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Spin motion of electrons during reflection from a ferromagnetic surface

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If electrons are reflected from a ferromagnet, the spin moves depending on the magnetization vector of the ferromagnetic surface. The spin motion, consisting of a precession around the magnetization direction and a rotation into it, is measured and explained in terms of the electronic band structure of the ferromagnet. If applications within a solid-state device are considered, sizeable transverse torques on the magnetization due to the spin precession can be expected.

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The manipulation of the magnetization by spin currents is one of the most intriguing concepts of contemporary magnetism.[1,2] Injection of polarized electrons into a thin ferromagnetic film generates a transverse torque[3] as well as a dampinglike torque[1,2] acting on the magnetization $\vec{M}$, and either type of torque may be used to switch $\vec{M}$ into a new direction, albeit on quite different time scales.[4–6] Recently, the transverse torque generated by spin injection has been determined by transmitting a polarized electron beam through ferromagnetic films and measuring the motion of the polarization vector $\vec{P}$ of the electrons upon transmission.[7] This experiment establishes in fact a new differential torquemeter measuring, by virtue of Newton's law of equal and opposite reaction, the torque generated by the exchange interaction of the injected electrons with the magnetization.

Quantitative understanding of a solid-state device, in which spin injection may be utilized, requires the consideration not only of transmission, but also of the reflection of the electrons within the device as will be shown below. The purpose of this paper is then to present a model experiment revealing the physical principles underlying the spin motion of the electrons in elastic reflection from a ferromagnetic surface. The experiment shows that torque is exercised by the reflected electrons on the magnetization and that the magnitude and even the sign of the torque depends critically on the electron energy and the nature of the ferromagnetic surface. However, the model experiment cannot be applied directly to devices as it does not cover electron energies closer to the Fermi energy relevant in the applications.

While numerous studies have been done previously on the scattering of polarized electrons from ferromagnets,[8] the present experiment is distinguished by the fact that $\vec{P}_0$ of the incident electrons is at an angle of $\vartheta = 90°$ to $\vec{M}$. It is only with this noncollinear initial configuration that the motion of $\vec{P}$ can be observed. We also can separately measure the precession angle ϵ and the rotation angle ϑ of $\vec{P}$ (see inset in Fig. 1).

The experiment is sketched in Fig. 1. The source of the polarized electron beam is a GaAs-type photocathode. The polarized electron beam impinges at an angle of 45° to the normal of the ferromagnetic surface, and the electrons elastically reflected at 45° can traverse the retardation grid and are accelerated to an energy of 100 keV for the measurement of the transverse components of $\vec{P}$ in the Mott polarimeter. The resolution of the retarding grid analyzer is 0.5 eV full-width at half maximum. While $\vec{M}$ lies in the scattering plane, $\vec{P}_0$ of the incident electron beam is perpendicular to it.

The samples investigated here are Co films grown on two types of substrates, namely, a (111)-textured polycrystalline Au film on glass and a Cu(001) single crystal. The metal films are deposited with electron-beam bombardment, and their thickness is measured by a quartz microbalance. The details of film growth are described in Refs. 9 and 10, respectively. The first type of substrate generates a polycrystalline Co film while the second type of film grown on Cu(001) is single crystalline fcc Co. Magnetic characterization is achieved with the magneto-optic Kerr effect. In the case of the polycrystalline Co/Au/glass films the easy direction of the magnetization is induced by oblique incidence of

