks in the shape of Co/Cu/Co trilayers are presented in the following that exhibit new sensor functionalities solely due to a customized deposition in oblique incidence.

The first trilayer is a simple spin-valve structure. The bottom cobalt layer is deposited in normal incidence with an isotropic in-plane magnetic behavior. The top cobalt layer is deposited at a large polar angle to form a hardmagnetic layer with a defined reference magnetization. Figure 5A shows the GMR curve of this Co$_{45\°}$/Cu/Co$_{45\°}$ trilayer as function of the azimuthal orientation $\alpha$ of an in-plane external field of constant magnitude ($B_{ext} = 5$ mT) which is rotated relative to the sample. Only the bottom layer magnetization follows the external field and causes a typical sinusoidal GMR spin-valve characteristic. It should be noted that no laborious alloying and heating procedure for the hardmagnetic reference layer or a pinning to an additional antiferromagnetic layer is necessary to realize this spin valve.

Figure 5B shows a Co$_{45\°}$/Cu/Co$_{45\°}$ pseudo spin-valve structure with two parallel easy axes. Striking new GMR characteristics can be identified depending on the magnitude of the external field. While a plateau-like signal with a period of 180\° can be seen for rotary fields which are just strong enough to switch only the bottom layer (8 mT), a periodically peaked signal is generated for fields exceeding the coercive field of both layers (22 mT). The GMR response is shaped by the magnitude of the imprinted anisotropy and defines at which field strength and angular orientation $\alpha$ of the rotary field relative to the easy axis the reversal takes place. This simple trilayer structure could be used for sensing and regulation of high speed rotations.

The functionality of the Co/Cu/Co trilayer can be further extended by introducing a canting angle between the easy axes (see the example for a 45\° canting in Figure 5C). Since the rotational symmetry is broken in this case, the difference $\Delta \alpha$ in the azimuthal orientations of the rotary field, at which the magnetization of the individual layers switches, depends on the sense of rotation. Thus not only the rotation frequency but also the sense of rotation can be detected. In addition to the width of the plateaus also the slope of the signal (positive/negative) can be used at selected field values to identify the sense of rotation. Such rotary sensors can be easily advanced in functionality by extra layers which allow to shape the GMR signal (e.g., to form a saw tooth or three-level signal to be used as angular encoders for example).

The example in Figure 5D shows the Co$_{45\°}$/Cu/Co trilayer structure with a 90\° canting of the easy axes. Depending on the strength of the external field $B_{ext}$ and thus the possibility of both ferromagnetic layers to follow the rotary field a peaked
6. Nanopatterning

Up to now all magnetic and magnetoresistive measurements were performed on extended sample systems. For sensing applications it is important to show that magnetic anisotropy control via OID can also be achieved in nanopatterned sensor structures. For GMR elements, for example, a large electrical resistance and thus low energy consumption is preferable. Thus layer structures have to be fabricated in the sub-micrometer regime.

Therefore, we investigate the magnetic switching behavior of a square-shaped Co$_{45}$/Cu/Co$_{75}$ layer system with 500 nm edge length, very similar to that shown in Figure 4A. Gold nanowires with a thickness of 30 nm are used as electrical contacts for the magnetoresistive measurements (Figure 6A). The easy axis points into the direction of the gold contact.

The current-in-plane signal is shown in Figure 6B. It identifies a sequential layer switching with extremely sharp switching fields very similar to that found for the extended layer structure. A significant increase of the switching field of the upper cobalt layer can be recognized. This is most probably caused by a flux closure of the magnetic stray fields in the nanostructure stack. The result clearly shows that the shape anisotropy and thus uniaxial easy axes which are introduced by the OID technique are functional also in this nanometer regime.

Figure 5. GMR multilayer tuning for sensing of rotary fields. OID is used to imprint various new functionalities into a Co/Cu/Co trilayer structure. A) Spin valve like GMR characteristics as result of one hardmagnetic cobalt layer with a uniaxial anisotropy and one Co layer deposited at normal incidence with isotropic magnetic behavior. Only the magnetization of the latter one follows the external field and causes the archetypal sinusoidal GMR characteristics. B) Trilayer with parallel easy axes and different strength of anisotropy (polar deposition angle $\theta$ = 60° and 73°). A plateau-like or peaked periodic signal can be seen if either one or both of the layers are switched by the rotary field (8 or 22 mT). C) An azimuthal shift of the easy axis of one layer (here by 45°) breaks the rotational symmetry, rendering the rotary field sensor sensitive to the rotation frequency and the sense of rotation. The magnetization vectors of both cobalt layers, $M_{\text{top}}$ and $M_{\text{bottom}}$, are switching when the orientation of the rotary field falls out of the light gray and dark gray sectors, respectively. D) GMR signal for a Co/Cu/Co system with a 90° crossing of the easy axes. A peaked 360° periodicity or a 90° oscillation period can be identified for an external field of 10 and 30 mT, respectively.
Nuclear resonant X-ray reflectometry of pulsed synchrotron radiation was employed to precisely determine the depth dependent spin structure of the Fe/C multilayer samples. This method relies on the 14.4 keV nuclear magnetic dipole transition of the Mössbauer isotope $^{57}$Fe which constitutes a very sensitive probe of the magnetization directions in a sample.[25,28] While the conventional electronic reflectivity curve depends on the electron density depth profile of the multilayer, the nuclear resonant reflectivity curve is sensitive to the depth profile of magnetization orientations in the sample. In particular, if the period of the magnetic structure does not coincide with the period of the chemical structure of the multilayer, magnetic superstructure peaks in the resonantly scattered intensity appear at corresponding angular positions. Thus, the magnetic depth profile in remanence and in response of applied external magnetic fields can be obtained from nuclear resonant X-ray reflectivity curves.

