A novel spin transfer torque effect in Ag$_2$Co granular films

Yuansu Luo$^1$, Markus Esseling$^1$, Markus Münzenberg$^2$ and Konrad Samwer$^1$

$^1$ I. Physikalisches Institut, Universität Göttingen, Friedrich-Hund Platz 1,
D-37077 Göttingen, Germany
$^2$ IV. Physikalisches Institut, Universität Göttingen, Friedrich-Hund Platz 1,
D-37077 Göttingen, Germany
E-mail: yluo@gwdg.de

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Abstract. We studied a spin transfer torque (STT) effect in Ag$_2$Co granular films, induced by a high current density $10^{8-9}$ A cm$^{-2}$ injected via a point contact. The system consists of single domain Co nanoparticles randomly embedded in Ag matrix, with a mean distance corresponding to the typical quantity of layer thicknesses used for the nonmagnetic space in multilayer nanopillars. A large giant magnetoresistance (GMR) effect of 55% measured at 4.2 K is an indication for high spin scattering anisotropy which is required for STT observations. Supposedly, a certain amount of large-sized Co particles saturated in external magnetic field $H$ acts here as the spin polarizer for the injected current $I$ and small-sized particles unsaturated at 4.2 K and $H_{\text{max}}$ (90 kOe) even act as the detector for switching. A novel STT effect was observed thereby as $I$ rises across a threshold value $I_c$, showing a sharp decrease in $R$ ($\Delta R/R = 130\%$ with two steps), which arises accordingly from further alignment of the small-sized Co granules. The behavior is polar and hysteretic, similar to properties measured for multilayer nanopillars. The two-step behavior could be an effect related to a lognormal particle size distribution. Depending on the spin polarization, $I_c$ is found to be field disproportional, indicating a larger STT efficiency at a higher $H$. 
1. Introduction

As theoretically argued by Slonczewski [1] and Berger [2], the spin vector can be transferred between separated magnetic layers by injecting a sufficiently large electric current, accompanied by exciting precession of magnet moments [3] and stimulated emission of spin waves [4]. The phenomena referred to as spin transfer torque (STT) or current-induced magnetization switching (CIMS) contain rather new physics and enormous prospects for technological applications which motivate current research on these topics worldwide [5]–[12]. Because of the very high current density (>10^7 A cm^2) needed for CIMS, relevant experiments were carried out with a current perpendicular to the plane (CPP) of magnetic multilayers, initially applying the single point contact technique [13] and subsequently nanopillars [14] with a diameter of about 0.1 μm. The magnetic multilayer is similar to a spin-valve giant magnetoresistance (GMR) structure, typically consisting of two ferromagnetic layers F_1 and F_2 with thicknesses t_1 > t_2 and a nonmagnetic space layer N with a thickness less than the spin diffusion length. In general, the thin layer F_2 is free for detecting switches and the thick layer F_1 is fixed. As a polarizer for electron spins, F_1 creates a highly spin-polarized current, usually carried by majority electrons, which passes through the layer N and transfers the spin angular momentum to spins of F_2 at the N/F_2 interface, rotating thus the magnetization of F_2 parallel to that of F_1. The parallel configuration then becomes destabilized by applying an opposite current and as a result, F_2 switches return to being antiparallel to F_1. The behavior depends therefore strongly on the current polarity. In connection with current-induced switching, resistive changes can be monitored due to the GMR effect.

The related research has been expanded into magnetic single films [12], [15]–[17], e.g. the current-induced motion of magnetic domain walls in magnetic nanowires, which offers storage memories in a new manner [12, 15]. More recently, an observation of STT-like effects in magnetic granular films was reported by Chen et al [18] with the result that a large spin disorder could arise from the combined effect of high density current and large magnetic field, accompanied with a large increase in R of about 400% which differs significantly from the normal GMR effect.

In the present paper, we report on a novel STT effect observed in GMR granular films of Ag_2Co consisting of magnetic single-domain Co particles with a mean size of 5 nm and a mean distance of 9 nm randomly embedded in nonmagnetic Ag matrix. The size distribution obeys a normal or lognormal function with a standard deviation from the mean size [19]. The volume fraction is about 25% for Co and 75% for Ag. Since a clear GMR effect is observed, the mean particle distance is less than the spin diffuse length. The composition is chosen as 2 : 1 for Ag and Co, because near this concentration the films show the largest GMR with an optimized...
size distribution of the nanoparticles [20, 21]. The special microstructure formed is based on immiscibility of the components and thus can be well controlled by heating substrates or by a post-annealing. At room temperature, the magnetic property of the films is superparamagnetic-like with zero remanence, but at liquid helium temperature it becomes ferromagnetic with an apparent hysteresis most likely due to large-sized Co particles. However, the spin vectors of Co granules are incompletely aligned even by an available maximal field of 90 kOe due to the existence of small-sized particles precipitated from the Ag matrix. A direct observation for the particle size distribution in similar granular films was made by Parkin et al [20] using transmission electron microscopy (TEM). Their result showed a large dispersion in particle size ranging from ~2 to 20 nm. The large GMR effect measured for the granular films implies a high scattering anisotropy of electron spins. It can be assumed that the large-sized Co particles act here as spin polarizers for current and the small-sized particles as detectors for switching. It is expected that a novel STT may occur among them when the electric current density is sufficiently high.

