Quantum-Size-Induced Oscillations of the Electron-Spin Motion in Cu Films on Co(001)

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(Received 30 May 2006; published 2 November 2006)

We report on spin-polarized electron reflection experiments in which the electron-spin motion is studied in spin-dependent quantum well structures. Oscillations of the electron-spin motion due to quantum interference are observed in the model system Cu/Co(001) both as a function of electron energy and Cu overlayer thickness. The reflectivity as well as the spin-motion data can be well interpreted in terms of a Fabry-Pérot interferometer model. In particular, this opens the possibility of studying the spin-dependent reflection properties of the buried Cu/Co interface.

DOI: 10.1103/PhysRevLett.97.187404 PACS numbers: 78.20.Ls, 72.25.Mk, 75.70.Cn, 78.67.De

In many of the most intriguing new concepts of contemporary magnetism such as the magnetization reversal by polarized electron currents [1–3], it is crucial to understand the interaction of polarized electrons with a ferromagnet. Because of spin-dependent scattering, the polarization of the interacting electrons is expected to change. In the past we measured this spin motion in both transmission [4,5] and reflection geometry [6,7] on simple ferromagnetic systems. Of even more interest from both the fundamental and the practical point of view are quantum well (QW) structures in which standing electron waves are formed. The appearance of QW states in these structures is at the origin of a number of different oscillatory phenomena. In ferromagnetic systems, the existence of magnetic interfaces results in a spin dependence of the quantum confinement which is, in particular, responsible for oscillations of the interlayer exchange coupling [8], the magneto-optical response [9], the induced magnetic moment [10], and the magnetic anisotropy [11]. However, the possibility of a spin motion of the electrons due to spin-dependent QW states has not been considered up to now.

In this Letter, spin-polarized electron reflection experiments on the QW system Cu/Co(001) are reported, showing how the polarization of an incident electron beam reflected off by the sample changes its direction in an oscillatory fashion both as a function of electron energy and Cu thickness. Then, the data are analyzed within a Fabry-Pérot interferometer model, which enabled us to study the properties of the buried Cu/Co interface. We obtain a metallic QW structure by depositing Cu onto a Co film evaporated on top of a Cu(001) single crystal [12]. This system, which has been extensively studied in the past, exhibits strong QW effects [13–15]. In addition, due to the spin-dependent electron reflectivity at the Cu/Co interface [16,17], one is dealing here with a spin-dependent QW structure.

Figure 1 shows the schematics of our experiment. The 70%-polarized electron beam is obtained by optically pumping a GaAs-type crystal with circularly polarized light. It is incident at a 45° angle with respect to the sample surface with the in-plane projection of the wave vector along the [110] direction. Typical beam currents are between 10 and 100 nA. The absolute thickness calibration for the Cu overlayer is accurate to within 10%. The polarization vector $\mathbf{P}_0$ of the incident electrons is perpendicularly oriented with respect to the magnetization $\mathbf{M}$ of the Co film. Upon reflection from the sample, the specular beam passes through a retarding field energy analyzer with a resolution of 0.3 eV. In the following we restrict the discussion on the elastically scattered electrons. The electrons are subsequently accelerated to an energy of 100 keV to measure the components of the polarization vector in the plane perpendicular to the reflected beam via Mott scattering. The effective Sherman factor of the Mott detector is 0.2.

The crucial point of our experimental setup is that the incident polarization vector $\mathbf{P}_0$ is chosen perpendicular to $\mathbf{M}$ [18]. In this way the spin motion of the reflected electrons is maximized. In contrast, no spin motion can be seen in a collinear geometry of $\mathbf{P}_0$ and $\mathbf{M}$ because no torque can be exerted in this case on the electron spins by the ferromagnetic film. For a completely polarized electron

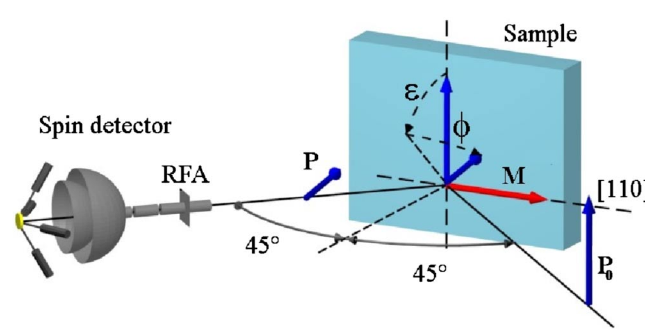

FIG. 1 (color online). The experiment consists of a polarized electron source, a Cu/Co QW structure in which the Co film is remanently magnetized in plane by a magnetic field pulse along the [110] direction, a retarding field energy analyzer (RFA), and a spin detector. The angles ε and ϕ which describe the motion of the polarization vector $\mathbf{P}$ are also shown.

