STERN GERLACH MEDAL

It’s the Coupling that Creates Resistance

Spin electronics in layered magnetic structures

Peter Grünberg

Fast-paced technological advancement is squeezing the data on computer hard disks ever closer together. For some ten years now, continuously shrinking and increasingly sensitive read/write heads are making use of the giant magnetoresistance (GMR) effect discovered in 1988. This term was coined for the effect that electric resistance of a magnetic layer system changes dramatically when the magnetization of the individual layers is reversed from antiparallel to parallel orientation. Very small exterior magnetic fields suffice to change the orientation and thus give GMR read/write heads their high sensitivity.

The German Physical Society’s highest award, the Stern Gerlach Medal, is named after Otto Stern and Walther Gerlach, who in 1922 were able to prove the quantum mechanical quantization of direction in a beam of silver atoms in a magnetic field. The same phenomenon is the reason why conduction band electrons of ferromagnetic metals can only take on either parallel (up) or antiparallel (down) alignment in relation to local magnetization. Upon current flow, inelastic scattering of electrons is responsible for ohmic resistance. If the spins flip only rarely upon scattering, the resulting total current primarily consists of two independent partial currents of one spin type each in accordance with Mott’s two-current model. The typically unequal scattering rates cause the resistances $R_\uparrow$ and $R_\downarrow$, respectively (see information box). This model successfully describes electronic transport in magnetic metals. Magnetic band shift provides microscopic proof for the non-equivalent behavior: it causes the spin up and spin down states at the Fermi edge to not only differ in state density, but also electronically through charge distribution and orbital character.

Transport in magnetic metals can be purposefully influenced by varying the concentration and make-up of the spin-independent scattering centers. This however necessitates the fabrication of a new sample each time, inevitably introducing an element of uncertainty. Much more elegant access is given by magnetic layer structures in which spin-dependent scattering depends on the relative magnetic alignment of neighboring layers. These systems furthermore offer the opportunity to make use of other spin-dependent processes such as interface reflectivity or the tunnel effect to influence electron behavior.

For some ten years now, the majority of hard disk read/write heads have been making use of the giant magnetoresistance principle for reading stored data.

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Depending on the materials used for the layered structure, different effects occur. In the following, we shall focus on trilayers (see **Figure 1**). We exclusively use 3d metals and their alloys for the two outer ferromagnetic layers. The non-ferromagnetic intermediate layers are classified into materials with bandgap (insulators and semiconductors) and without (metals).

The experiment by Jullière on the tunnel magnetoresistance (TMR) is considered to be the forerunner to giant magnetoresistance [1]. TMR can be observed when electrons tunnel through the barrier of a layer system containing an insulating or semiconducting

COMPACT

- In magnetic multilayer systems, the relative orientation of magnetization of ferromagnetic layers depends on the coupling across an intermediate non-ferromagnetic layer.
- The relative magnetic orientation of neighboring layers in turn influences the spin-dependent scattering and with it, resistance. This grows with increasing angle between the magnetizations to a maximum for antiparallel alignment (GMR).
- Conversely, a current may rotate the magnetization of a layered system because electrons with spin up and down possess different scattering rates at interfaces and therefore cause torque.

Prof. Dr. Peter Grünberg, Institute of Solid State Research at Jülich Research Center – prize winner article on the occasion of his 2007 Stern Gerlach Medal Award at the DPG’s 71st Annual Meeting in Regensburg, Germany.

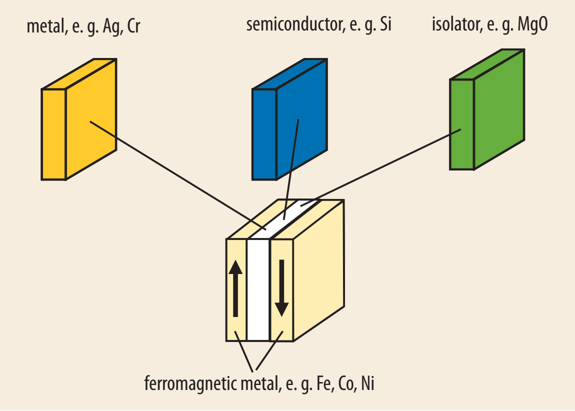

Fig. 1 The structures considered here consist of a minimum of two ferromagnetic layers with a typical thickness of 10 nm separated by a non-ferromagnetic intermediate layer of approx. 1 nm thickness.

