PHYSICAL REVIEW B **81**, 134428 (2010)

Large amplitude oscillation of magnetic anisotropy engineered by substrate step density

U. Bauer[1,*] and M. Przybylski[1,2,†]
[1]*Max-Planck-Institut für Mikrostrukturphysik, Weinberg 2, 06120 Halle, Germany*
[2]*Faculty of Physics and Applied Computer Science, AGH University of Science and Technology, al. Mickiewicza 30, 30-059 Kraków, Poland*

(Received 28 January 2010; revised manuscript received 29 March 2010; published 22 April 2010)

Large amplitude quantum oscillations of magnetic anisotropy in Fe films grown on Ag surfaces of high step density are reported. Distortion of the film structure by the steps is found to be responsible for the anisotropy modification which oscillates with increasing film thickness. The larger the distorted fraction of the film volume, the larger the observed amplitude of the anisotropy oscillations. Such dependence of the anisotropy oscillations on the step density offers an easy tool to manipulate the strength of the anisotropy and orientation of the easy magnetization axis.

DOI: 10.1103/PhysRevB.81.134428 PACS number(s): 75.70.−i, 73.21.Fg

I. INTRODUCTION

Magnetic anisotropy is one of the most important properties of magnetic materials. It can determine the orientation of the easy magnetization axis, and is thus crucial for magnetoelectronic technology and its applications. Magnetic anisotropy is caused by spin-orbit coupling of the electrons and is therefore affected by an altered electronic band structure.[1,2]

In thin films grown on stepped surfaces, magnetic anisotropy can be modified in comparison to the anisotropy of films grown on atomically flat surfaces. Such a modification is often described as an additional uniaxial anisotropy with the easy magnetization axis in the film plane, usually[3,4] (but not always, see[5]) oriented along the step direction. In case the steps are oriented along one of the easy axes of the fourfold anisotropy of the film, one of them becomes the easiest magnetization axis. Growing the films on such stepped surfaces can result in an easiest magnetization axis perpendicular to the steps even though the anisotropy forces the easiest magnetization axis along the steps for large film thicknesses. How the anisotropy is modified in detail depends on the film thickness (d), on the surface step density,[3] and on the covering material.[4]

In particular, quantum well states (QWS) can be formed in ferromagnetic (FM) thin films.[6] QWS can modulate the electronic structure at the Fermi level and alter the magnetic anisotropy strongly[7] as it has been shown experimentally for Fe films grown on a stepped Ag(1,1,10) surface.[4] As a consequence, the magnetic anisotropy and easy magnetization axis oscillate as a function of film thickness. This oscillatory behavior can be utilized to define two different states characterized by easy magnetization axes oriented perpendicular to each other. For possible applications it is crucial that the energy difference between the two states can be made large, yet smaller than a given threshold value, to allow selective manipulation of the states. This can be realized only if the energy difference and therefore the oscillation amplitude can be tuned freely to fit into the desired energy window.

In this contribution, we report on the oscillation amplitude that can be tuned freely between a value as low as 10 Oe and as high as 550 Oe. We find that the QWS which are responsible for the anisotropy oscillations are extended over the whole film volume and show how this can be exploited to manipulate the oscillatory contribution to the magnetic anisotropy. We compare Fe films grown on Ag(1,1,10) to Fe films grown on a nominal Ag(001) surface (of very low step density) and on a Ag(1,1,6) surface with much higher step density. A model explaining how and why the effect of anisotropy oscillation depends on the step density is proposed and discussed.

II. EXPERIMENT

The experiments were performed in a multichamber ultrahigh vacuum system with a pressure below 2×10^{-10} mbar during Fe deposition. The Ag substrates were prepared by cycles of 1 keV Ar ion sputtering and subsequent annealing at $\sim 600\ ^\circ\mathrm{C}$. As demonstrated before,[4,8] this surface preparation procedure yields vicinal surfaces characterized by regular monoatomic steps with the step edges oriented along the Ag[110] crystalline direction and an average terrace width as expected from the crystalline indices. The vicinal angle of Ag(1,1,6) is 13.3° in comparison to 8.1° for Ag(1,1,10), which corresponds to a terrace width of 0.86 and 1.44 nm, respectively. The expected terrace width of Ag(1,1,6) and Ag(1,1,10) is confirmed quantitatively by low energy electron diffraction (LEED) where sharp double-split diffraction spots were observed. The Fe films were grown at RT by molecular beam epitaxy in a double-wedged shape with a slope of ~ 4 ML/mm along the $[\bar{1}10]$ direction of the Ag substrate, i.e., along the [100] direction of the Fe film. After the growth process, the films were annealed at 150 °C for 30 min in order to improve the surface morphology.[9,10] To avoid contamination during the measurements, most samples were capped with a 5 ML thick Au layer. The magnetic anisotropy was probed by the *in situ* longitudinal (incidence angle 21°) and polar (incidence angle of 69° to the sample normal) magneto-optical Kerr effect (MOKE) with a laser diode of wavelength 670 nm and beam diameter <0.2 mm.

