Induced spin polarization and interlayer exchange coupling of the systems Rh/Co(0001) and Ru/Co(0001)

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Spin- and angle-resolved photoemission spectroscopy in an off-normal geometry at $h\nu=21.2$ eV proves that one atomic layer (AL) of Rh or Ru on Co(0001) possesses an induced positive spin polarization at the investigated **k** point. The oscillatory interlayer exchange coupling in MBE-grown Co/Rh/Co and Co/Ru/Co trilayers has been probed by the spin polarization of the secondary electrons from the top Co layer. The oscillation period lengths found are $\lambda_{Rh}=8\pm1$ AL and $\lambda_{Ru}=9\pm1$ AL. In spite of the induced positive spin polarization at the Fermi level the interlayer coupling through Ru and Rh is antiferromagnetic already for an interlayer thickness of 1.5 AL Ru and 2.5 AL Rh.

During the past few years magnetic multilayers consisting of alternating layers of a ferromagnetic and a paramagnetic metal have been investigated intensively. In particular, the oscillatory interlayer exchange coupling, which causes a ferromagnetic or antiferromagnetic coupling of the ferromagnetic layers as a function of the interlayer thickness,[1,2] has attracted strong attention. This coupling can be explained by a Ruderman-Kittel-Kasuya-Yosida-like model[3] or equivalently by a quantum-well model.[4] The coupling through transition metals, like Pd and Pt and also Rh and Ru, which possess a magnetic polarization at the interface with the ferromagnet,[5–9] is of particular interest.

This prompted us to investigate the electronic structure of Rh and Ru overlayers on Co(0001) by means of spin- and angle-resolved photoemission spectroscopy. Furthermore, the oscillatory interlayer exchange coupling has been examined in corresponding molecular-beam-epitaxy-(MBE-) grown Co/Rh/Co and Co/Ru/Co trilayers as a function of the interlayer thickness.

Details of the experimental setup for spin- and angle-resolved photoemission spectroscopy have been published elsewhere.[10] Spin- and angle-resolved spectra were taken with vacuum ultraviolet light of $h\nu=21.2$ eV. The electrons were detected with a 180° hemispherical energy analyzer with an angular resolution of ±3° and an energy resolution of 200 meV. The spin analysis of the photoelectrons was performed using a 100-keV Mott detector. The ferromagnetic Co layers, which were grown on a W(110) single crystal, exhibit a W-induced twofold symmetry. They were remanently magnetized along the Co$[10\bar{1}0]$ direction with a field pulse of approximately 500 Oe.

The layers were prepared *in situ* in an UHV chamber with a base pressure of 1×10^{-10} mbar, which increased during electron-beam evaporation to 5×10^{-10} mbar. The layer thickness was monitored by a calibrated quartz microbalance and determined with an accuracy of ±5%. 12-AL thick Co(0001) films were evaporated at a rate of 0.5 AL/min onto the W(110) single crystal held at a temperature of 400 K.[11] Rh and Ru layers were evaporated at a rate of 0.2 AL/min onto these Co "substrate" films held at room temperature to avoid interdiffusion. For studies of the oscillatory interlayer exchange coupling an additional Co layer was evaporated onto the Rh or Ru layer resulting in trilayers of Co/Rh/Co or Co/Ru/Co.

Low-energy electron-diffraction (LEED) studies of the system Rh/Co/W(110) show that Co grows in the hcp(0001) orientation and Rh in the fcc(111) orientation. The LEED patterns of 1 AL Rh on Co show a (1×10) superstructure similar to the "Nishiyama-Wassermann" growth mode. Along the Co$[10\bar{1}0]$ direction Rh grows pseudomorphically, while along the Co$[\bar{1}2\bar{1}0]$ direction the misfit leads to a 10:11 coincidence corresponding to ten Rh atoms on eleven Co atoms. LEED studies of the system Ru/Co/W(110) suggest that Ru grows in the hcp(0001) orientation. The LEED patterns of 5 AL Rh or Ru prove that they possess their bulk in-plane lattice constants.