Structure	$U - E_F$ in eV	$\Delta R/R_p$ in %
Co/Ge(10 nm)/Co		16 (4,2 K)
CoFe/ZnS/CoFe	0,580 0,565	5 (270 K) 10 (6 K)
Fe/GaAs/Fe		1,55 (300 K)
CoFeB/Al$_2$O$_3$/CoFeB		70 (300 K)
CoFeB/MgO/CoFeB		472 (300 K) 804 (5 K)
CoFe/MgO/CoFe	1,1 ... 1,7	220 (300 K) 300 (4,2 K)
Fe/MgO/Fe	0,37… 0,40	180 (300 K)
Fe/Si/Fe	0,3 … 0,8	≈ 0

Tab. 1 TMR for a selection of material combinations [7]. Bracketed values are the temperatures at which the TMR was measured. The barrier height U-E_F is a measure for the isolating properties of the intermediate layer and corresponds to the distance between the lower edge of the conduction band U and the Fermi level E_F.

intermediate layer. The tunnel current then depends on the relative orientation of magnetization direction in the outer ferromagnetic layers. The strength of TMR is given by $\Delta R/R_p = (R_{ap}-R_p)/R_p$ with tunnel resistances R_p for parallel and R_{ap} for antiparallel magnetization alignments. Jullière proposed that the voltage applied on one side of the barrier causes unoccupied states into which electrons from the other side may tunnel under retention of energy and spin. The spin polarization $P_{\text{bulk}} = (N\uparrow-N\downarrow)/(N\uparrow+N\downarrow)$ of the bulk material conduction band electrons can be defined with the help of densities of state, leading to the change of resistance: $\Delta R/R_p = 2\,P^2_{\text{bulk}}/(1\text{-}P^2_{\text{bulk}})$.

Jullière's experiment garnered little interest upon its publication in 1975. This probably stemmed from the fact that the effect observed was only a few percent and could only be measured at low temperatures. Furthermore, it proved impossible to this day to reproduce this effect with the germanium barrier thicknesses of 10 to 15 nm cited by Jullière. The enormous progress nevertheless made since is demonstrated by solid proof of $\Delta R/R_p$ values of some 500 % at room temperature for MgO barriers. **Table 1** summarizes the values obtained so far for several material combinations.

Any description of the TMR effect based solely upon the spin polarization P_{bulk} of the magnetic layers neglects any possible effects contributed by the intermediate layer. This contradicts experimental results such as the high value for MgO barriers, which is caused by the particular band structure of MgO [2]. Descriptively put, MgO provides electronic states that cause a high spin polarization during transition of the electrons between the ferromagnetic layers. Most of the electrons tunnel via this channel and cause a strong TMR effect. In order to take these influences into account, P_{bulk} needs to be replaced by an effective spin polarization P_{eff} that includes the properties of the barrier (e.g., its height U–E_F). Subsequently, the effective spin polarization is also supplemented with a parameter which takes the spin asymmetry of electron scattering in the bulk and at interfaces into account.

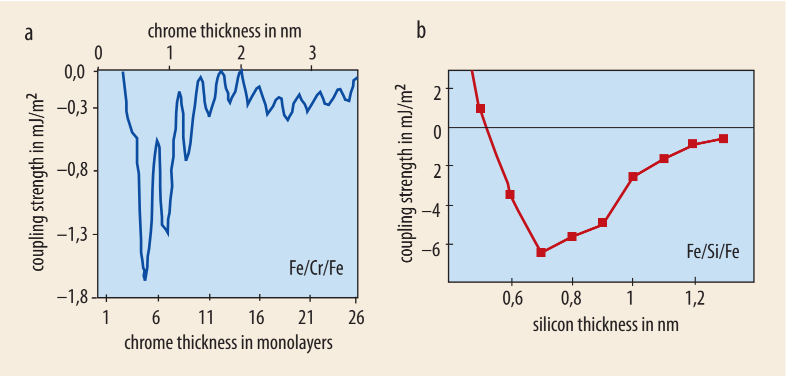

Fig. 2 Coupling is negative – antiferromagnetic – for both metallic intermediate layers (chrome, a) as well as semiconducting ones (silicon, b), however, a metallic intermediate layer leads to an oscillating coupling strength as a function of the intermediate layer's thickness (a).