III. RESULTS AND DISCUSSION

Fe films grown on a Ag(001) surface exhibit a spin reorientation transition (SRT) at a film thickness, d_{Fe}, of ~ 5 ML

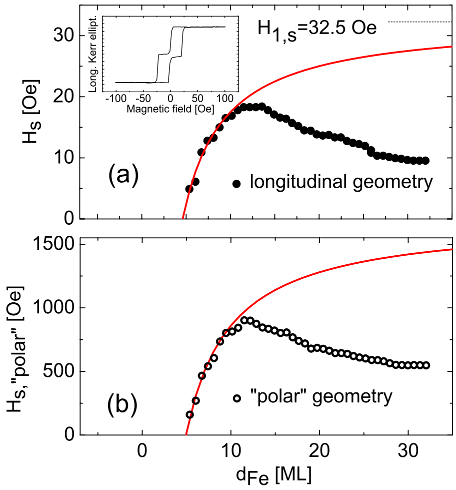

FIG. 1. (Color online) Shift field, H_s, as a function of Fe film thickness, d_{Fe}, measured at RT for Au-covered Fe films grown on nominal Ag(001) with the magnetic field applied in the sample plane (a) and almost perpendicular to the sample plane (b). The red lines are results of fitting with the formula $H_s(d_{\mathrm{Fe}})=H_{1,s}+H_{2,s}/d_{\mathrm{Fe}}$.

(at RT) when covered with Au. Above the SRT thickness, the Fe films show a fourfold anisotropy with the easy axis parallel to the [100] or [010] directions of the Fe film {i.e., along the [110] directions of Ag(001)}. However, when the films are grown on stepped surfaces, double-split hysteresis loops can be observed when the magnetic field is applied perpendicular to the steps, i.e., along the [010] direction (as shown in the inset of Fig. 1). This is due to the steps which modify magnetic anisotropy and make the [100] and [010] easy axes of the fourfold anisotropy nonequivalent (i.e., the [100] easy axis becomes easiest, i.e., easier with respect to the harder [010] direction). The split loops are characterized by a shift field (H_s being defined as half of the distance between two constituent loops), which can be taken as a measure of the anisotropy modification due to the steps.[3,4,8,11] At low coverage, H_s can change sign, i.e., the double-split loops can be measured with magnetic field applied parallel to the steps. Since H_s is sensitive to the direction in which the field is applied with respect to the steps, the sample orientation was always checked carefully. The plotted values of H_s are the minimum values obtained after measuring at several angles by rotating the sample around the position in which the field is expected to be applied perpendicular (or parallel) to the steps.

When the modified anisotropy is explained as a superposition of fourfold anisotropy and an additional uniaxial anisotropy, with the easy magnetization axis oriented along one of the easy axes of the fourfold anisotropy, H_s cannot be taken directly as the anisotropy field of the step-induced uniaxial anisotropy mentioned in the introduction. A more detailed analysis needs to be applied.[11] Following the model described there, the uniaxial anisotropy field, H_u, should be calculated as an average of the field at which the system saturates if a perfect hard-axis behavior occurs (which can be extrapolated from the zero field slope of the hysteresis loops) and the field at which magnetization switches back to the easiest magnetization axis.[11] However, the zero field slope is difficult to measure if the separation of the split hysteresis loops is not sufficiently large. Additionally, from a practical point of view, the field at which the easiest magnetization axis switches between along and perpendicular to the steps is more important. Thus we restrict our comparison of Fe films grown on different vicinal surfaces of Ag(001) to the values of H_s (discussing H_u only where its accurate determination is possible).