The growth mode of Rh on Co was examined by Auger electron spectroscopy. The Auger line of Co at 775 eV and that of Rh at 302 eV were measured. An exponential decrease of the 775-eV line and an exponential increase of the 302-eV line as a function of the Rh thickness were measured. The 775-eV line of Co decreases with a decay length $\Lambda=12.4$ Å, and the 302-eV line of Rh increases with $\Lambda=7.8$ Å. A comparison with the inelastic mean free path[12] shows that this is at least consistent with the layer-by-layer growth mode. Analogous results have been obtained for Ru on Co.

Figure 1(a) displays the spin-resolved energy distribution curves (EDC's) of Co and of Co covered by 1 AL Rh. The spectra are plotted on the same absolute intensity scale. The angle between the electron emission direction and the sample normal was 30° along the $\bar{\Gamma}\bar{M}$ direction of the surface Brillouin zone of Co(0001) ($\bar{\Gamma}\bar{M}=1.45$ Å^{-1}). At this **k** point ($\mathbf{k}_{\parallel}=1.03$ Å^{-1}) the reversal of the spin polarization (see below) is most pronounced. On the one hand, when Co is covered by 1 AL Rh, the intensity of the majority spin channel increases for all binding energies, especially at about 0.2 eV. On the other hand, the intensity in the minority spin channel at about −0.2 eV remains unchanged. This results in a reversal of the spin polarization [see Fig. 1(b)] at a binding energy of about

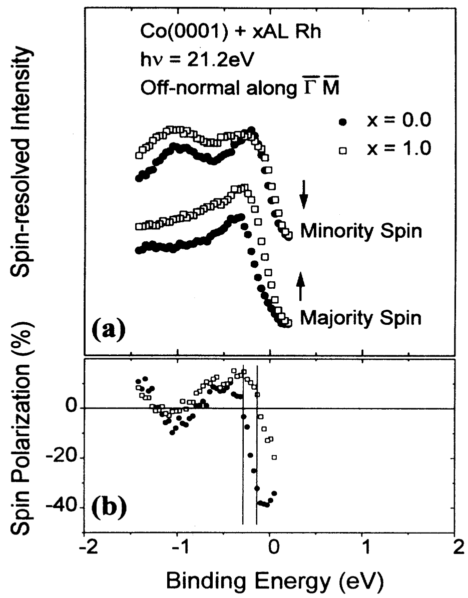

FIG. 1. (a) Spin-resolved EDC's for 0 and 1 AL Rh on Co(0001) plotted on an absolute intensity scale and (b) corresponding spin polarization. The vertical bars in (b) are guide lines marking the binding-energy interval within which the spin polarization reverses its sign.

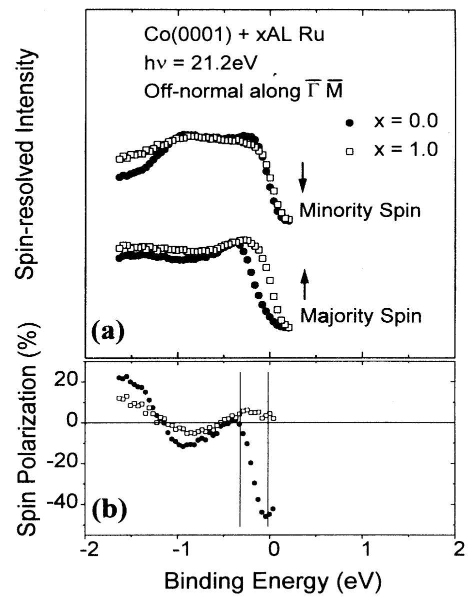

FIG. 2. (a) Spin-resolved EDC's for 0 and 1 AL Ru on Co(0001) plotted on an absolute intensity scale and (b) corresponding spin polarization. The vertical bars in (b) are guide lines marking the binding energy interval within which the spin polarization reverses its sign.