Coupling via Intermediate Layers

Aside from Jullière's and others' experiments on structures with insulating or semiconducting intermediate layers, the coupling over non-magnetic metallic intermediate layers was also examined in the 1970's. So-called pinhole coupling over holes in the intermediate layer results from bridges that directly connect the two ferromagnetic layers. Although this kind of coupling is difficult to identify unambiguously, it has been made responsible time and again for ferromagnetic coupling.

The real breakthrough occurred as late as 1986 with the discovery of exchange coupling of Gd respectively Dy layers through Y intermediate layers as well as Fe layers via Cr [3, 4]. Exchange coupling causes the relative orientation of magnetization of ferromagnetic layers to depend on the intermediate layer's thickness. The surface area density associated with the coupling has proven itself to be a reliable quantitative description of experimental results, with

$$E_{\text{exch}} = -J_1\cos(\Delta\varphi) = -J_1\cdot\frac{\boldsymbol{M}_1\cdot\boldsymbol{M}_2}{|\boldsymbol{M}_1\cdot\boldsymbol{M}_2|}$$

$\Delta\varphi$ is the angle between the magnetizations $\boldsymbol{M}_1$ and $\boldsymbol{M}_2$

of neighboring coupled layers and J_1 is a phenomenological parameter. This expression is actually used mostly in purely empirical fashion, however it can be theoretically explained by the underlying RKKY interaction [5, 6], which is based on the spin polarization of conduction band electrons and is named for Ruderman, Kittel, Kasuya and Yosida. Depending on intermediate layer thickness, the RKKY interaction leads to a ferromagnetic (F) or antiferromagnetic (AF) coupling between the outer layers. These F and AF couplings are described by positive and negative J_1 values, respectively.[1]

It can be derived from theory that for metallic intermediate layers, e.g., for the Fe/Cr/Fe system, the coupling oscillates as a function of the intermediate layer's thickness while it decays exponentially for insulating and semiconducting ones. While oscillating coupling over metallic intermediate layers has been demonstrated for numerous cases (see **Fig. 2a**), Si and MgO remain the only known examples for non-metallic intermediate layers (see **Fig. 2b**). The decrease in absolute value below 0.7 nm in **Figure 2b** is probably caused by holes in the intermediate layer and ferromagnetic bridges through them. Thicker layers result in the expected exponential curve.

Surprisingly, the largest reliably and reproducibly measured AF coupling strength comes from Si intermediate layers with $J_1 \approx -6$ mJ/m^2. Next in line is Ru with $J_1 \approx -5$ mJ/m^2 [8]. Ruthenium is preferred for applications of the AF coupling such as synthetic antiferromagnets (SAFs) or AFC media (antiferromagnetically coupled media) despite the fact that the J_1 values actually achieved in technical implementations are significantly lower and reach only $J_1 \approx -0.1$ mJ/m^2 in the case of the SAFs [9] and $J_1 \approx -0.06$ mJ/m^2 for AFC media [10]. The strong coupling via Si is particularly surprising because of the extremely low TMR effect in this system, while theoretically the free electron model puts high (low) coupling strengths in correlation with strong (weak) TMR effects [5]. In contradiction to this, Fe/Si/Fe shows particularly strong coupling experimentally although the TMR remains undetectable. Impurities in the intermediate layer causing discrete energy levels might explain this were they to resonate with the Fermi edge of the neighboring Fe. However, the true reason probably is the improvement of growth and crystallinity over time leading to successively stronger coupling (see **Fig. 3**).