A. Anisotropy of Fe on nominal Ag(001)

The nominally flat Ag(001) crystal used for our experiments is not perfectly flat. It shows terraces separated by monoatomic steps, mostly oriented along the [100] direction. This is why the crystal is called “nominal Ag(001)” and appears to be a good candidate for a stepped surface with a low step density. Using scanning tunneling microscopy (STM), an average terrace width of the monoatomic terraces of 100 nm was determined (which corresponds to a vicinal angle of 0.1°). Even such steps seem to modify magnetic anisotropy, however, the difference between the [100] or [010] axes is very small. The H_s values are plotted as a function of Fe thickness in Fig. 1.

Since the observed anisotropy changes are relatively small, we repeated the experiment with the magnetic field applied almost perpendicular to the sample plane. In this case split loops can be observed, too. $H_{s,'polar'}$ obtained from the “polar” loops scales with H_s deduced from the longitudinal loops approximately with a simple geometrical formula: $H_{s,'polar'}=H_s/\sin\gamma$, where γ is the angle of misalignment of the sample normal with respect to the magnetic field. In this way, $H_{s,'polar'}$ is large and very sensitive to the tiny changes of H_s, i.e., of the in-plane anisotropy. $H_{s,'polar'}$ is plotted versus film thickness, d_{Fe}, in Fig. 1(b). In fact, this is the perpendicular field, which needs to be applied to result in an in-plane component sufficiently strong to switch the in-plane magnetization from parallel to perpendicular to the steps. The H_s values measured in longitudinal geometry [Fig. 1(a)] at RT are <17 Oe. As a consequence, with a tilting angle of $\sim 1°$ one would expect $H_{s,'polar'}$ values of <1000 Oe which are roughly by factor 50 larger and very close to the measured values [Fig. 1(b)]. Moreover, the harder easy axis probed in longitudinal geometry is equivalent to the direction along which the in-plane field component was applied in the “polar” MOKE geometry. Therefore “polar” and longitudinal MOKE results are consistent.

Up to a thickness of approximately 12 ML, H_s increases strongly with increasing film thickness [see Fig. 1(a)]. The increasing value of H_s is equivalent to an increasing anisotropy with the easy magnetization axis oriented along the steps. The data can be fitted with the formula $H_s(d_{\mathrm{Fe}})=H_{1,s}+H_{2,s}/d_{\mathrm{Fe}}$. In this formula, $H_{1,s}$ is the value which H_s approaches in the limit of large film thickness. Since $H_{1,s}$ is independent of d_{Fe}, it can be interpreted as the result of the structural distortion in the film volume. $H_{2,s}$ is a fitting parameter that contains information on how the anisotropy modification depends on the film thickness. The fitted value of $H_{1,s}=32.5\pm 10$ Oe has large uncertainty since the data points are available in a limited thickness range only. Nevertheless, it is small reflecting a minor modification of the anisotropy due to the steps for Fe films grown on a nominal Ag(001) surface. It is a common belief that stepped surfaces influence magnetic anisotropy by breaking the symmetry at and above the steps.[8,12] Both effects can be found also for the Fe films grown on the nominal Ag(100) substrate. The step-induced modification of the anisotropy is expected to be strong when the difference between the substrate step height, $d_{substrate}$, and the lattice parameter of the FM film, d_{film}, [i.e., $w_{film/substrate}=(d_{substrate}-d_{film})/d_{substrate}$] is large. For the Fe/Ag(001) system $w_{\mathrm{Fe/Ag}}$ is indeed large as a simple consequence of very different lattice constants of Fe and Ag, which fit to each other only by a rotation of 45° in the film plane. However, along the film normal $w_{\mathrm{Fe/Ag}}=29.7\%$ remains and affects the atomic layers of the Fe film above the steps (i.e., it is of volume character) and thus leads to a large modification of the anisotropy in comparison to the Fe films grown on atomically flat Ag(001). The small value of $H_{1,s}$ for Fe/nominal Ag(001) shows that the perturbed film volume, which is the fraction of the total film volume that contributes to the step-induced modification of the anisotropy, is small in this case.

Above $d_{\mathrm{Fe}}=12$ ML, H_s decreases more-or-less [Fig. 1(a)] proportionally to the reciprocal of the film thickness. This suggests that the step-induced modification of the anisotropy decreases with increasing film thickness (i.e., less field is necessary to switch the magnetization perpendicular to the steps), which is not surprising since the step density is low. Surprisingly, it is reported that the step-induced anisotropy modification can be detected up to a film thickness of 300 ML even when the easy magnetization axis is oriented perpendicular to the steps.[5] The reason is that for densely packed steps the structural perturbation cannot relax along the terraces which are simply too narrow (another step appears in a short distance). Only in the case of wide terraces [as observed for our nominal Ag(001) surface] the vertical perturbation (which modifies the anisotropy) has a chance to relax and disappear with increasing film thickness (e.g., by dislocation formation).