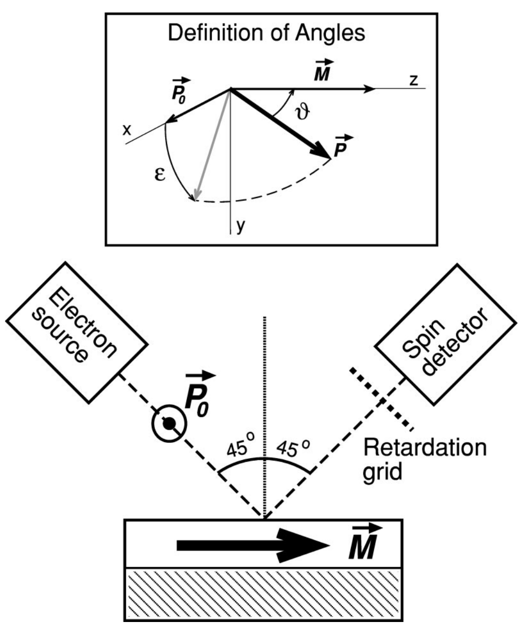

FIG. 1. Principle of the experiment. The experiment consists of a polarized electron source of the GaAs type, a ferromagnetic Co film which is magnetized remanently in-plane, a retarding field energy analyzer, and a Mott polarimeter. The inset defines the angles ϵ and ϑ used in the discussion.

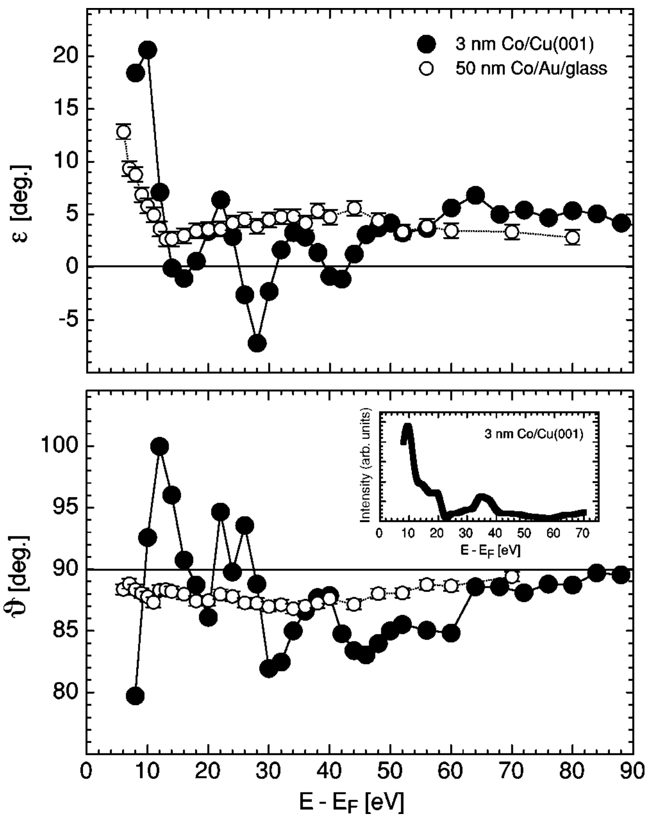

FIG. 2. The angle ϵ of precession and the angle ϑ of rotation of $\vec{P}$ with single-crystalline (closed symbols) and polycrystalline Co (open symbols) vs the energy of the electrons above the Fermi energy. The inset shows the spin-integrated intensity of the specularly reflected electron beam as a function of electron energy for the single-crystalline case. The lines are guides to the eye.

the atom beam during deposition. With fcc Co, the easy direction is along one of the (110) directions.[10] Of importance to the present experiment is the observation that both types of films exhibit full magnetic remanence, i.e., they can be investigated while in a single domain state without applying an external magnetic field. The direction of the remanent magnetization is set by applying an external magnetic field pulse.

Both types of spin motion, the precession about $\vec{M}$ by an angle ϵ as well as the rotation into $\vec{M}$ by an angle $90°-\vartheta$, induce components of the spin-polarization vector in the reflection plane. To distinguish the precession from the rotation, the direction in space as well as the relative alignment of $\vec{P}_0$ and $\vec{M}$ must be interchanged. On reversing $\vec{P}_0$, only ϵ changes sign, while on reversing $\vec{M}$, the sense of both precession and rotation change sign. Hence it is possible to obtain the contribution of each motion separately. The technique of changing both the absolute direction of $\vec{P}_0$ and $\vec{M}$ as well as their relative orientation also eliminates the effects of spin-orbit interaction.

