Nanoscale Magnetism

J. Fassbender
J. McCord

Control of saturation magnetization, anisotropy and damping due to Ni implantation in thin Ni$_{81}$Fe$_{19}$ layers
The static and dynamic magnetic properties of 20 nm thick Ni$_{81}$Fe$_{19}$ films implanted with Ni-ions have been investigated as a function of the ion fluence up to $1 \times 10^{16}$ cm$^{-2}$ (~5 at.%). The implantation has been performed at 30 keV. The maximum of the projected ion range is located in the center of the ferromagnetic layer for a rather homogeneous ion distribution throughout the film. With increasing ion fluence the saturation magnetization and the effective magnetic anisotropies (static and dynamic) are reduced. However, the effective magnetic damping is drastically enhanced for higher ion fluences. This increase can be explained mainly by the drop in saturation magnetization in connection with structural changes. In addition ion implantation in an applied magnetic field allows the setting of the uniaxial anisotropy direction irrespective of the initial orientation.

Collaboration: 1Leibniz Institute of Solid State and Materials Research Dresden, Germany

J. Fassbender
J. von Borany
A. Mücklich
K. Potzger
W. Möller
J. McCord
L. Schultz
R. Mattheis

Structural and magnetic modifications in Cr implanted permalloy
The static and dynamic magnetic properties, especially the magnetic damping behavior, have been investigated as a function of saturation magnetization in thin Ni$_{81}$Fe$_{19}$ (permalloy) films. Ion implantation doping with Cr in the percentage regime has been used to effectively reduce the Curie temperature and thus the saturation magnetization at room temperature. In order to understand the magnetic modifications the changes in stoichiometry but also the ion induced structural changes have been addressed. As a function of fluence first an improvement of the (111) fiber texture, then a lattice expansion and finally a partial amorphization of the interface near region of the permalloy layer is found. The region of amorphization can be understood quantitatively by simulation of the concentration profiles as a function of depth in combination with irradiation induced damage formation. The magnetic properties change correspondingly. For increasing Cr doping a drop in saturation magnetization and a decrease of the uniaxial magnetic anisotropy is observed. For a fluence of $0.8 \times 10^{16}$ Cr/cm$^2$ (~4 at.%) the magnetic damping parameter $\alpha$ increases by a factor of 7. This strong increase is mainly caused by the reduction of the saturation magnetization and a change of the sample crystallinity.

Collaboration: 1Leibniz Institute of Solid State and Materials Research Dresden, Germany, 2Institute for Physical High Technology Jena, Germany

V. Cantelli
J. v. Borany
J. Grenzer
J. Fassbender
R. Kaltofen
J. Schumann

Influence of He ion irradiation on thin NiMn/Ni$_{81}$Fe$_{19}$ exchange bias films
Magnetron sputtered film stacks of 5 nm Ta/50(15) nm NiMn/20 nm Ni$_{81}$Fe$_{19}$/5 nm Ta deposited at SiO$_2$/Si substrates were subsequently irradiated with He$^+$ ions (30 keV, $1 \times 10^{15} - 3 \times 10^{16}$ cm$^{-2}$, RT or 250°C). The transition from the paramagnetic NiMn phase (fcc) to the chemically ordered, antiferromagnetic tetragonal L$_{10}$ phase during annealing (100 – 500°C, Vacuum) was studied by in-situ XRD using synchrotron radiation. A small L$_{10}$ fraction (<15%) is already available after deposition. The transformation to a dominating L$_{10}$ ordered NiMn film (long-range order parameter $S>0.5$) takes place between 300 – 400°C irrespective of the irradiation. This is consistent with magnetization reversal measurements of the corresponding permalloy layers. Annealing at elevated temperatures ($T_s>400°C$) leads to a loss of L$_{10}$ ordering due to a complete intermixing of the NiMn and the permalloy films. The benefit of low-fluence ion irradiation ($1 \times 10^{15}$ cm$^{-2}$) is a reduction of the mosaicity for both the NiMn and the permalloy film, and a smoothing of
internal interfaces.