beam in the perpendicular geometry, the spin part of the incident electron wave function is a superposition of a majority-spin and a minority-spin wave function having equal amplitudes: $\psi_0 \propto (1,0) + (0,1)$. Because of spin-dependent scattering at the Cu/Co interface, the spin wave function of the electron beam after reflection from the sample must present different reflection amplitudes for the two spin components: $\psi \propto |r^{\uparrow}|\exp(i\theta^{\uparrow})(1,0) + |r^{\downarrow}|\exp(i\theta^{\downarrow})(0,1)$, where $|r^{\uparrow,\downarrow}|$ and $\theta^{\uparrow,\downarrow}$ are the module and the phase of the spin-dependent reflection amplitudes, respectively. This change of the spin wave function corresponds, in real space, to a precession of the polarization vector $\mathbf{P}$ around $\mathbf{M}$ by an angle $\varepsilon = \theta^{\downarrow} - \theta^{\uparrow}$ and a rotation away from the initial perpendicular configuration by an angle ϕ in the plane spanned by $\mathbf{P}$ and $\mathbf{M}$ (see Fig. 1): $\phi = \arctan([|r^{\uparrow}|^2 - |r^{\downarrow}|^2]/2|r^{\uparrow}||r^{\downarrow}|)$. In the following the values of ϕ are always normalized to a fully polarized incident electron beam. Because of the spin motion, the projections of $\mathbf{P}$ onto the spin-detector plane change. By exploiting the different symmetries of the two spin-motion angles with respect to an inversion of $\mathbf{P}_0$ and $\mathbf{M}$ the spin motion can be determined without directly measuring the component of $\mathbf{P}$ along the axis of the reflected beam.

In a first experiment we study the reflectivity $|r|^2$ as a function of the primary electron energy [Fig. 2(a), left column]. The spectrum of uncovered Co exhibits a peak at $E - E_F = 11$ eV, signaling the presence of a gap in the band structure of Co. Indeed, band structure calculations show that electrons of about 11 eV energy should encounter a band gap [19]. The coverage of the Co surface by Cu, however, changes the spectrum completely. A new peak at around 8.5 eV, whose energy position is independent of the Cu coverage, appears, while the initial Co structure at 11 eV disappears. Apart from this bulk structure we observe at higher electron energies additional structures whose energy positions change with the Cu thickness. This is a clear indication of the presence of QW effects in the Cu film. Figure 2(b) shows the energy positions of the maxima (open stars) and the minima (open circles) of $|r|^2$ in an energy-thickness diagram. Similar behavior of the QW states is reported in the literature for many systems [20] and is explained by the phase accumulation model [21]. If the electron system is confined to a Cu film of thickness d, constructive interference requires the wave vector k_{Cu} of the electrons in Cu to fulfill the quantization condition: $2k_{\mathrm{Cu}}d\cos(\alpha) + \gamma = 2\pi n$, with α the angle of incidence of the electrons reflected at the Cu/Co interface [Fig. 3(a)], γ a phase shift due to the reflections at the vacuum/Cu and the Cu/Co interface, and n an integer. We note, however, that the periodicity of the QW oscillations is not determined by the momentum k_{Cu} of the rapidly oscillating Bloch wave function within the QW, but by the momentum k_{env} of the so-called envelope function which modulates the Bloch wave function [14,22]. The wavelength of the envelope function is given by $\Gamma = \pi/k_{\mathrm{env}}$.

To study the spin motion of the reflected electrons we measure ε and ϕ as a function of the primary electron energy [Fig. 2(a), right column]. In the case of uncovered Co, ε exhibits a positive peak while ϕ shows a plus/minus structure. Such a behavior is explained by the presence of a spin-dependent gap in the band structure of the ferromagnet [7,23]. As soon as Co is covered by Cu we observe an oscillatory behavior of both ε and ϕ. Figure 2(b) shows the energy positions of both the maxima (solid stars) and the minima (solid circles) in ε. We note that there is always a phase shift of $\pi/2$ in the energy positions of the extrema between ε and ϕ. The behavior of ε is quite similar to that of $|r|^2$, and the energy positions are in good agreement with those of the extrema in $|r|^2$. This demonstrates that the