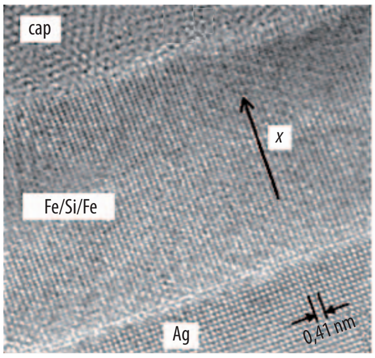

Fig. 3 Electron microscopic image of an Fe/Si/Fe system showing a slanting stripe in the center which represents a sideways cut through the entire sample. The Fe/Si and Si/Fe border lines are invisible to the naked eye, however, evaluation of the atom distances in direction of the arrow followed by averaging perpendicular to it brings out the distortion in the Si lattice, with which the location of the silicon layer can be determined.

MOTT'S TWO-CURRENT MODEL

Mott's two-current model (MTM) simplifies the dealing with electric transport phenomena in ferromagnetic materials: electric current consists of an electron drift movement and the resistance stems from inelastic scattering processes. MTM describes the total current in a ferromagnet in the shape of two partial currents with spin up and spin down flowing parallel to each other, i.e., with parallel and antiparallel alignment of their spins in respect to the magnetization *M*. The resistances are each determined by their associated scattering rates. Spin flip processes involving spin inversion are neglected. This is illustrated in **Figure i** under the premise that the scattering rate of electrons having spin down is greater than that for spin up. Justification of the MTM is derived from the influence of directional quantization as caused by magnetization of the transport electrons and the shift of the bands.

Despite the interaction causing ferromagnetism being the exchange part of the Coulomb interaction, it can be imagined in molecular field approximation as a magnetic field especially for symmetry purposes. Subsequently, the band shifts typical for ferromagnetism result (with temperatures *T* equivalent to 10.000 K), as do differing orbital wave functions at the Fermi edge for spin up and spin down. The right half of **Figure i** shows a band structure typical for magnetic 3d metals, in which the spin up and spin down bands are shifted relative to each other. The d bands are significantly stronger than the s bands. According to current knowledge, it is the s electrons that predominantly carry the current due to their higher mobility, while the resistance is mainly caused by s electrons scattering into vacant d states at the Fermi edge. In the present example, d electrons with spin down have the higher density of states at the Fermi edge E_F, which is responsible for the stronger scattering of electrons with spin down.

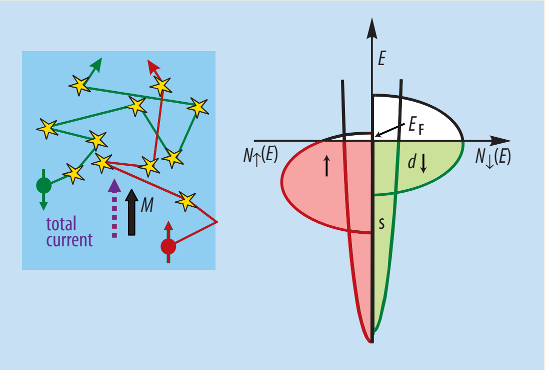

Fig. i *According to the MTM (left side, asterisks mark inelastic scattering processes) the total current splits into two partial currents. The unequal behavior of electrons with spin up and down results from the magnetic band split and the shift of the densities of states (right side).*

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[1] For a more accurate description, an additional quadratic term is needed in $\cos\Delta\varphi$, which is however omitted here.

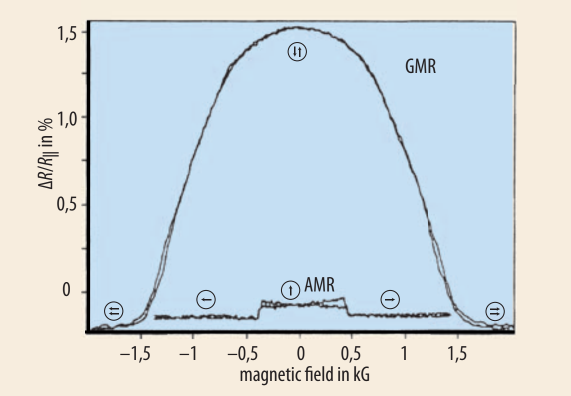

Fig. 4 Compared to the AMR effect from a 25 nm thick Fe film, the GMR effect from a trilayer system Fe/Cr/Fe with iron thicknesses of 12 nm is significantly larger.