2. Experimental details

The Ag₂Co films with a thickness of about 150 nm were prepared by dc-magnetron-sputtering from an alloy target. The base pressure is 1 × 10⁻⁸ mbar and the sputtering pressure of Ar is 3 × 10⁻³ mbar. Thermally oxidized Si was used as substrates and kept at 100 °C during the film growth. The deposition temperature was chosen because of the largest GMR effect measured, concerning a nearly complete separation of the components and an optimized size distribution of the Co precipitates. The concentration of the film was checked by means of energy dispersive x-ray (EDX) analysis with the result of 67 at.% for Ag and 33 at.% for Co, i.e. the chemical formula of the films as Ag₂Co. The mean size and distance of Co particles were experimentally determined by grazing-incidence small-angle x-ray scattering (GISAXS) [22], using parallel x-ray focused by a Göbel-mirror of the diffractometer D8 (Brucker AXS). The grazing-incidence angle used is slightly larger than the critical angle \( \theta_c = (2\delta)^{1/2} \) with \( \delta \) denoted as the refraction index. The GISAXS data give a direct measure of the auto-correlation of the deviation of the local electron density from the average electron density.

Magnetotransport measurements with an in-plane magnetic field \( (H) \) up to 90 kOe were performed both by standard 4-point probe geometry and by a single point contact technique (schematic in the inset of figure 3) to show a normal GMR and a potential STT effect, respectively. The GMR value given here is defined as the ratio \( \Delta R/R_{\text{min}} \), i.e. percentage changes in resistance normalized to the minimum. For the point contact, a metallic tip (IrPt) was used on the film surface with a contact area estimated to be about 10⁴–⁵ nm², which corresponds to a current density of about 10⁸–⁹ A cm⁻² when applying a current \( I = 100 \text{ mA} \). Current scans within ±0.3 A and field scans within ±85 kOe \( (H_{\text{max}}) \) were done alternatively at low temperatures to determine the dependence of the critical current \( I_c \) on the magnetic field. To describe the current polarity of STT, the sign of the electric current flowing from the tip into the film is defined as positive.

3. Results and discussion

GISAXS data measured for the Ag₂Co film are presented in figure 1, showing a diffuse scattering near \( 2\theta = 0.025 \) (rad) caused by the correlation of the Co particles with the electron
Figure 1. GISAXS data measured for the Ag$_2$Co granular film. The dotted line represents the background intensity from the surface diffuse and parasitic scattering. The mean particle size of $\sim$4.8 nm is extracted from the slopes of the logarithmic intensity versus the square of $2\theta$ (rad). The inset is the data after subtraction of the background, showing a peak centered at $q_{\text{max}} = 0.7$ nm$^{-1}$ corresponding to a mean particle distance of $\sim$9 nm.

density different from that of the Ag matrix. Subtracting the intensity contribution from surface diffuse and parasitic scattering yields a clear peak, as plotted versus the magnitude of the scattering vector $q = (4\pi/\lambda) \sin(\theta - \theta_c)$ in the inset to figure 1. The peak is broad and asymmetrical possibly due to a lognormal distribution of the particles both in size and distance [19]. The peak is centered at $q_{\text{max}} = 0.7$ nm$^{-1}$, so the mean distance between Co particles is given by $\Lambda = 2\pi/q_{\text{max}} = 9$ nm. Moreover, the mean size of the particles was evaluated by means of Guinier’s approximation [23], using the logarithmic intensity $\ln I_{SA}(2\theta) = \ln{Mn^2I_e - 4/3(\pi/\lambda)^2R_G^2(2\theta)^2}$ with $M$ denoted as the number of Co particles, $n$ as the number of the total electrons, $I_e$ as scattering intensity of a single electron and $R_G$ as the Guinier’s radius. Here, we assumed nanoparticles to be spherical with a form factor equal to 1. The slopes of the curve give the values of $R_G$ averaged at about 2.4 nm, i.e. the mean size equals 4.8 nm in diameter. Similar values for the mean particle size and distance were also determined from the full width at half-maximum of wide-angle x-ray diffraction peaks according to the Scherrer formula [24], where we assumed the mean particle distance to be approximately equal to the grain size of Ag.