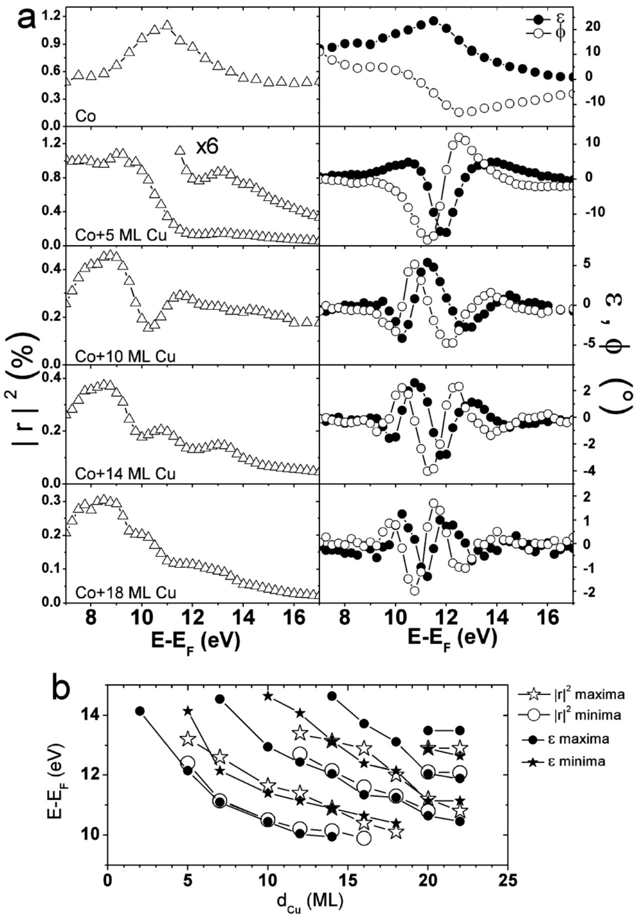

FIG. 2. QW oscillations of the spin motion as a function of the primary electron energy. (a) The left column shows the spin-integrated reflectivity $|r|^2$ for 5 different structures [uncovered Co film and Co films covered by 5, 10, 14, and 18 ML (monolayers) of Cu]. The right column shows for the same structures both ε (solid symbols) and ϕ (open symbols). The absolute error in $|r|^2$ is $\pm 0.02\%$. The error in ε and ϕ is $\pm 0.2°$. The lines are guides to the eye. (b) Energy versus Cu-thickness diagram of the oscillations in $|r|^2$ and ε. Open stars (open circles) indicate the energy positions of the maxima (minima) in $|r|^2$, while solid stars (solid circles) indicate those of the maxima (minima) in ε. The error in energy is given by the size of the symbols. Data points at different thicknesses with the same quantum number n are connected by lines.

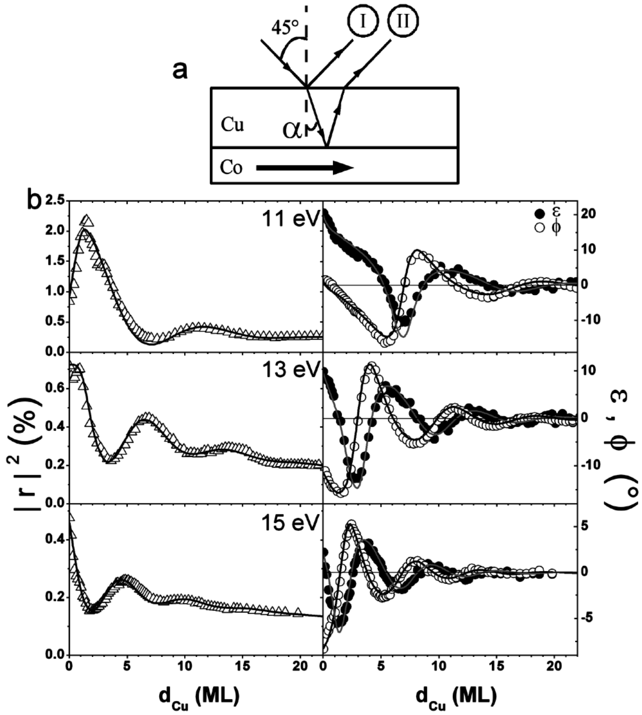

FIG. 3. QW oscillations of the spin motion as a function of the Cu overlayer thickness. (a) A Fabry-Pérot interferometer model. While ray I is reflected at the vacuum/Cu interface, ray II is reflected at the Cu/Co interface. (b) The left column shows $|r|^2$ for 3 different primary electron energies ($E - E_F = 11$, 13, and 15 eV). The right column shows for the same energies both ε (solid symbols) and ϕ (open symbols). The absolute error in $|r|^2$ is $\pm 0.02\%$. The error in ε and ϕ is $\pm 0.2°$. The lines are fits to the experimental data based on the Fabry-Pérot interferometer model discussed in the text [30].

existence of QW states is at the origin of the oscillations of both the reflectivity and the spin motion.