System	$\Delta R/R_p$ in %	t_{mag} in nm
Fe/Cr/Fe	1,5	12
Fe/Cr/Fe	2	5
[Fe/Cr(1,2 nm)]50	42	0,45
Co/Cu/Co	2,0	10
Co/Cu/Co	19	3
[Co/Cu(0,9 nm)]30	48	1,5
Co90Fe10/Cu/Co90Fe10	6	0,8
Co/Cu/Co	16	2,8
[Co/Cu(0,9 nm)]16	65	1

Tab. 2 GMR values for trilayers and multilayers at room temperature. Supplemental layers which do not contribute to the GMR effect are omitted. t_{mag} is the thickness of one of the magnetic layers.

When Magnetoresistance Turns Into a Giant

The GMR effect can be observed in layered structures of ferromagnetic materials separated by non-ferromagnetic, metallic intermediate layers. It consists of a change in resistance when the angle between the magnetization direction of neighboring ferromagnetic layers changes. Resistance is particularly high for antiparallel alignment while it becomes low upon parallel alignment. This effect, discovered simultaneously in 1988 in Orsay for multilayers and in Jülich for double layers, emphasizes the particular importance of electron spin for electric transport properties. In both cases, antiferromagnetic exchange coupling via the intermediate layer gave rise to antiparallel alignment in weak magnetic fields and parallel alignment in sufficiently strong ones. The GMR is defined as $\Delta R/R_p = (R_{ap}-R_p)/R_p$. Usually the current flows in the layer plane, but submicron structuring by electron lithography is capable of creating current flow perpendicular to it.

Table 2 shows especially large GMR values for both the double layer and the multilayer. The highest value recorded from a multilayer at room temperature is 65 %. A value of similar magnitude was found in Orsay and is so uncommon for purely metallic materials that it can deservedly be called 'giant'. The first experiment on the double layer yielded only 1.5%, but this change is still significantly larger than the anisotropic magnetoresistance effect (AMR) of a single Fe layer as thick as the double layer (see **Fig. 4**).[2] To date, larger values in double layers have been achieved solely for the Co/Cu/Co system (see **Table 2**). Fert explained the GMR effect on the basis of Mott's two-current model and spin-dependent electron scattering [11]. This explanation was later confirmed by means of more precise analysis of experimental data with the help of the Boltzmann equation [12]. For currents in the layer plane, spin-dependent electron scattering alone leads to the GMR effect.

GMR occurs when the relative direction of magnetization of neighboring ferromagnetic layers changes. This can be achieved in several ways, e. g., by AF intermediate layer coupling, which causes antiparallel magnetization in zero field. In the presence of sufficiently strong external fields, saturation occurs and the spins are aligned in parallel with the field vector. Alternatively, it is possible to exploit different coercitive field strengths of neighboring layers. This allows suitable external fields to cause remagnetization of one layer while the other remains in prior state. Sufficiently strong coercitive field strengths can be created by unidirectional interface anisotropy through addition of an antiferromagnetic layer to a ferromagnetic one (exchange anisotropy effect). When GMR is not caused by AF coupling but in one of the ways mentioned last, the term spin valve system is applied although the mechanism of the GMR effect doesn't differ from that of GMR induced by AF coupling.