B. Anisotropy of Fe on Ag(1,1,6)

Since we see a clear difference in the thickness dependence of H_s on d_{Fe} between Fe films grown on nominal Ag(001) and on Ag(1,1,10),[4] it is of great interest to perform a more systematic study. Therefore we performed a MOKE analysis of Fe films grown on Ag(1,1,6). This surface is characterized by a higher step density in comparison to Ag(1,1,10). The H_s dependence on d_{Fe} for Au-covered Fe films grown on Ag(1,1,6) [and on Ag(1,1,10) for comparison] are shown in Fig. 2. From the fits [with the formula $H_s(d_{\mathrm{Fe}})=H_{1,s}+H_{2,s}/d_{\mathrm{Fe}}$] shown in Fig. 2 it can be deduced that the value of $H_{1,s}=605$ Oe, i.e., is by a factor of 4 larger than the one observed for Au/Fe films grown on Ag(1,1,10). Similar to what was observed for Au/Fe/Ag(1,1,10),[4] $H_{1,s}$ for Au-covered Fe films on Ag(1,1,6) is almost the same as for uncovered Fe films ($H_{1,s}=690$ Oe), which confirms the volume character of the step-induced modification of the anisotropy.

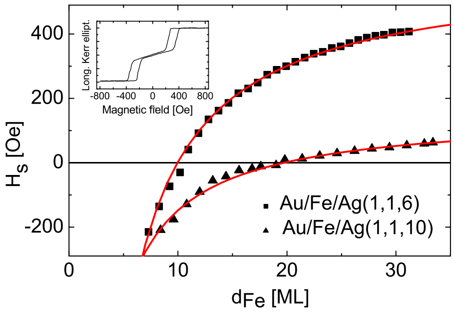

FIG. 2. (Color online) Shift field, H_s, as a function of d_{Fe} measured at RT for Au-covered Fe films grown on Ag(1,1,10) and Ag(1,1,6). The shift field H_s is defined as negative when the double-split hysteresis loops occur for the magnetic field applied parallel to the steps. The data for Ag(1,1,10) are taken from Ref. 4. The red lines are results of fitting as described in the text. A representative longitudinal hysteresis loop is shown in the inset.

In the case of Fe films grown on Ag(1,1,10), it is found that covering the films with Au causes the easiest magnetization axis to switch perpendicular to the steps below a thickness of 20 ML at room temperature (RT).[4] Similarly, for uncovered and Au-covered Fe films on Ag(1,1,6) the values of $H_{2,s}$ are −3100 Oe ML and −5975 Oe ML, respectively. The strong increase of $H_{2,s}$ suggests that covering with Au plays an important role in determining how the step-induced anisotropy modification depends on the film thickness.

The values of H_u for Au/Fe/Ag(1,1,6), obtained as described in subsection III.A., are plotted in Fig. 3. The values of H_u are expected to be larger than the values of H_s due to the fourfold contribution to the anisotropy.[11] From the fit with the formula $H_u(d_{\mathrm{Fe}})=H_{1,u}+H_{2,u}/d_{\mathrm{Fe}}$ (shown in red) and the fitting parameters ($H_{1,u}=1240$ Oe and $H_{2,u}=-11200$ Oe ML) one can conclude that the fourfold anisotropy field depends on the thickness approaching the $H_{1,fourfold}=H_{1,u}-H_{1,s}$ value of 635 Oe. For uncovered Fe/Ag(1,1,6) the fitted values of $H_{1,u}$ and $H_{2,u}$ are 1390 Oe and −9000 Oe ML, respectively, which results in a very similar fourfold contribution to the anisotropy ($H_{1,fourfold}=700$ Oe in this case). $H_{2,fourfold}$ for the Au-covered Fe film is slightly larger than for the uncovered Fe film, which again suggests an important role of the Au/Fe interface in determining the magnetic anisotropy. Nevertheless, the H_u (determined fol-

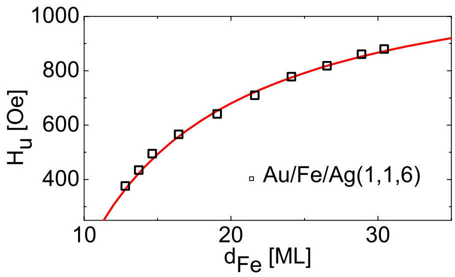

FIG. 3. (Color online) Uniaxial anisotropy field, H_u, as a function of d_{Fe} for Au-covered Fe films grown on Ag(1,1,6). H_u was calculated from the hysteresis loops measured perpendicular to the steps at RT according to the model proposed in Ref. 11. The red line is a result of fitting as described in the text.

lowing the procedure outlined in Ref. 11) dependence on Fe thickness shows that H_s underestimates the uniaxial contribution to the step-modified anisotropy of the Fe films grown on Ag(1,1,6) by roughly a factor of 2.