Optimization of OID Magnetic and Magnetoresistive Devices: Several of the conventional approaches to increase the magnitude of the GMR signal can be applied to OID layer systems as well. Outside the scope of this work and without systematic studies we can report the following observations: A multiple stacking of the trilayer building blocks can be employed to significantly increase the GMR. The magnitude of the magnetoresistive signal can likewise significantly be improved by optimization of the nonmagnetic spacer layer systems. This includes GMR layer thicknesses of the ferromagnetic layers. A relatively large copper spacer layer thickness was chosen for the examples in this study to ensure a negligible interlayer coupling of the cobalt layers. We expect that this thickness can be carefully reduced further to significantly increase the magnitude of the GMR signal.

Local maxima in the magnitude of the GMR effect are usually observed in dependence of the interlayer thickness especially for materials showing the oscillatory interlayer exchange coupling. These maxima coincide with those causing an antiferromagnetic coupling of the ferromagnetic layers. While the magnitude of the GMR effect only slowly decreases approximately on a linear basis with higher order coupling maxima the coupling strength often decreases on a logarithmic scale.[19] This, for OID systems with very high magnetic anisotropy and thus an interlayer roughness of more than one nanometer it can be preferable to choose a relatively large spacer layer thickness of the higher order exchange coupling maxima. This suppresses both, an unwanted Orange Peel coupling and an interlayer exchange coupling but yields a high magnitude of the GMR signal. Parkin shows that the interlayer coupling strength in Py/Au multilayer drastically reduces by two orders of magnitude when the interlayer thickness is increased from 1 to 4 nm, corresponding to the position of the peaks in first and forth order exchange coupling strength. In contrast, the strength of maximal magnetoresistance decreases only by a factor of two.[19]

Further measures can be applied for optimization of the magnetoresistive signal like an annealing procedure which modifies the nanocrystalline structure of the multilayer. We recognized that the basic functionality of the Co/Cu/Co systems presented in this work is not affected for temporary annealing cycles in air up to 370 °C. If cobalt is replaced in the multilayer structures by iron or permalloy the accompanying decrease of the GMR signal[33] can be significantly compensated by inserting of a few monolayers of Co at the spacer layer interfaces.

An important requirement for large scale fabrication of magnetic and magnetoresistive multilayers is sufficiently high layer homogeneity. The deposition in oblique incidence causes a thickness gradient along the azimuthal deposition direction for extended sample systems. This gradient can be compensated with a two-step deposition at opposing azimuthal orientations. The magnetic OID characteristic of the film will not be influenced by this fabrication process.

8. Experimental Section

All polycrystalline thin films and multilayers were sputter deposited at room temperature in custom-made ultrahigh vacuum deposition chambers with base pressures better than $1 \times 10^{-7}$ mbar. A low argon pressure of $6 \times 10^{-3}$ mbar was used for deposition in oblique incidence to obtain a large mean free path of the sputtered atoms and to achieve a directed deposition from the sputter target relative to the sample surface.

Figure 6. GMR behavior of a nanopatterned OID system. A) Scanning electron microscopy image of a Ta/Co$_{45}^{°}$/Cu/Co$_{75}^{°}$/Ta pseudo spin-valve structure with a lateral size of 500 nm x 500 nm and gold nanowire contacts for current in-plane resistivity measurements. B) GMR characteristics of the nanostructured system. A sequential layer switching with a lateral size of 500 nm and gold nanowire contacts for current in-plane resistivity measurements.
and Guido Meier, Max-Planck Institute for Structure and Dynamics, Hamburg, for helpful discussions and Claas Albert, TU Wien, Vienna, for micromagnetic simulations. Moreover, the authors wish to thank Rudolf Rüffer, Daniel Merkel, and Dimitrios Bessas for their help during an in-situ sputter deposition experiment at the European Synchrotron Radiation Facility (ESRF, Beamline ID18) which initially inspired us to employ OID for multilayer fabrication. Financial support of the Deutsche Forschungsgemeinschaft via excellence cluster “The Hamburg Centre for Ultrafast Imaging – Structure, Dynamics and Control of Matter on the Atomic Scale” is gratefully acknowledged.

Received: June 25, 2016
Published online: September 8, 2016

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