From the microscopic point of view, spin-dependent electron scattering is responsible for the GMR, for it is also the basis for Mott's two-current model (see **Fig. i**). **Figure 5a** shows representative scattering processes (asterisks), idealized however by the assumption that only electrons with spin antiparallel to local magnetization

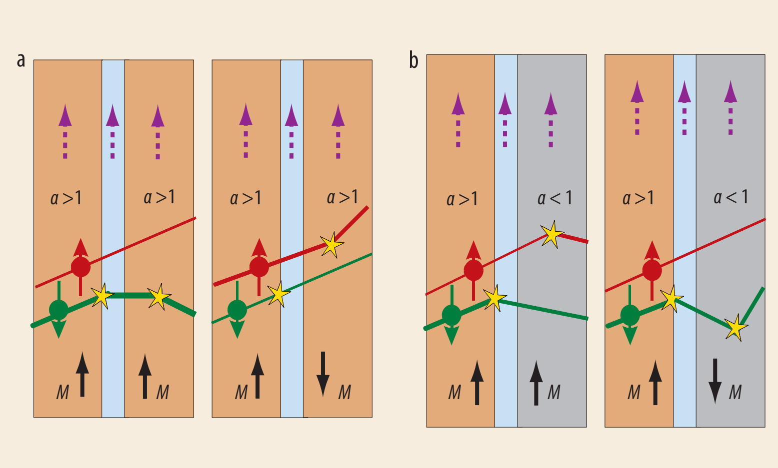

Fig. 5 In the idealized processes shown here, only electrons with spin down ($a > 1$) or spin up ($a < 1$) are scattered, depending on the nature of the magnetic material and interface (asterisks mark scattering processes). If a is either greater or lesser 1 in both layers, the normal GMR effect results (a). The combination of $a > 1$ and $a < 1$ leads to the inverse GMR effect (b) for which $R_p > R_{ap}$. Spin-dependent interface reflectivity is omitted since it does not change the electron impulse in current direction due to translational symmetry in the layer plane. In the case of currents vertical to the layer plane, reflexion joins scattering as an additional contributor to the GMR effect.

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[2] The AMR effect is defined as the difference in electrical resistance for currents flowing parallel to the magnetization direction, and perpendicular to it.

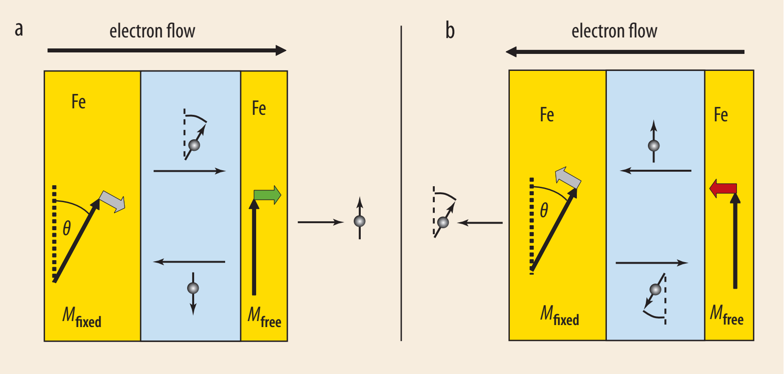

Fig. 6 Assuming positive spin polarization ($\alpha > 1$), current-induced switching leads to electron flow from the hard magnetic layer to the soft one (a) and vice versa (b). Electrons flowing in direction of the current are polarized in parallel while reflected ones are antiparallel. When the electrons submit to the direction of magnetization, they cause torque and rotate it.

are scattered. In the case of parallel magnetization direction, electrons with spin up do not scatter at all and consequently cause a short circuit. The latter is eliminated by antiparallel magnetization alignment (**Fig. 5a**, right) and the redistribution of scattering processes caused by it. So much for the idealized picture; in truth, it is always the case that both electron types are scattered, but a discrepancy in the scattering rates suffices to generate an increase in resistance for antiparallel magnetization alignment.

For general consideration it is advisable to define a local scattering symmetry parameter $\alpha = \rho_{\downarrow}/\rho_{\uparrow}$ with local specific resistances $\rho_{\downarrow}$ and $\rho_{\uparrow}$. Depending on whether electrons with spin up or spin down are scattered more strongly, α becomes < 1 or > 1. When materials with $\alpha < 1$ and $\alpha > 1$ are combined in a layered system (see **Fig. 5b**), the higher resistance results for parallel alignment of the magnetizations as can be deduced from the difference in distribution of the scattering processes. In contrast to the normal GMR effect depicted in **Figure 5a**, this is termed 'inverse' GMR. The microscopic cause behind the scattering asymmetry observed is the magnetic band shift that brings about differing electronic properties of the two spin types at the Fermi edge, and subsequently, of the conducting electrons (see information box).