Since $H_{1,s}$ for Au/Fe/Ag(1,1,6) is much larger than for Au/Fe/Ag(1,1,10), which is in turn much larger than for Au/Fe/nominal Ag(001), we prove that the step-induced modification of the anisotropy amplifies with increasing step density (in the sense that a larger magnetic field is necessary to switch the magnetization to the harder magnetization axis). The fraction of the structurally perturbed film volume increases with the step density. For those Fe films grown on Ag(1,1,6), having a terrace width of 0.86 nm (i.e., 3 atoms wide) the modification becomes really strong. In fact, we find that $H_{1,s}$ increases quadratically with the step density, which is in agreement with the experimental observation of a "quadratic dependence of the step-induced uniaxial magnetic anisotropy on the vicinal angle α (Ref. 3)." This is correct since $H_{1,s}$ is equivalent to H_s in a thick film limit, while "the step-induced uniaxial magnetic anisotropy" was estimated from H_s,[3] which scales with H_u (see above). In our case we consider a dependence on the step density, not on α, because the linear relation between α and the step density holds only for $\alpha < 10°$.

It is worth to mention that covering the Fe films changes the thickness dependence of the anisotropy remarkably.[4] Similar to Fe/Ag(1,1,10), in the case of Fe/Ag(1,1,6) the easiest magnetization axis is much more forced to be oriented perpendicular to the steps after covering with 5 ML of Au. Despite of the strongly increased value of $H_{1,s}$ in comparison to the Fe/Ag(1,1,10) system, this tendency is sufficiently strong to keep the easy magnetization axis perpendicular to the steps up to a thickness of 10 ML. The fitting parameter $H_{2,s}$ can provide some insight as to how strongly the anisotropy modification depends on the film thickness for different step densities. Its value increases roughly by a factor of 2 when Fe films grown on Ag(1,1,6) ($H_{2,s}=-5975$ Oe ML obtained from the fit shown in Fig. 2) are compared to the films grown on Ag(1,1,10) [$H_{2,s}=-3000$ Oe ML (Ref. 4)], whereas $H_{1,s}$ increases by a factor of 4 under the same conditions.

C. Anisotropy oscillations

Looking at the anisotropy modification at $T=5$ K, the oscillations of H_s with increasing Fe thickness are not very clear in the case of Fe films grown on nominal Ag(001). Nevertheless, we were able to see a small oscillation amplitude of the order of a few Oe when measured in longitudinal geometry. The oscillation amplitude measured in "polar" geometry (as described in Sec. III A) around a thickness of 10 ML of Fe, is found to be about 600 Oe of the perpendicular field, which is actually measured (as it is shown in the inset of Fig. 4). Having in mind that measuring in "polar" geometry amplifies the field by roughly a factor of 50, the real oscillation amplitude is of the order of 10 Oe only. This is in agreement with what was measured in longitudinal MOKE.

It can be expected that the amplitude of the oscillations is related to how strongly the anisotropy is modified by the steps. In order to prove this concept, another Fe/Ag(001) sample with a stronger anisotropy modification is required. According to our previous considerations (see Sec. III B) this can be realized by using a vicinal Ag(100) surface with a smaller terrace width (i.e., a larger vicinal angle). For the Au/Fe/Ag(1,1,6) sample, at 5 K, H_s clearly oscillates with Fe thickness (see Fig. 4) with a period of 5.9 ± 0.4 ML, which is exactly the same as observed for the Fe films grown on Ag(1,1,10).[4] This is natural since there is the same ultrathin film of Fe, grown on the same Ag(001) substrate. The width of each succeeding maximum of H_s increases with increasing film thickness. This is at least in part due to the surface quality which degrades with increasing film thickness. Consequently, sharp conditions to form QWS are not fulfilled anymore for thicker films. The sharpest maximum should correspond to the first period which is expected around 5.9 ML. This is below the SRT which is observed around 9–10 ML (at $T=5$ K) for Fe/Ag(1,1,6) and thus cannot be seen from longitudinal MOKE measurements.