Figure 2 gives the GMR effect for the Ag$_2$Co film, measured at 300, 100 and 4.2 K by means of the 4-point probe geometry with $I = 10$ mA and $H$ up to 25 kOe. As can be followed, at 300 K the magnetoresistance is about 26% without a hysteresis in accordance with the superparamagnetic property of the nanoparticles. At 100 K the effect rises up to 44% with a slight hysteresis. At 4.2 K, it increases up to 55% and the hysteresis becomes pronounced likely due to large-sized Co particles. The large GMR effect observed in the Ag$_2$Co granular films implies a high scattering anisotropy of electron spins which is necessary for phenomena of the STT.
Figure 2. GMR effect, measured for Ag$_2$Co granular films at 300, 100 and 4.2 K by means of standard 4-point probe geometry, signifying a large spin scattering asymmetry necessary for STT experiments.

Figure 3. Current scans of the point contact performed at 4.2 K for Ag$_2$Co film under a magnetic field $H = 10$ and 60 kOe, respectively, the latter indicates a novel current induced switching with an abrupt decrease in $R$ near $-0.2$ A, which is hysteretic but asymmetrical with $I$. Inset: scheme for the point contact.

Current scans of the point contact were done at 4.2 K within $\pm 0.3$ A under a series of constant $H$ from 0 to 85 kOe and the results are plotted in figures 3 and 4. For comparison, figure 3 reveals $R$ versus $I$ for $H = 10$ and 60 kOe, respectively. First of all, it can be followed from the $R(I)$ curve for $H = 60$ kOe, that the electric resistance drops abruptly, as $I$ exceeds a threshold value $I_c$ of about 0.21 A. On the other hand, the $R(I)$ curve for $H = 10$ kOe does not
Figure 4. Current scans of the point contact from \( I = 0 \) to \(-0.3 \) A at 4.2 K for the \( \text{Ag}_2\text{Co} \) film under varied magnetic field \( H \) from 0 to 85 kOe, used for extracting the field dependency of the critical current \( I_c \). Inset: \( I_c \) versus \( H \), showing a disproportional relation.

display these changes, besides a slight increase with \( I \) in a parabola manner which is typical for the point contact due to heating by the high current density.

Moreover, the abrupt change in \( R \) has two steps, initially from 6.5 \( \Omega \) down to 5.4 \( \Omega \) at 0.21 A and subsequently from circa 4.9 \( \Omega \) down to 3.0 \( \Omega \) at about 0.275 A. In-between the change is smooth and plateau-like. The behavior observed here could be associated with the lognormal size distribution which is hidden within the typical magnetoresistance found in particular for the granular system. In a current-induced switching experiment, the two tails of the distribution function marked by a strong change in the slope could naturally define the onset of the switching at different threshold currents. In a simple model, this could result in two step-like increases in \( R \) and a characteristic plateau being observed.

Conversely, when reducing \( I \) down, \( R \) increases sharply at 0.25 and 0.175 A respectively, indicating an obvious hysteresis with \( I \), as denoted by arrows in figure 3. Actually, within the current range used the abrupt change in \( R \) emerges already at \( H \geq 40 \) kOe (see figure 4). It does not come out however when applying an opposite current and thus is asymmetrical with respect to the current, as shown in figure 3. Both the hysteretic behavior with \( I \) and the current polarity are typical characters of the STT effect found in magnetic multilayers. Dissimilarly, for the granular structures there exists an onset field \( H_o \) for switching which is relatively high, needed perhaps for creating a sufficiently high spin polarization in the current. A similar effect was found in magnetic nanopillars with a vortex structure as a magnetic ground state [17], where the onset field for switching corresponds to the saturation field needed to saturate the polarizing layer until a sufficiently high spin polarization in the current is achieved.