Remagnetizing with Current

The scattering asymmetry expressed by α is also highly significant for current-induced magnetic switching (CIMS): asymmetric scattering gives currents spin polarization, which in turn causes precession of the magnetic system when current densities increase, finally leading to remagnetization of the system in direction of the spin current. CIMS was first postulated [13], then proven by experiment [14].

The implementation of current-induced magnetic switching takes the shape of a hard magnetic layer with a fixed magnetization M_{fixed}, a separation layer (blue) and a soft magnetic layer whose magnetization M_{free} can rotate freely (see **Fig. 6**). Suitable contacting allows current to flow perpendicular to the layer plane under confinement of the current path to a diameter of about 100 nm and current densities of roughly 10^7 A/cm^2. Under these circumstances, more electrons with spin down are scattered out of the current flow for $\alpha > 1$. The majority of the remaining electrons moving in the direction of the current flow is therefore polarized parallel to the respective magnetization. For the same reason, the reflected electrons are polarized antiparallel. It is furthermore assumed that M_{fixed} is slightly rotated by a small angle θ out of the (vertical) static magnetization (see **Fig. 6a**). During diffusion through the layer system, the electrons moving in current flow direction adjust themselves to the magnetizations they encounter by

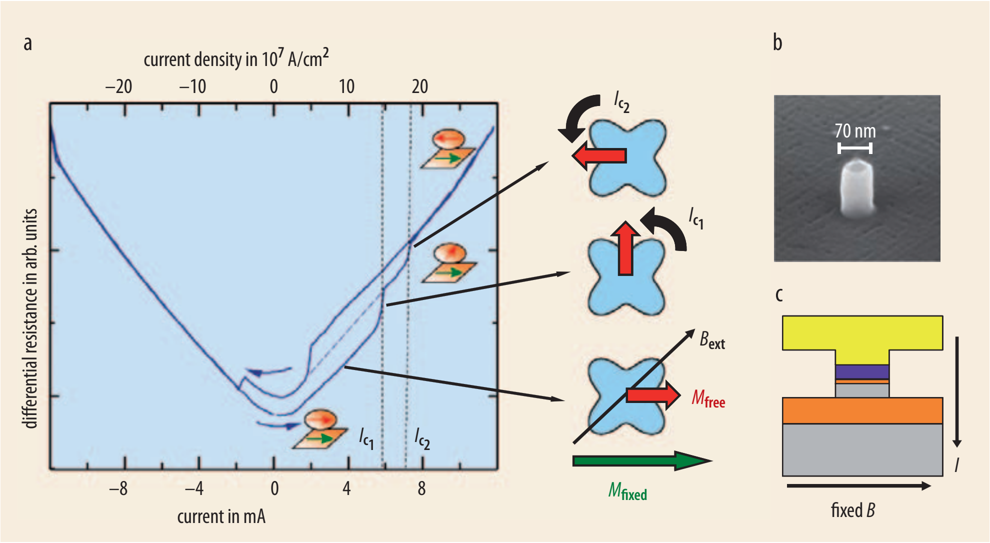

Fig. 7 During current-induced switching ($T = 5$ K, $B = 7.9$ mT), Fe/Ag/Fe samples show resistance deviations from U- respectively V-shaped characteristics (a). Alignment is parallel for negative currents, however with growing current, the free magnetization begins to rotate at critical current I_{c1} and reaches antiparallel alignment at I_{c2}. An electron micrograph shows the nanopillar prior to contacting (b), while the scheme depicts the layer arrangement with contacts (c). Positive currents correspond to current flows from top to bottom.

shedding the transversal spin moment which they previously picked up. Due to conservation of momentum, torque is caused which acts upon the magnetization (green arrow) until parallel alignment is achieved. The torque upon M_{fixed} (grey arrow) exerted by the reflected electrons remains noneffective since that magnetization cannot be rotated. The reasoning for **Figure 6b** is similar except that the reflected electrons cause torque which results in antiparallel alignment (red arrow).