**All-optical probe of precessional magnetization dynamics in exchange biased Ni$_{81}$Fe$_{19}$/FeMn bilayers**

An internal anisotropy pulse field is launched by an 8.3 ps short laser excitation, which triggers precessional magnetization dynamics of a polycrystalline Ni$_{81}$Fe$_{19}$/FeMn exchange bias system on a picosecond timescale. Due to the excitation the exchange coupling across the interface between the ferromagnetic and the antiferromagnetic layer is reduced, leading to a fast reduction of the exchange bias field and to a dramatic increase of the zero-field susceptibility. The fast optical unpinning is followed by a slower recovery of the interfacial exchange coupling dominated by spin-lattice and heat flow relaxation with a time constant of the order of 160 ps. The measured picosecond time evolution of the exchange decoupling and restoration is interpreted as an anisotropy pulse field giving rise to fast precessional magnetization dynamics of the ferromagnetic layer. The strength of the internal pulse field and even the initial magnetization deflection direction from the equilibrium orientation can be controlled by the absorbed photons. The dependence of the effective Gilbert damping on both small and large angle precessional motion was studied, yielding that both cases can be modeled with reasonable accuracy within the Landau-Lifshitz and Gilbert framework.

**Collaboration:** ¹Department of Physics, TU Kaiserslautern, Germany

**Suppression of vortex core motion by means of focused ion beams**

Recently, vortex-core driven magnetization dynamics has become a hot topic. The gyrotropic motion of the vortex core is found to be in the sub-GHz regime and thus easily accessible with high-resolution synchrotron-based time-resolved transmission x-ray microscopy (TR-TXM) techniques. In order to investigate the influence of artificial magnetic defects positioned within the vortex structure on the magnetization dynamics and the potential switching between individual defects focused ion beam milling has been employed. The understanding and control of these mechanisms is of utmost scientific and technological relevance. A series of circular and square shaped permalloy (Ni$_{81}$Fe$_{19}$) microstructures have been investigated, which exhibit a nanoscopic hole at different positions. The gyrotropic motion of the vortex core is excited by means of a microwave sine-excitation with different excitation amplitudes. The magnetization dynamics is sensed by TR-TXM. It is found that a defect located far away from the vortex core has almost no influence on the magnetization dynamics. However, a point defect located in the centre of the structure suppresses the gyrotropic motion of the vortex core completely.

**Collaboration:** ¹Max-Planck Institute for Metal Research, Stuttgart, Germany, ²Advanced Light Source, Lawrence Berkeley National Laboratory, Berkeley, USA, ³Institute for Experimental and Applied Physics, University of Regensburg, Germany

**Real-time evidence of two-magnon scattering in exchange coupled bilayers**

Coherent spin waves in exchange biased bilayers have been excited by ultrafast photomodulation of the exchange bias anisotropy. Photoinduced precession in CoFe/IrMn samples with different IrMn thickness, thus, different exchange bias fields, has been studied in real-time by time-resolved Kerr-effect. The extracted effective damping parameter is proportional to the square of the exchange bias field. Two-magnon scattering of the coherent precession of the ferromagnetic layer at local interfacial fluctuations of the exchange bias field can account for the observed increase. Hence, there is time-domain evidence of two-magnon damping involved in the relaxation of photoexcited
K. Küpper
L. Bischoff
R. Mattheis
P. Fischer
J. Fassbender

Magnetic domains and magnetization reversal of ion-induced magnetically patterned RKKY-coupled Ni$_{81}$Fe$_{19}$/Ru/Co$_{90}$Fe$_{10}$ films

Pure magnetic patterning by means of ion beam irradiation of magnetic thin films and multilayers result often from a post deposition local modification of the interface structure with only minor effects on the film topography. In this study a 60 keV fine focused Co ion beam was used to change the coupling in a Ni$_{81}$Fe$_{19}$/Ru/Co$_{90}$Fe$_{10}$ structure from antiferromagnetic to ferromagnetic on a micron scale. Thereby an artificial structure with locally varying interlayer exchange coupling and therefore magnetization alignment is produced. High-resolution full-field x-ray microscopy is used to determine the magnetic domain configuration during the magnetization reversal process locally and layer resolved due to the element specific contrast in circular x-ray dichroism. In the magnetically patterned structure there is in addition to the locally varying interlayer exchange coupling across the Ru layer also the direct exchange coupling within each ferromagnetic layer present. Therefore the magnetization reversal behaviour of the irradiated stripes is largely influenced by the surrounding magnetic film.