The critical current \( I_c \) can be extracted from figure 4, which represents the increasing branch of current scans from 0 to \(-0.3 \) A under varied \( H \) from 0 to 85 kOe in more detail. For the case of \( H < 40 \) kOe, \( R \) is reduced due to the normal GMR effect, but without an effect from the maximal possible current, excluding the heating effect mentioned above. Above 40 kOe, a sharp drop in \( R \) comes out. The value of \( I_c \) can be easily evaluated from the first break point.
Figure 5. Field scans of the point contact carried out at 4.2 K for the Ag$_2$Co film with $I = -10$ mA, and $\pm 0.275$ A respectively, including the result obtained at 55 K with $I = -0.275$ A (upper curve). For the case of 10 mA ($< I_c$) there is only a normal GMR effect with $R$ changes dominant in low fields ($< 15$ kOe). Oppositely for 0.275 A ($> I_c$) an additional drop in $R$ (130%) occurs near 40 kOe, presumably arising from further alignment of small-sized Co particles induced by STT.

and is plotted versus $H$ in the inset of figure 4. The result evidently indicates a disproportional function (red shift), in contrast to the case of magnetic multilayered nanopillars, where $I_c$ is mostly found to be field proportional [9, 13] and is in general an indication for an increased precession frequency of an excited mode with $H$ (blue shift). The observed disproportional function points to a higher efficiency of the spin torque with higher applied fields.

Figure 5 demonstrates the result of field scans with a current $I = -10$ mA, $-0.275$ A and 0.275 A, respectively. Obviously, for $I = -10$ mA there is merely a normal GMR effect occurring at relatively low fields ($< 20$ kOe) with a hysteresis symmetrical to $H$, whereas for $I = -0.275$ A a sharp decrease in $R$ additionally emerges near $H = 50$ kOe with a two-step hysteresis asymmetrical to $H$. Otherwise, when a positive current (0.275 A) is applied, the abrupt change of $R$ takes place in the opposite field direction. The field asymmetry of STT observed in the granular films is dissimilar to the situation in multilayers of Co/Cu/Co [14], where, for $I > I_c$, additional $R$ changes induced by STT come out as well at relatively larger $H$ compared to GMR, but are nearly symmetrical with respect to $H$.

Moreover, as can be followed in figure 5, above $H = 20$ kOe the relative change $\Delta R/R \cong 130\%$, which is much larger than the normal GMR contribution within 20 kOe. Presumably, it could be associated with a further alignment of spins of small-sized Co particles driven by STT, which could be still superparamagnetic even at 4.2 K and unsaturated in maximal available magnetic field. By assuming a roughly linear $R$ drop with $H$ above 20 kOe (figure 5), from $\Delta R/R \cong 130\%$ we can estimate a field of about $2 \times 10^3$ kOe needed for aligning the spins of the small Co particles. An enhancement of magnetoresistance induced by STT in similar granular films has also been reported by Chen et al [18]. They observed however a sharp increase in $R$.
under a large $H$ with a ratio of $\Delta R/R \cong 400\%$ even. Accordingly, the authors suggested an antiferromagnetic spin configuration of small-sized magnetic granules.

Additionally, the upper curve in figure 5 presents the result obtained at 55 K with $I = -0.275$ A. The behavior is identical to that measured for 4.2 K, but without a clear hysteresis for the low-field GMR effect, indicating a more pronounced heating effect caused by the high density current. For the case of low current (10 mA), the field hysteresis emerges even at 100 K (see figure 2). At 4.2 K, the heating effect is unimportant, since the hysteresis for GMR is more or less seen even for 0.275 A.

Detailed field scans with a current in the range from 10 mA to 0.3 A are illustrated in figure 6, where the curves for 10 mA and 0.275 A start from $H_{\text{max}}$ and the other from zero. Actually, within the maximal available $H$, the novel STT effect is already seen for 0.15 A and shows an onset field $H_o$ for switching of about 75 kOe. $H_o$ decreases systematically with increased $I$ and is about 30 kOe for 0.3 A. The values of $H_o$ evaluated for varied $I$ are plotted in the inset of figure 6, exhibiting again a disproportional relation between the current and field, identical to that shown in the inset of figure 4. One should note that the onset field $H_o$ evaluated from the field scans seems to be slightly less than the corresponding value measured by the current scans, which mirrors a history dependence of $H$ and $I$ in regard to the hysteretic behaviors mentioned above. Accordingly, the curve for 0.275 A, which starts from the maximal field of 85 kOe, shows a hysteresis of STT, which seems to be wider than those starting from zero field.

Additionally, there are remarkable characteristics for low $R$ states as shown in figure 6. Firstly, as soon as STT happens, $R$ becomes quite noisy though it intensively decreases in size. Secondly, it seems to increase slightly with $H$, in contrast to the case prior to the occurrence of STT.