Figure 2 shows the experimental results for ϵ and ϑ obtained with polycrystalline and single-crystalline fcc Co films and with elastic reflection of electrons of energy 5–90 eV above the Fermi energy. With the polycrystalline film, ϵ is always positive and ϑ is always reduced. Therefore, the precession about $\vec{M}$ has always the sense of a right-handed screw independent of the energy of the electrons, and the sense of the rotation indicates that $\vec{P}$ and $\vec{M}$ tend toward a parallel alignment.[11] The same behavior of $\vec{P}$ has also been observed with electrons injected into the bulk of polycrystalline Ni, Fe, and Co.[7] This sense of the precession of $\vec{P}$ is explained by the exchange field to which an electron is subjected as soon as it interacts with the ferromagnet, while the rotation into $\vec{M}$ has been explained by preferential inelastic scattering of minority spins into the holes of the $3d$ shell.[12] However, Fig. 2 shows that with single-crystalline Co, both precession and rotation show strong changes as the energy is varied.

To analyze this phenomenon, we consider the spin part of the wave function of a single electron with its spin perpendicular to $\vec{M}$. In this case it is a coherent superposition of a majority-spin and a minority-spin wave function: $\psi_0 \sim [(1,0)+(0,1)]e^{i\varphi}$. The two partial waves have an arbitrary but identical phase φ prior to the interaction with the ferromagnet. If one now takes into account that the reflection at the ferromagnetic surface is spin selective, the reflected intensity of the majority spins I^+ will be different from that of the minority spins I^-. This defines the spin asymmetry of the reflection $A=(I^+-I^-)/(I^++I^-)$. Furthermore, spin-up and spin-down waves may have different phase velocities leading to a difference ϵ in phase between the two partial waves after a time t of interaction: $\epsilon=[(E^--E^+)/\hbar]t$. In real space this phase difference corresponds to the precession of the spin-polarization vector about $\vec{M}$. Here E^+ is the energy of the majority spins and E^- the energy of the minority spins, both with respect to the inner potential. In reflection, t is determined by the length of the pathway within the material, hence t is governed by the absorptive properties of the ferromagnet. Therefore, the precession angle ϵ in reflection is determined by both the action of the exchange field and the spin-dependent absorption. This is analogous to the case of light, where the Kerr rotation in reflection is determined by both the real and imaginary parts of the refractive indices for left- and right-circularly polarized light.[13] Furthermore, there may also be a jump in phase upon reflection of the waves. If this jump is of different magnitude for spin-up and spin-down waves or if it occurs at different energies, there will be an additional contribution to ϵ. The spin part of the wave function of the reflected electron is then: $\psi \sim [\sqrt{1+A}(1,0)e^{-i\epsilon/2}+\sqrt{1-A}(0,1)e^{i\epsilon/2}]\, e^{i\varphi}$.

Taking now into account the incomplete spin polarization P_0 of the incident electron beam, the expectation values of the Pauli matrices yield the spin polarization of the reflected beam: $\vec{P}=(P_0\sqrt{1-A^2}\cos\epsilon, P_0\sqrt{1-A^2}\sin\epsilon, A)$. The z component of $\vec{P}$ yields $\cos\vartheta=A/|\vec{P}|$. Therefore, ϑ greater than 90° means that minority spins are reflected more efficiently compared to majority spins. This is in contrast to both transmission through and reflection from polycrystalline Co where always the majority spins are transmitted or reflected, respectively, with greater efficiency. This is due to the fact