Collaboration: ¹Department of Physics, TU Kaiserslautern, Germany, ²Hitachi Global Storage Technologies, San Jose, USA

M.O. Liedke
K. Potzger
A.H. Bothmer
B. Hillebrands
M. Rickart
P.P. Freitas
J. Fassbender

Domain structure during magnetization reversal of PtMn/CoFe exchange bias micro patterned lines

The magnetic domain configuration and the magnetization reversal behaviour of micropatterned exchange bias elements were investigated by means of magnetic force microscopy. In addition to the unidirectional anisotropy the shape anisotropy determines the overall magnetization reversal behaviour. In order to modify the ratio between both anisotropy contributions the exchange bias field strength was reduced by means of 5 keV He$^+$ ion irradiation. For the as-prepared samples a mono-domain magnetization state with the magnetization direction aligned along the exchange bias field direction was found regardless of the element shape. After irradiation the unidirectional anisotropy contribution is reduced and hence the previously homogeneous magnetization state brakes up into small domains with $360^\circ$ domain walls in between. The appearance of these domain walls, which was mainly observed for the descending branch of the magnetization reversal, is found to depend strongly on the structure width and orientation.

Collaboration: ¹Institute for Physical High Technology Jena, Germany, ²Center for X-Ray Optics, Lawrence Berkeley National Laboratory, Berkeley, USA

P. Candeloro
S. Blomeier
P.A. Beck
H. Schultheiß
H.T. Nembach
B. Hillebrands
M.O. Liedke
J. Fassbender
B. Reuscher

Evidence of lateral coupling in exchange bias double layers with lateral modulation of the exchange bias field

Magnetic properties of a Ni$_{81}$Fe$_{19}$/FeMn exchange bias bilayer were modified on the micron and submicron scale by ion irradiation, without significant changes in the sample topography. The resulting magnetic patterns were investigated by MOKE and MFM. The hysteresis loops measured by MOKE reveal that the magnetization reversal is not proceeding independently in irradiated and non-irradiated areas. This magnetic coupling is confirmed by MFM measurements, which clearly show that magnetic domains in irradiated and non-irradiated elements are mutually influencing each other during the reversal process.

Collaboration: ¹Department of Physics, TU Kaiserslautern, Germany, ²Institut für Oberflächen- und Schichtanalytik (IFOS), Kaiserslautern, Germany

Supported by EU

Collaboration: ¹Department of Physics, TU Kaiserslautern, Germany, ²Institut für Oberflächen- und Schichtanalytik (IFOS), Kaiserslautern, Germany

Supported by DFG

Collaboration: ¹Department of Physics, TU Kaiserslautern, Germany, ²Hitachi Global Storage Technologies, San Jose, USA
Ferromagnetic Gd-implanted ZnO single crystals

In order to introduce ferromagnetic properties, ZnO single crystals have been implanted with Gd ions at 180 keV ion energy and two different fluences. Magnetization reversal hysteresis loops have been recorded for as-implanted as well as annealed samples using a SQUID magnetometer. For a fluence of $5 \times 10^{15}$ ions/cm$^2$, post implantation annealing leads to an increase of the saturation moment up to $1.8 \mu_B$/Gd at exactly 300 K, thus excluding Gd, ZnGd or Gd$_2$O$_3$ secondary phases to be the origin of the observed ferromagnetism.

Collaboration: 1Dresden High Magnetic Field Laboratory, Forschungszentrum Rossendorf, Germany

Structure and ferromagnetism of Mn$^+$ ion-implanted ZnO thin films on sapphire

Slow positron implantation spectroscopy (SPIS), based on the generation, implantation and subsequent annihilation of mono-energetic positrons in a sample, has been used to study depth dependent vacancy-type damage in three ZnO films grown by PLD on c-plane sapphire. Doping was achieved by implantation of 250 keV Mn$^+$ ions at 300°C with three different fluences - $10^{16}$, $3 \times 10^{16}$, and $6 \times 10^{16}$ cm$^{-2}$, and subsequent thermal annealing in air. The evolution of the open volume damage, its depth distribution, and the magnetic behaviour was investigated by SPIS and MFM. No indication of magnetic domain formation was found in any of the three films after implantation and the first annealing at 500°C, whereas after the second annealing at 750°C the two samples having the higher fluence showed stripe-like magnetic domains.

Collaboration: 1Institut für Experimentelle Physik II, Universität Leipzig, Germany

Mn-silicide nanoparticles formed in Si using ion implantation

300 keV Mn$^+$ ions were implanted into Si with a fluence of $1 \times 10^{15}$ cm$^{-2}$, $1 \times 10^{16}$ cm$^{-2}$, $5 \times 10^{16}$ cm$^{-2}$, respectively. The samples were annealed at 800°C in N$_2$ ambient for 5 min by rapid thermal annealing method. RBS/C, TEM and XRD were applied for structural characterization. It was found that this annealing is not sufficient to remove the implantation damage. Moreover no evidence is found for Mn substituting Si sites. Mn$_x$Si$_y$ nanoparticles were formed after annealing. The control of these effects is essential for the design of Si-based diluted magnetic semiconductors.