Figure 7 shows an example of CIMS from an experiment recently carried out in Jülich. Epitactic Fe/Ag/Fe layer structures with quaternary cubic in-plane anisotropy were used [15]. The U- or V-shaped rise of the differential resistance for high absolute current strengths goes back to Joule heating. In **Figure 7c**, positive currents correspond to flows from top to bottom. In accordance with **Figure 6a** we expect parallel alignment of the magnetizations, which prevails for weak positive currents. Rising positive currents rotate the system until eventually antiparallel alignment is reached. Due to the superimposed cubic anisotropy, this happens here via an intermediate step with a 90° configuration.

The explanation for the switching processes shown in **Figure 6** rests upon the assumption of positive spin polarization of the electrons in current flow direction as confirmed by the Fe/Ag interface in **Figure 7**. For negative polarization as occurs at the Fe/Cr interface, qualitatively the same switching processes take place after inversion of the electron flow direction [15, 16].

Besides CIMS, the excitations of M_{free} occurring during the switching processes are currently under investigation. Due to the GMR effect between M_{free} and M_{fixed}, they cause emittance of microwaves. The intensity observed from a single contact is most certainly too low for actual application, however it has already been shown that synchronized driving of N contacts allows amplification by a factor of N^2. Autosynchronization by means of nonlinear effects is already known for other examples.

Giant Magnetoresistances in Everyday Life

There is a surprising number of applications for giant magnetoresistance besides the read sensor, for example in positioning and movement sensing of magnetically marked objects. Marking is either achieved by inherent magnetism of the object or by attachment of a tiny permanent magnet. This finds application in fields such as control over moving parts in vehicles (e. g., antiblocking systems), in robotics, or in conveyor belts. Cars contain enough magnetic parts to make use of them in multistory parking lots. Sensors embedded in the individual places can tell whether they are occupied or free. Sensors based on GMR are not only highly sensitive, but can also be packaged in very small dimensions.

The two principles mentioned earlier, spin valve and exchange coupling, are also found in sensors. Multilayers with high magnetic field susceptibility can be used for coupled sensors. Commercially available sensors however only measure the absolute value (unipolarity). In contrast, spin valve sensors also register the polarity, however, they are limited to a maximum of three magnetic layers, which narrows down the sensitivity achievable.

Antiferromagnetic coupling may also find application in the shape of artificial antiferromagnets. They for example help fixing the hard layer in a spin valve sensor. In a similar way, this can also be used for AFC media in respect to the information stored [10]. For tunnel magnetoresistance, potential applications are especially found in future MRAMs (magnetic random access memories) for current-induced magnetic switching during the write process, and for microwave sources in the nanometer size region.

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Translated by Martin Ottmar

THE AUTHOR

Günter Staudinger

In his youth, **Peter Grünberg** (right, here with de president of the German Physical Society Eberhard Umbach) was so fascinated by Newton's realization of gravity being what holds the planets in their orbits that besides sports and music, he developed a keen interest for physics. He studied physics in Frankfurt and Darmstadt, obtaining his Ph.D. in 1969. After a research stay in Ottawa (Canada), he joined the newly founded Institute for Magnetism at Jülich Research Center. In 1984, he completed his habilitation (facultas docendi) in Cologne and was able to prove the existence of antiferromagnetic coupling in Fe/Cr layer systems in 1986. The discovery of giant magnetoresistance followed two years later, today made use of in most computer hard disks. Peter Grünberg has received numerous awards for his accomplishments, amongst others the Future Prize of the German Federal President in 1998 and the Japan Prize in 2007. Jülich Research Center has benefited from the patent licence fees in double digit millions. Most notably, the great impact of Peter Grünberg's work has been recognized by the 2007 Nobel Prize in Physics.

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