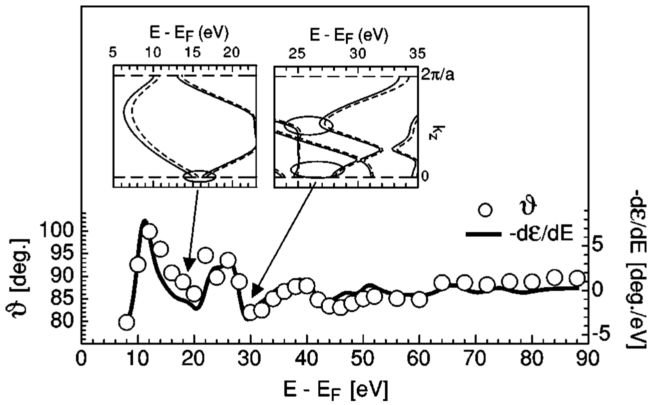

FIG. 3. The derivative $d\epsilon/dE$ of the precession angle vs energy for single-crystalline Co. $\vartheta(E)$ is replotted from Fig. 2. The lines are guides to the eye. The inset shows the result of self-consistent band-structure calculations along the $\vec{k}$ lines relevant in the experiment (solid lines, majority-spin bands; dashed lines, minority-spin bands). Left: $k_x = k_y = 0.425(2\pi/a)$. Right: $k_x = k_y = 0.2(2\pi/a)$. In both cases k_z varies between 0 and $2\pi/a$.

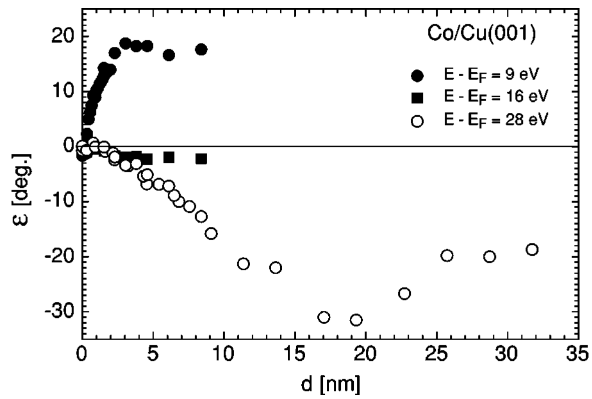

FIG. 4. The precession angle ϵ vs thickness of the single-crystalline fcc-Co layer for three selected electron energies.

that in polycrystalline Co, where one has to consider rather the density of states than the k-resolved band structure, the unoccupied density of states of the minority spin is larger than that of the majority spin.

It is well known that spin-dependent band gaps dominate the reflection of electrons from single-crystalline surfaces, in fact, this is used to image the magnetization[14] and to efficiently detect the electron-spin polarization.[15] As the energy is varied across a band gap, first the majority spins will be preferentially reflected in the middle of the majority gap. Subsequently, the minority spins will be preferentially reflected in the middle of the minority gap that lies higher in energy by the exchange splitting $(E^- - E^+)$. Thus, the existence of the exchange splitting causes a change of sign in $\cos\vartheta$. There is also an increasing phase shift of the wave function on changing the energy from the top of the lower band to the bottom of the higher band.[16] This phase shift occurs at different energies for up and down partial waves and hence leads to a contribution to ϵ. The band gaps should therefore produce changes in the sign of $\cos\vartheta$ accompanied by changes of the relative phase shift ϵ.

According to Fig. 2, structures in ϵ and ϑ occur at $E - E_F = 16$ eV, 28 eV, and 41 eV. To establish whether there are absolute or relative band gaps at these electron energies with the present experimental geometry, we have performed band-structure calculations (tight-binding linear muffin-tin orbital). Because of the non-normal incidence geometry, the band structures along high-symmetry $\vec{k}$ directions of the Brillouin zone are not sufficient. Instead, for each energy, an independent calculation has to be performed. The inset in Fig. 3 shows the resulting band structure along two different $\vec{k}$ lines, which have to be considered if we want to know the conditions encountered by the electrons of 16 and 28 eV, respectively. The calculations indeed reveal relative band gaps around these energies. The agreement between the energies of the structures observed in ϵ and ϑ and the location of the relative band gaps is not perfect but satisfactory, keeping in mind that the calculations do not include any self-energy effects, such as energy shifts and lifetime broadening. At 41 eV, however, many bands are involved, and we have not been able to find clear correlations so far.