Collaboration: 1Institut für Experimentelle Physik II, Universität Leipzig, Germany

Magnetic and structural properties of $^{57}$Fe implanted GaN

In order to investigate the possibility to create and stabilize a DMS (diluted magnetic semiconductor) behaviour in the (Ga,Fe)N-system, p-doped GaN was implanted with $^{57}$Fe$^+$ ions (200 keV, $1 - 16 \times 10^{16}$ cm$^{-2}$) at 350°C and subsequently annealed between 700 and 900°C in N$_2$-flux for 5 min. CEMS measurements of the as-implanted samples (1 – $16 \times 10^{16}$ cm$^{-2}$) show a magnetic hyperfine field of $B_{hf} = 10$ T which cannot only be attributed to $\alpha$-Fe ($B_{hf} = 33$ T). However, annealing of the high-fluence implanted samples ($\geq 6 \times 10^{16}$ cm$^{-2}$) result in the formation of fiber-textured $\alpha$-Fe-clusters with 5 and 15 nm size after 700 and 900°C annealing, respectively. For the highest Fe-doped sample ($16 \times 10^{16}$ cm$^{-2}$) annealed at 900°C, AES reveals a dispersion of the Fe-implantation profile due to radiation-enhanced diffusion and the existence of Fe-rich regions which reflects the formation of Fe clusters. Zero-field-cooled/field-cooled SQUID measurements of the sample implanted with $1 \times 10^{16}$ cm$^{-2}$ and annealed at 850°C show a Curie-temperature of 250 – 270°C, which is associated with the DMS. However it also indicates the presence of superparamagnetic Fe-clusters with a blocking temperature of 40 K. No other crystalline phases like iron-nitrides were found by XRD.

Supported by

DFG
V. Heera
R. Höhne
P. Esquinazi

Magnetic properties of ion implanted diamond and graphite

Recent experimental and theoretical studies suggest the existence of intrinsic ferromagnetism in carbon structures with predominant $sp^2$-bonds like highly oriented pyrolytic graphite (HOPG) and fullerene polymers. In contrast, ferromagnetism in diamond with $sp^3$-bonds has never been observed. It is speculated that the magnetism in the carbon phases is caused by special lattice defects and not, as sometimes suggested, by magnetic impurities. In order to elucidate the role of lattice defects, nonmagnetic and magnetic impurities in different carbon phases, a series of implantation experiments was carried out. Diamond and HOPG samples were implanted with $F^+$ and $Fe^+$. Defect-rich surface layers with impurity concentrations from 50 to 500 ppm extending to a depth of about 2 µm were produced by multiple energy implantation in the MeV range. The magnetic properties were measured with a SQUID magnetometer. Preliminary results show that the weak ferromagnetism of the unimplanted HOPG is not markedly influenced after implantation of iron or fluorine. The paramagnetic part of the magnetization of HOPG and diamond clearly increases by ion implantation mainly due to the enhancement of disorder. No ferromagnetism was detected in the diamond samples.

Collaboration: ¹University of Leipzig, Germany

K. Potzger
H. Reuther
S. Zhou
A. Mücklich
R. Grötzschel
F. Eichhorn
M.O. Liedke
J. Fassbender
H. Lichte
A. Lenk

Ion beam synthesis of Fe nanoparticles in MgO and yttria stabilized zirconia (YSZ)

In order to synthesize embedded Fe nanoparticles MgO(001) and YSZ(001), single crystals have been implanted with $Fe^+$ ions at different temperatures and ion energies of 100 keV and 110 keV respectively. Using a fixed ion fluence of $6 \times 10^{16}$ cm$^{-2}$, γ-Fe nanoparticles are formed inside the MgO substrate up to a temperature of 1073 K. In contrast, ferromagnetic $α$-Fe nanoparticles are formed inside YSZ at elevated temperatures with an efficiency of 100% at an implantation temperature of 1273 K. Their ferromagnetic behaviour is reflected by a magnetic hyperfine field of 330 kOe and a hysteretic magnetization reversal. Electron holography measurements have been carried out in order to visualize the stray field of the particles.