−0.2 eV from negative values for the Co surface (−20%) to positive values at a coverage of 1 AL Rh (+10%). This proves unambiguously that at this $\mathbf{k}_{\parallel}$ point in the surface Brillouin zone 1 AL Rh on Co(0001) possesses an induced positive spin polarization, i.e., a spin-polarized electronic structure. This hints at an induced magnetic moment at the interface. Our spin-resolved measurements of Ru on Co(0001) show similar results (Fig. 2): An induced spin polarization of 1 AL Ru is indicated by the reversal of the spin polarization between −0.3-eV binding energy and the Fermi level. These results were obtained in a geometry with an angle of 35° between the emission direction and the sample normal ($\mathbf{k}_{\parallel}=1.19$ Å^{-1}). With further coverage the spin polarization strongly decreases for all binding energies and already a coverage of 3 AL Rh (or 3 AL Ru) exhibits no measurable spin polarization. The error in the spin polarization is determined by the scattering of the experimental data points with an upper limit of approximately ±3% in the case of Rh and ±1% in the case of Ru.

Furthermore, the oscillatory interlayer exchange coupling between Co layers through Rh or Ru interlayers has been investigated for trilayers of the following sequence: 12 AL Co/x AL Rh or Ru/7 AL Co. Due to its larger thickness the 12-AL Co base layer was always remanently magnetized in the field direction. Thus, as a function of the interlayer thickness the thinner Co top layer couples parallel (ferromagnetically) or antiparallel (antiferromagnetically) to the Co base layer according to the interlayer exchange coupling. The spin polarization of the secondary electrons (SPSE) of the top Co layer, which is proportional to its magnetization, has been measured. In Fig. 3 the SPSE is plotted as a function of the interlayer thickness. Positive (negative) values of the SPSE correspond to ferromagnetic (antiferromagnetic) coupling. The period lengths of the oscillation are estimated by taking twice the difference between the second and third zero crossing point and amount to $\lambda_{Rh}=8\pm1$ AL and $\lambda_{Ru}=9\pm1$ AL. It should be pointed out that already at an interlayer thickness of 1.5 AL Ru and 2.5 AL Rh the coupling is antiferromagnetic, despite the magnetic polarization for 1 AL coverage of Ru or Rh on Co. The error in λ_{Rh} and λ_{Ru} is due to the uncertainty in the thickness calibration of the quartz microbalance and in determination of the zero crossing points.

In the following discussion we first want to consider the reversal of the spin polarization, which is seen when Co is covered by 1 AL Rh or Ru. This reversal of the spin polarization [Figs. 1(b) and 2(b)] proves that 1 AL of Rh and Ru on Co(0001) possesses a spin-polarized electronic structure. Two mechanisms can explain this: (i) The number of the nearest-neighbor atoms is reduced in this two-dimensional overlayer. Consequently, this results in a weaker d-d hybridization between the overlayer atoms and therefore in a narrower bandwidth of the overlayer d electrons than in the bulk crystal. This causes a higher density of states at the Fermi level, the Stoner criterion may be fulfilled, and ferromagnetism may be favored. In previous theoretical work Blügel[13] has determined this mechanism to be responsible for the fer-

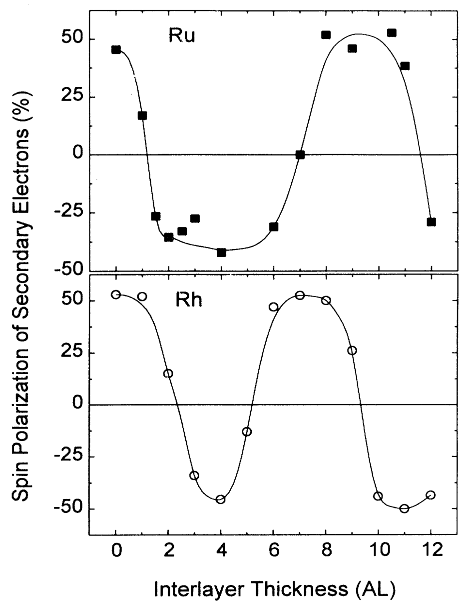

FIG. 3. Spin polarization of the secondary electrons of the top Co layer of the Co/(Rh or Ru)/Co trilayer as a function of the interlayer thickness.