Figure 3 also shows a remarkable additional result of this experiment. The derivative $d\epsilon/dE$ traces closely the energy dependence of ϑ. Elementary optical dispersion theory connects the reflection, absorption, and the index of refraction n. $1/n$ is proportional to the phase velocity in the medium which changes abruptly depending on the width and magnitude of the reflection peak. Figure 3 thus suggests that there is a physical analogy between magneto-optics and polarized electron scattering. In fact, the present experiment is formally identical to the longitudinal magneto-optic Kerr effect. In both optics and polarized electron scattering, the matrix F that connects the incident wave ψ_0 with the reflected wave $\psi = F\psi_0$ contains the material constants A and ϵ, while the off-diagonal elements that mix the two polarizations or spin channels, respectively, remain zero. It is emphasized that the contribution of elastic spin-exchange scattering is indeed negligible.[17,12] Consequently, spin precession due to elastic spin-exchange scattering, as discussed in Ref. 18, can be excluded here.

Figure 4 shows the variation of the precession angle ϵ with the thickness of the single-crystalline fcc Co film on the Cu(001) substrate. As Cu will not produce any precession, one expects that ϵ grows from zero to its final saturation value when the thickness of Co is on the order of the penetration depth of the electrons and/or when the spin-polarized ferromagnetic band structure of Co has reached the final configuration. At 9 eV energy, ϵ saturates indeed yielding an inelastic mean free path λ of about 1 nm; while at 28 eV, a linear decrease of ϵ occurs up to 20 nm thickness followed by a slower increase at still larger thickness. While 1 nm is consistent with the inelastic mean free path of low-energy electrons in Co,[19] the decrease of ϵ at 28 eV signals that a final band structure is still not established even at these sizeable thicknesses. It is, in fact, known that the strain induced by the misfit between the Co overlayer and the Cu substrate relaxes from 2 nm thickness onwards, but even at 7 nm, the lattice parameter of the Co film still is changing both in the interior and at the surface.[10] Assuming an extraordinary sensitivity of the hybridization gap at 28 eV to the crystal structure, this may then explain the decrease of ϵ in this thickness range. The fact that the transformation of fcc Co into hcp Co occurs from 20 nm thickness onwards[20] correlates with the observed turning point of ϵ (28 eV) at this thickness.

The most important finding is the occurrence of large positive precession angles in reflection of low-energy electrons. This shows that a significant transverse torque per volume is exercised on the surface magnetization upon reflection of polarized electrons, adding at low energies to the torque generated by the fraction of the electrons that are transmitted and absorbed. The torque density is equivalent to a pressure on $\vec{M}$ tending to turn it into $\vec{P}$. The magnitude of this pressure is commonly expressed in terms of an effective magnetic field from which the actual motion of $\vec{M}$ may then be calculated, e.g., with the Landau-Lifshitz equation. Following Ref. 7, the effective field B_{eff} produced by the reflection of the polarized electrons may be calculated from the precession angle $\epsilon \sim 20°$ acquired over the distance $\lambda \sim 1$ nm the reflected electrons have traveled in the ferromagnet. This arises because the transverse torque exercised by $\vec{M}$ on the electrons is equal to the transverse torque exercised by the electrons on $\vec{M}$ by virtue of Newton's third law. Knowing that the exchange interaction tends to even increase on approaching the energy of the $3d$ orbitals close to the Fermi energy, the contribution of specularly elastic reflected electrons to the torque in a solid-state device is expected to be significant and probably even larger per reflected electron than observed here at the higher energies. The largest reported current densities $j = 10^9$ A/cm^2 (Refs. 21,22) and the largest possible $P_0 = 1$ combined with complete specular and elastic reflection lead to $B_{\mathrm{eff}} \sim 1$ T for the above example of Co.

In conclusion, precessional motion of the spin-polarization vector of electrons reflected at a ferromagnetic surface is observed. Because of angular-momentum conservation torque is exercised by the reflected electrons on the ferromagnetic surface region. Sizeable transverse torques due to reflected polarized electrons can be expected in solid-state devices.

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