Collaboration: ¹Triebenberg Laboratory for High-Resolution Electron Microscopy, TU Dresden, Germany

V. Cantelli
J. von Borany
J. Fassbender
N. Schell
S. Zhou

Influence of energetic atoms on the L\textsubscript{10} ordering of FePt films fabricated by magnetron sputtering

The L\textsubscript{10}-ordering of stoichiometric FePt films (30 – 120 nm) deposited on SiO\textsubscript{2}/Si substrates by dc magnetron sputtering from elemental targets has been studied. A low deposition rate (0.6 Å/s) and Ar pressure (0.3 Pa) was used. The kinetics of A1→L\textsubscript{10} transition and ordering in FePt films have been investigated by in-situ XRD at the Synchrotron beamline ROBL at ESRF. The transition has been obtained at relatively low temperatures of (300 ± 20)°C leading to almost complete L\textsubscript{10} ordered films with an ordering parameter $S > 0.8$. No remarkable differences are obtained by combining deposition at room temperature and post-deposition annealing or deposition at the annealing temperature except of slightly variations in the grain size. An additional ion irradiation with He$^+$ (50 keV, $1 \times 10^{15} – 3 \times 10^{16}$ cm$^{-2}$) does not influence the transition temperature and the degree of ordering. Calculations reveal that for our experimental conditions there is no thermalization of the sputtered target atoms and the reflected Ar neutrals, thus a considerable fraction of atoms meet the substrate with energies exceeding the displacement threshold. This corresponds to the formations of point defects already during deposition which support the L\textsubscript{10} ordering if they get mobile at temperatures >250°C.
Even-odd effect of anisotropy transfer from a stack of metal films to the L1₀ superstructure

Atomic collisions in solids are often associated with the concept of disorder. However, recently we demonstrated that irradiation may induce chemical order in intermetallic alloys, where significant structural L1₀ order of alternating (001)Fe and (001)Pt atomic layers in almost fcc-type FePt was obtained and controlled in FePt by postgrowth He ion irradiation well below the ordering temperature. Now, the irradiation-assisted L1₀ phase formation from a stack of several atomic layers thick Fe and Pt films was studied by kinetic Monte-Carlo simulations. An unexpected even-odd effect in the anisotropy of the final L1₀ phase was discovered: Whereas stacks of films consisting of an even number of atomic (001) layers show no preferred c-axis selection of the final structure, stacks of films consisting of an odd number of atomic (001) layers may show an almost perfect c-axis alignment perpendicular to the substrate. This very selective L1₀ phase formation has been understood by the peculiarity of the reaction pathway in a stack of films: The L₁₀ FePt phase forms from Fe and Pt via the two L₁₂ phases (Fe₃Pt, FePt₃), where the L₁₂ unit cells fit commensurably or incommensurably in a single film of one metal. Thus, during the formation of the L₁₀ superstructure from the two L₁₂ phases, the anisotropy of the Fe/Pt interface will be either transferred to a single L₁₀ variant or will be lost completely. This evolution of anisotropy of layered systems is very important for the synthesis of new magnetic recording films.

Exchange bias on rippled substrates

Monoatomic steps at the interfaces between a ferromagnetic and an antiferromagnetic layer give rise to uncompensated spins which are the origin of the exchange bias phenomenon. Such steps have been generated by substrate surface patterning by means of Ar⁺ ion erosion. Depending on the primary energy and the angle of incidence, a rippled surface with a well defined periodicity (~20 – 100 nm) and peak-to-valley height (~2 – 5 nm) has been created. On top of this surface, an exchange bias system consisting of 5 nm Ni₈₁Fe₁₉ coupled to 10 nm Fe₅₀Mn₅₀ has been prepared by MBE. The interface corrugation remains throughout the layer stack. By means of a field annealing cycle the exchange bias direction has been initialized either along or perpendicular to the ripple direction, which causes to align the uniaxial and unidirectional anisotropy contributions either parallel or perpendicular to each other. The magnetization reversal behaviour has been investigated by means of MOKE. For both cases the magnetic easy- and hard-axes remained identical as the uniaxial anisotropy contribution is much larger than the unidirectional one. However, exchange bias initialization along or perpendicular to the ripple direction shifts the magnetization reversal loop of the easy-axis or hard-axis, respectively. A complete angular dependence of the magnetization reversal behaviour has been investigated for both cases and compared to simulations based on a Stoner-Wohlfarth coherent rotation model. A good agreement between experimental data and simulations is found.