romagnetism of 1 AL Rh and Ru on Ag(100) or Au(100). (ii) Also a hybridization between the *d* electrons of the overlayer and the ferromagnetic substrate could lead to a spin-polarized electronic structure. This results in a complex spin-polarized electronic band structure, which is accessible only by layer-projected spin-density functional calculations. This hybridization mechanism has previously been considered to be responsible for the induced spin polarization of Pd and Pt overlayers on Fe or Co.[6,7]

Spin-polarized Rh and Ru monolayers on Fe(100) have already been found in previous experiments. Kachel *et al.*[8] found a spin-polarized electronic structure of 1 AL Rh on Fe(100) using spin-resolved photoemission, which was analyzed by *ab initio* calculations. Totland *et al.*[9] measured spin-polarized Auger electrons of Ru on Fe(100). They found that Rh (Ru) possess an induced magnetic moment of about $0.82\mu_B$ ($0.7\mu_B$).

In this part we want to discuss our results concerning the oscillatory interlayer exchange coupling through Rh and Ru. The observed period lengths are $\lambda_{Ru}=9\pm1$ AL and $\lambda_{Rh}=8\pm1$ AL. They strongly differ from those found for sputtered samples with $\lambda_{Rh}=5$ AL and $\lambda_{Rh}=4$ AL,[2] and that of MBE-grown samples on mica with $\lambda_{Ru}=5$ AL.[14] This may be attributed to the different preparation conditions. Stiles[15] derived theoretically the period lengths from vectors connecting extremal points of the Fermi surfaces of Rh and Ru. He calculated period lengths of 2–6 AL and 19 AL for Rh(111) interlayers and of 4–12 AL and 20 AL for Ru(0001) interlayers. Only our value found for λ_{Ru} is in agreement with these calculations.

A very interesting feature is the antiferromagnetic coupling through a minimum thickness of 1.5 AL Ru. This is rather remarkable, since 1 AL Ru on Co possesses an induced positive spin polarization between −0.3-eV binding energy and the Fermi level [Fig. 2(b)]. Hence a ferromagnetic coupling would appear more reasonable as observed for Pd: (i) A Pd monolayer on Fe(100) exhibits an induced spin-polarized electronic structure corresponding to an induced magnetic moment.[7] (ii) Up to 10 AL Pd the interlayer coupling is ferromagnetic in Fe/Pd/Fe(100) trilayers[16] and only for thicker Pd layers does the coupling start to oscillate between antiferromagnetic and ferromagnetic values. This difference between the coupling through Pd and Ru may be due to the different Pauli spin susceptibilities of their conduction electrons. Pd possesses a Stoner-enhanced susceptibility, which is by a factor of 15 larger than that of Ru.[17] Therefore the conduction electrons of Pd are long-range positively polarized, whereas those of Ru may be not.

In conclusion, spin- and angle-resolved photoemission in off-normal geometry proves that 1 AL Ru and 1 AL Rh on Co(0001) possess an induced positive spin polarization at the investigated **k** point. The period lengths of the oscillatory interlayer exchange coupling in MBE-grown Co/(Rh or Ru)/Co(0001) trilayers have been determined to $\lambda_{Rh}=8\pm1$ AL and $\lambda_{Ru}=9\pm1$ AL. Although an induced positive spin polarization of Ru between −0.3-eV binding energy and the Fermi level has been identified by spin-polarized photoemission, the interlayer coupling is antiferromagnetic already for an interlayer thickness of 1.5 AL Ru. It has to be concluded that the conduction electrons of Ru are not long-range positively polarized as in the case of Pd.

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