The simplest view of a QW structure is that of a Fabry-Pérot interferometer. Changing the thickness of the QW is equivalent to changing the spacing between the two plates in the optical analogue. However, multiple reflections, which occur usually in an optical interferometer, do not exist in our experiment. This is due to the small electron reflectivity and to the strong electron attenuation in the investigated electron energy range. Thus, the total spin-dependent amplitude of the reflected electron wave reads as follows: $r^{\uparrow,\downarrow} = r_1/\sqrt{2} + r_2^{\uparrow,\downarrow}\exp(-i\delta)$, with $r_1 = |r_1|\exp(i\theta_1)$ the spin-independent reflection amplitude at the vacuum/Cu interface, $r_2^{\uparrow,\downarrow} = |r_2^{\uparrow,\downarrow}|\exp(i\theta_2^{\uparrow,\downarrow})$ the spin-dependent reflection amplitude at the Cu/Co interface, and δ a complex phase factor. The latter contains the phase difference between electron rays I and II sketched in Fig. 3(a) as well as an attenuation factor due to the finite inelastic mean free path λ of the electrons in Cu: $\delta(d) = 2d[\frac{\pi\cos(\alpha)}{\Gamma} - \frac{i}{\lambda\cos(\alpha)}]$. The angle of incidence α of the electrons reflected at the Cu/Co interface is given by $\sin(\alpha) = \sin(45°)\sqrt{E_{\mathrm{kin}}/(E_{\mathrm{kin}} + U)}$ with E_{kin} the kinetic energy of the electrons in vacuum and U the inner potential in Cu ($\approx$12 eV [24]).

Can the behavior of both the reflectivity and the spin motion be understood in terms of a Fabry-Pérot interferometer model? That the behavior of the electron intensity of a QW system can indeed be described in such a manner has been shown in a photoemission experiment from Ag films on Fe(001) [25]. In the case of the spin motion, however, this has still to be proven. To get a set of data to compare with the above model, we studied the spin-dependent electron reflection as a function of Cu thickness. Oscillations in $|r|^2$ as well as in ε and ϕ are observed for electron energies between 10 and 17 eV, while no oscillations are found at higher energies. In a second step, we fitted the data with the interferometer model. For the growth of Cu on Co we assume the model of Cohen *et al.* [26], which has been developed to explain the intensity oscillations in reflection high-energy electron diffraction as a function of film thickness. We choose the thickness-dependent film roughness in this growth model to be consistent with our experimental studies of the exchange-coupled system Co/Cu/Co(001) [27]. We always observed the long oscillation wavelength of the exchange coupling [6 ML (monolayers) of Cu] while the short oscillation wavelength (2.7 ML of Cu) were seldom visible. This produces a rough estimation of the Cu film roughness. A simultaneous fit of the three quantities $|r|^2$, ε, and ϕ is done with the standard Levenberg-Marquardt algorithm using the six following variable parameters: Γ, λ, $\theta_2 - \theta_1$, $|r_2^{\uparrow,\downarrow}|/|r_1|$ [28], and ε_2 with $\theta_2 = (\theta_2^{\uparrow} + \theta_2^{\downarrow})/2$ and $\varepsilon_2 = \theta_2^{\downarrow} - \theta_2^{\uparrow}$. We found that both the reflectivity and the spin motion can be fitted with the same set of parameters demonstrating that both aspects of the present experiment are well described within the same interferometer model [Fig. 3(b)]. Figure 4(a) shows the resulting values of both Γ and λ. The strong increase of Γ towards lower

