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# Crucial tests of spin filtering

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The spin polarization $P$ of the photoelectrons emitted at the photothreshold from hcp and fcc Co is found to be *positive*, i.e., the majority of these photoelectrons have their spin magnetic moment directed parallel to the magnetization. This is in contrast to calculations, which find a *negative* polarization at the Fermi level. Furthermore, $P$ at the photothreshold of very thin fcc Co layers is *negative*. These results are interpreted as evidence for a spin-filter effect caused by a spin-dependent inelastic mean free path.

This paper investigates the relationship between the measured quantity—namely the polarization $P$ of the emitted electrons after they left the surface—and the ground-state polarization. The measured quantity is the polarization $P=(N\uparrow-N\downarrow)/(N\uparrow+N\downarrow)$, where $N\uparrow(N\downarrow)$ is the number of emitted electrons with spin magnetic moment parallel (antiparallel) to the magnetization. For a detailed understanding of any spectra it is indispensable to know how the measured polarization is related to the ground-state polarization. Indeed, various scattering processes[1–5]—elastic and/or inelastic—can affect $P$. In this paper we provide evidence—in addition to other recent work[3,6–9]—that spin-dependent inelastic scattering alters $P$ during the transport of the electrons to the vacuum. It reduces the number of emitted minority electrons, i.e., of those electrons with spin magnetic moment directed antiparallel to the magnetization.

Co is a strong ferromagnet, i.e., it has a completely filled majority $d$ band,[10] see Fig. 1. Therefore, close to the Fermi level $E_F<E<E_F+0.5$ eV the minority electrons dominate and thus the total polarization is negative.

To measure this, we prepared a clean Co(0001) single crystal surface and a Cu(100) substrate. After the usual sputtering/annealing cycles no contamination on the surfaces was visible by Auger spectroscopy. Co films were evaporated onto a Cu(001) crystal in a pressure less than $10^{-8}$ Pa. Co grown on Cu(001) forms an epitaxial fcc (100) structure with good long-range order [> 500 Å (Ref. 12)],[13] because of similar lattice constants. Extremely sharp low-energy electron diffraction patterns of the Co/Cu(001) system—even for the thickest Co films—gave evidence of a good Co crystallinity. A Co evaporation rate of 0.3 Å/mim was determined by Auger spectroscopy. After preparation, a small amount of Cs was deposited on the surface in order to lower the photothreshold. Cs is known *not* to affect $P$.[11] By a Fowler plot the threshold was found to be always around $1.55\pm0.07$ eV. Magnetic saturation even for the thinnest Co films was achieved in a magnetic field of 1.9 T applied perpendicular to the sample surface. The sample temperature was held at 220 K during the measurements. Monochromatic light in the energy range between 1.4 and 3.5 eV was used to excite photoelectrons.

In contrast to calculations[11] and the picture schematically given in Fig. 1, $P$ at the photothreshold is found to be positive for the hcp and thick (=bulk) fcc Co films, see Fig. 2. The lack of negative spin polarization at the photothreshold proves that in Co the photoelectrons do not maintain the polarization of the ground state.

Why is the polarization of the photoelectrons emitted from ferromagnetic Co positive, i.e., enhanced with respect to the bulk polarization? As shown in Ref. 3, the inelastic mean free path is spin dependent: $d$ holes remove electrons with the same spin from the photocurrent. As a consequence, we expect the minority photocurrent to become measurably attenuated with respect to the majority electrons. Ultimately, the majority electrons from the $s$ $p$ states excited at $E_F$ should dominate in photoemission and make the polarization of the photoelectrons positive.

From spin polarized electron spectroscopy from ferromagnets, the polarization for electron energies higher than ~15 eV is known to be equal to the bulk (respectively ground) polarization.[3,14] The polarization of secondary electrons, however, is systematically enhanced.[3] We conclude that electrons with a relatively high energy ($E>15$ eV) do not scatter into the $d$ holes and are not affected by the spin-

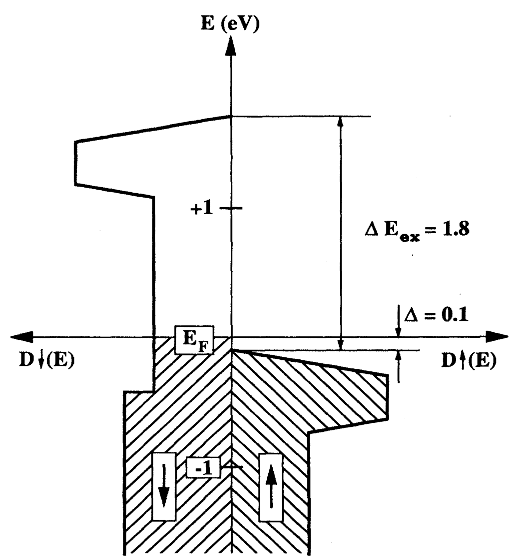


FIG. 1. Schematic spin-polarized density of states $D^{\uparrow}(E)$ and $D^{\downarrow}(E)$ of the $d$ electrons in ferromagnetic cobalt. The directions of the spin magnetic moments are indicated by the arrows: up (down) refer to the majority (minority) electrons. $E_F$: Fermi energy; $\Delta E_{ex}$: exchange splitting; $\Delta$: Stoner gap.