Figure 6. Detailed field scans at 4.2 K for Ag$_2$Co film with different currents from 10 mA to 0.3 A. Inset: the current dependence of the onset field $H_o$ for switching, showing a disproportional relation.
4. Conclusion

In conclusion, we explored the STT effect in sputtered Ag$_2$Co granular films by means of a single-point contact. The system consists of single domain Co nanoparticles randomly embedded in Ag matrix, where the mean particle distance (9 nm) corresponds to the typical scalar of layer thicknesses used for the nonmagnetic space in multilayer nanopillars and less than the spin diffuse length, giving rise to a large GMR effect (55% at 4.2 K) which is an indication for high spin scattering anisotropy required for STT experiments. A novel STT effect was observed as the current rises across a threshold value $I_c$, accompanied by a two-step sharp decrease in $R$ ($\Delta R/R = 130\%$) which presumably arises from further alignment of the unsaturated small-sized Co granules. The behavior is polar and hysteretic with respect to the current, similar to properties measured for multilayer nanopillars. As an interpretation, we assumed that the large-sized Co particles, which are ferromagnetic at low temperatures, act here as the spin polarizer for the current and the small-sized particles, which are still nonaligned at 4.2 K and $H_{\text{max}}$, act as the detector for current-induced switching. Depending on the alignment of the large-sized particles, i.e. on the spin polarization degree, the critical current is measured to be disproportional to the magnetic field, demonstrating a more powerful STT efficiency at a higher field. The two-step switching observed could be an effect associated with a lognormal size distribution of the Co nanoparticles. This behavior could be influenced by modifying the particle size distribution after a series post-annealing.

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References

[1] Slonczewski J C 1996 J. Magn. Magn. Mater. 159 L1
Slonczewski J C 1999 J. Magn. Magn. Mater. 195 261
[2] Berger L 1966 Phys. Rev. B 54 9355
[3] Schumacher H W, Chappert C, Crozat P and Hillebrands B 2003 Phys. Rev. Lett. 90 017201
[4] Kiselev S I, Sanyk J C, Krivorotov I N, Emley N E, Schoelkopf R J, Buhrman R A and Ralph D C 2003 Nature 425 380
[5] Myers E B, Ralph D C, Katine J A, Louie R N and Buhrman R A 1999 Science 285 869
[6] Zhang S, Levy P M and Fert A 2002 Phys. Rev. Lett. 88 236601
[7] Barnas J, Fert A, Gmitra M, Weymann I and Dugaev V K 2005 Phys. Rev. B 72 024426
[8] Albert F J, Emley N C, Myers E B, Ralph D C and Buhrman R A 2002 Phys. Rev. Lett. 89 226802
[9] Katine J A, Albert F J, Buhrman R A, Myers E B and Ralph D C 2000 Phys. Rev. Lett. 84 3149
[10] Buchmeier M, Schreiber R, Bürgler D E and Grünberg P 2003 Europhys. Lett. 63 874
[11] AlHajDarwish M, Kurt H, Urazhdin S, Fert A, Loloee R, Pratt W P Jr and Bass J 2004 Phys. Rev. Lett. 93 157203
[12] Klüuii M, Jubert P-O, Allenspach R, Bischof A, Bland J A C, Faini G, Rüdiger U, Vaz C A F, Vila L and Vouille C 2005 Phys. Rev. Lett. 95 026601
[13] Tsoi M, Jansen A G M, Bass J, Chaing W-C, Seck M, Tsoi V and Wyder P 1998 Phys. Rev. Lett. 80 4281
[14] Özyilmaz B, Kent A D, Monsma D, Sun J Z, Rook M J and Koch R H 2003 Phys. Rev. Lett. 91 067203
[15] Thomas L, Hayashi M, Jiang X, Moriya R, Rettern C and Parkin S S 2006 Nature 443 197
[16] Chen T Y, Ji Y, Chien C L and Stiles M D 2004 Phys. Rev. Lett. 93 026601

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[17] Parge A, Niermann T, Seibt M and Münzenberg M 2007 J. Appl. Phys. 101 1
[18] Chen T Y, Huang S X, Chien C L and Stiles M D 2006 Phys. Rev. Lett. 96 207203
[19] Helmolt R, Wecker J and Samwer K 1994 Phys. Status Solidi b 182 K25
[20] Parkin S S P, Farrow R F C, Rabedeau T A, Markes R F, Harp G R, Lam Q, Chappert C, Toney M F, Savoy R and Geiss R 1993 Europhys. Lett. 22 455
[21] Lorenz T, Moske M, Geisler H, von Helmolt R, Weiss M and Samwer K 1996 Thin Solid Films 275 220
[22] Levine J R, Cohen J B, Chung Y W and Georgopoulos P 1989 J. Appl. Crystallogr. 22 528
[23] Guinier A and Fournet G 1947 Nature 160 501
[24] Cullity B D 1978 Elements of X-Ray Diffraction (London: Addison-Wesley) p 102