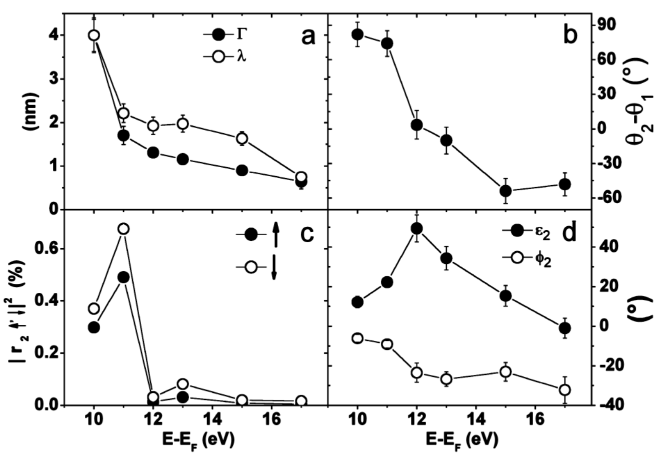

FIG. 4. Values of (a) the oscillation wavelength Γ and the inelastic mean free path λ, (b) the phase difference $\theta_2 - \theta_1$, (c) the spin-dependent reflectivity $|r_2^{\uparrow,\downarrow}|^2$, and (d) ε_2 and ϕ_2 deduced from the interferometer model. The lines are guides to the eye.

energies can be explained by the existence of a gap in the band structure of Cu below 10 eV [16]. In fact, on approaching the top of the band gap, Γ should diverge. From our data we expect the top of the gap to be between 9 and 10 eV, which is consistent with other experiments [16,17].

It is of great practical importance to analyze both the reflectivity and the spin-motion data within the above interferometer model as it allows the determination of the complex reflection amplitude (except the absolute value of the phase) of the buried Cu/Co interface. Figure 4(b) shows the phase difference $\theta_2 - \theta_1$. We emphasize that the phase shift θ of the uncovered Co surface as a function of energy cannot be measured directly. However, via a measurement of the Cu covered Co surface and its analysis within the Fabry-Pérot model, this becomes partly possible. Assuming only small variations of the phase θ_1 of the vacuum/Cu interface in the investigated energy range, the phase θ_2 of the Cu/Co interface can be determined. The spin-dependent reflectivity $|r_2^{\uparrow,\downarrow}|^2$ of the Cu/Co interface is shown in Fig. 4(c). To determine it, the reflectivity $|r_1|^2$ of the Cu surface has to be known and is given by the reflectivity at large Cu thicknesses. Similar to the uncovered Co [Fig. 2(a), first panel], the buried interface exhibits a strong reflectivity at 11 eV. That we should observe the reflectivity maximum at the same position as for the vacuum/Co interface is not obvious. In fact, due to different angles of incidence and thus different directions in the reciprocal space that are probed in the two cases, the position of the gap might change. For energies outside the gap, however, the reflectivity is much smaller compared to that of the uncovered Co. This is due to an almost constant kinetic electron energy before and after the potential step of the Cu/Co interface. Figure 4(d) shows both ε_2 and $\phi_2 = \arctan([|r_2^{\uparrow}|^2 - |r_2^{\downarrow}|^2]/2|r_2^{\uparrow}||r_2^{\downarrow}|)$. They are the precession and the rotation angle, respectively, of the Cu covered Co film, which one would measure if there were no interference effect. Of course, there is always interference so that these two quantities cannot directly be measured. By comparing ε_2 with ε of the uncovered Co [Fig. 2(a), first panel], we find a much more pronounced structure for the Cu/Co interface. In fact, the maximal value at around 12 eV has been doubled by the presence of the Cu overlayer. Concerning the quantity ϕ_2 one can make a similar statement. Although the overall course of the ϕ_2 curve resembles that of the ϕ curve in Fig. 2(a), we find again roughly a doubling of the extremal value. Whether this is due to the Cu coverage, which is known to influence the magnetic characteristics of Co(001) films [29], the changed angle of incidence at the Cu/Co interface with respect to that of the vacuum/Co interface or both, however, cannot be said at the moment.

In conclusion, we observe oscillations of the electron-spin motion in the magnetic QW system Cu/Co(001) both as a function of the electron energy and the Cu overlayer thickness. It is the particular geometry of spin polarization and magnetization in our experiment which enables us to reveal this new aspect of a magnetic QW system. Moreover, the data as a function of the Cu overlayer thickness show that not only the reflected electron intensity but also the electron-spin motion can be well described within a Fabry-Pérot interferometer model. An analysis within this model opened us the possibility of studying the spin-dependent reflection properties of the buried Cu/Co interface.

We thank F. Scheurer for helpful advice during the measurements.

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