 

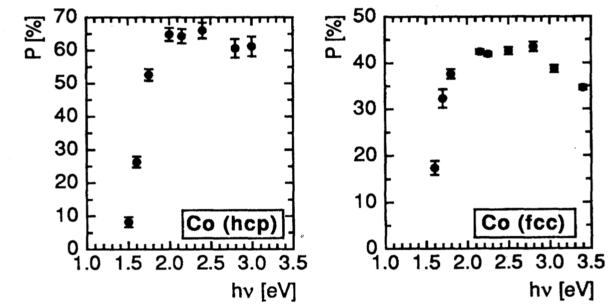


FIG. 2. The polarization of the total photocurrent emitted from Co(0001) and 48 Å Co(001) on Cu(001) is *positive* at the photothreshold $\Phi$, which was adjusted by depositing cesium on top of the clean metal surfaces. Left: $\Phi = 1.50$ eV; right $\Phi = 1.55$ eV.

filter effect. If the light energy is increased above 15 eV the measured polarization should become equal to the ground state polarization, i.e., become negative in the case of Co. Schneider *et al.*[15] indeed observed a negative polarization at the Fermi level of bulk Co.

To further test the idea of spin filtering, we measured $P$ for thin fcc Co films. When the thickness of the Co films is of the order of the inelastic mean free path, the spin filtering effect should be reduced, so that $P$ at the threshold should be equal to the ground-state polarization and therefore be negative. Thus, we expect the polarization at the threshold as a function of the Co film thickness to immediately reveal the existence of spin-dependent scattering.

In Fig. 3 the spectra are presented. It is important to measure as close as possible to the photothreshold to compare the polarization data with the theory. Unfortunately the light intensities of the monochromatic Hg-Xe lamp are only high at some specific wavelength. It was therefore not always possible to measure directly at the threshold due to vanishing small electron counting rates. For this reason the polarization spectra as a function of the light energy minus the threshold $\Phi$ are plotted. In Fig. 3 one recognizes indeed a negative

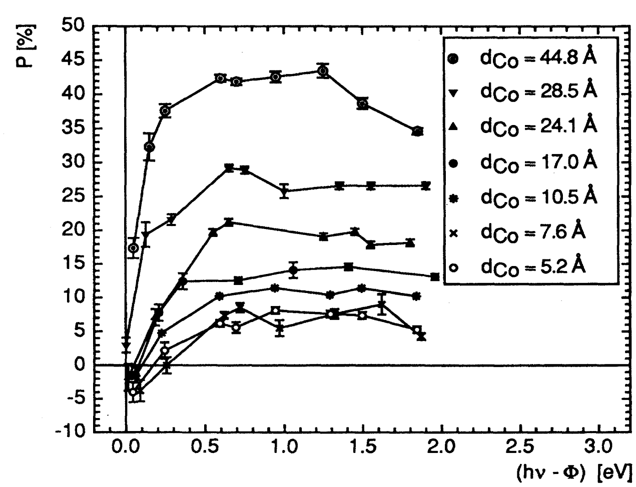


FIG. 3. Polarization spectra $(h/\nu\text{-}\Phi)$ of the Co/Cu(001) system with different Co film thickness. Thin ferromagnetic Co films have at the threshold a $P<0$, whereas thick films have a $P>0$.

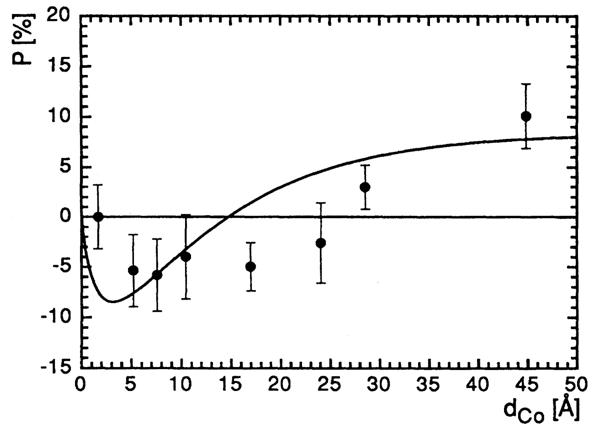


FIG. 4. Extrapolated polarization (dots) at the photothreshold $(h\nu\text{-}\Phi)=0$ vs Co film thickness. The change of sign in the polarization is nicely reproduced by the spin filter model (continuous line).

polarization for thin Co films close to the photothreshold. In Fig. 4 $P$ at the photothreshold is plotted vs Co film thickness. The polarization of a 2-Å-thick Co layer is equal to zero, due to a lack of ferromagnetic coupling and a large contribution of unpolarized Cu electrons. The spin-filter effect can then also be neglected. Up to ~27 Å Co the polarization of the total emitted electrons remains negative due to a strongly negative ground-state polarization in ferromagnetic Co. The recombination rate of minority electrons increases rapidly with increasing Co film thickness, and above 27 Å the polarization becomes positive. The continuous line in Fig. 4 has been obtained using the model calculation described in the following.

The total number and the polarization of the emitted Cu electrons which travel through the ferromagnetic film into the vacuum is (assuming spin-dependent scattering)

$$N_{\mathrm{Cu}}(d_{\mathrm{Co}}) = \frac{N_{\mathrm{Cu}}}{2}\left(e^{-d_{\mathrm{Co}}/\lambda^+} + e^{-d_{\mathrm{Co}}/\lambda^-}\right), \qquad (1)$$

$$P_{\mathrm{Cu}}(d_{\mathrm{Co}}) = \frac{e^{-d_{\mathrm{Co}}/\lambda^+} - e^{-d_{\mathrm{Co}}/\lambda^-}}{e^{-d_{\mathrm{Co}}/\lambda^+} + e^{-d_{\mathrm{Co}}/\lambda^-}}. \qquad (2)$$

$\lambda^+$, respectively, $\lambda^-$ are the spin-dependent inelastic mean free paths of polarized electrons with spin "+" (up), respectively, spin "−" (down) in Co. Since $\lambda^+ > \lambda^-$ the polarization of the emitted Cu electrons is always positive, as has been confirmed experimentally.[3] The Co electrons are also spin filtered on their way to the surface:

$$N_{\mathrm{Co}}(d_{\mathrm{Co}}) = N^+(\mathrm{Co})\lambda^+\left(1 - e^{-d_{\mathrm{Co}}/\lambda^+}\right) + N^-(\mathrm{Co})\lambda^-\left(1 - e^{-d_{\mathrm{Co}}/\lambda^-}\right). \qquad (3)$$

$N_{\mathrm{Co}}(d_{\mathrm{Co}})$ is the total number of Co electrons extracted from the ferromagnetic film. $N^{+(-)}$ (Co) are the numbers of excited Co electrons according to the spin direction. $N^+$ and $N^-$ are related to each other by the polarization of the ground state. The net polarization of the Co electrons is

$$P_{\rm Co}({\rm Co}) = \frac{N^+({\rm Co})\lambda^+(1-e^{-d_{\rm Co}/\lambda^+})-N^-({\rm Co})\lambda^-(1-e^{-d_{\rm Co}/\lambda^-})}{N^+({\rm Co})\lambda^+(1-e^{-d_{\rm Co}/\lambda^+})+N^-({\rm Co})\lambda^-(1-e^{-d_{\rm Co}/\lambda^-})}. \quad (4)$$

In order to calculate the total polarization $P_{\rm tot}$

$$P_{\rm tot}=\frac{P_{\rm Cu}(d_{\rm Co})N_{\rm Cu}(d_{\rm Co})+P_{\rm Co}(d_{\rm Co})N_{\rm Co}(d_{\rm Co})}{N_{\rm Cu}(d_{\rm Co})+N_{\rm Co}(d_{\rm Co})} \quad (5)$$

the relative weight $t$ of the electron intensities emitted by the same photoenergy both in Co and in Cu has been taken from literature.[3,16] $P$ at the photothreshold (continuous line in Fig. 4) has been calculated assuming: $\lambda_{\rm Cu}=14$ Å, $\lambda^+_{\rm Co}=14.7$ Å, $\lambda^-_{\rm Co}=5.4$ Å, $t=0.1$, and $P_{\rm Co}(d_{\rm Co}=\infty)=8.5\%$.

The most significant fact of Fig. 4—the change of sign—is well reproduced by our model. The discrepancy in the zero crossing between theory and experiment is probably due to uncertainty in the thickness calibration of the Co films by Auger spectroscopy. But it is also possible, that the inelastic mean free paths at electron energies between 1.5–3.5 eV are different than those taken out of Ref. 3 where energies between 5–10 eV are considered. A spin-dependent scattering at the Co/Cu interface has also not been considered.

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