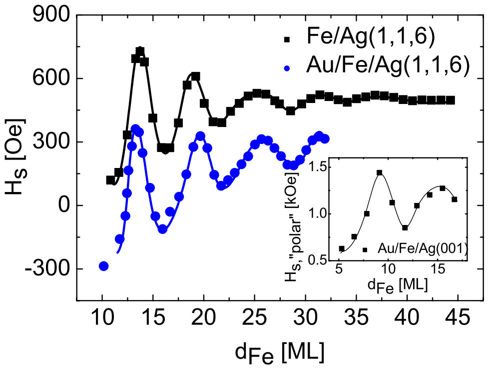

FIG. 4. (Color online) H_s as a function of d_{Fe} measured at 5 K both for uncovered and Au-covered Fe films grown on Ag(1,1,6). The oscillation amplitude is almost four times larger than that observed for Fe films grown on Ag(1,1,10) (Ref. 4). H_s as a function of d_{Fe} measured in "polar" geometry (described in text) at 5 K for Au-covered Fe films grown on Ag(001) is shown in the inset.

There are no theoretical calculations available to which we can compare our experimental results. However, a very similar value for the period of a strong oscillation of magnetic coupling (as a function of the thickness of one of the Fe electrodes) was obtained for the Fe/Cr/Fe system. This confirms that QWS formed in the same electron band are responsible for the oscillatory behavior observed for magnetic anisotropy and for interlayer coupling.[13]

The oscillation amplitude (i.e., the difference between the first maximum and the first minimum of H_s) measured for Au/Fe/Ag(1,1,6) is about 550 Oe [i.e., nearly four times larger than for Au/Fe/Ag(1,1,10)].[4] Above 35 ML no oscillatory behavior can be observed. In general, large magnetic anisotropy can be expected while there are at least two electronic states of small energy separation (resulting from the lifted degeneration due to the spin-orbit coupling), one located below and the other above the Fermi level (E_F).[1,2] QWS can periodically modulate the density of states at E_F and thus alternate the magnetic anisotropy.[4,14] The small amplitude of the anisotropy oscillation observed for the Fe on nominal Ag(001) system does not come as a surprise. In

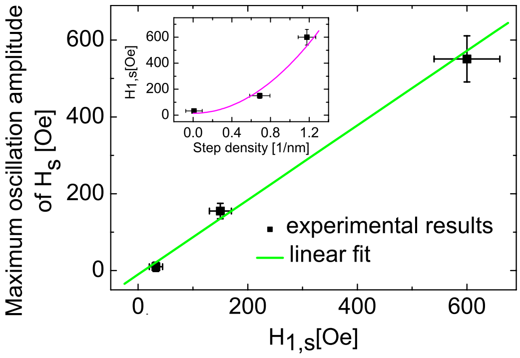

FIG. 5. (Color online) Maximum oscillation amplitude of H_s (at 5 K) as a function of $H_{1,s}$ (measured at RT) for Au-covered Fe films grown on nominal Ag(001), Ag(1,1,10) and Ag(1,1,6). The full line represents a linear fit. The error bars correspond to the experimental error estimated assuming 3 deg uncertainty of the field orientation with respect to the steps. $H_{1,s}$ as a quadratic function of the step density is shown in the inset.

general, in order to see oscillations of H_s, we need some modification of the fourfold anisotropy, which is introduced by the steps. The anisotropy is stronger the more the film is structurally perturbed by the steps.[3] Thus, increasing the perturbation of the film by increasing the step density from m to m', results in an amplification of the film anisotropy by a factor g, $H_{1,s}^{m'}=g(H_{1,s}^{m}\pm\Delta H_{1,s}^{m})$. Consequently, the strength ($H_{1,s}$) and oscillation amplitude ($\Delta H_{1,s}$) should scale the same with increasing step density. Therefore, if the experimentally measured oscillation amplitude would be proportional to $H_{1,s}$, the anisotropy oscillation could be attributed to the step-induced structural perturbation of the film volume.

In Fig. 5 we plot the oscillation amplitude (i.e., the difference between the first maximum and the first minimum of H_s) measured at 5 K for Au-covered Fe films grown on nominal Ag(001), Ag(1,1,10) and Ag(1,1,6) as a function of $H_{1,s}$ (measured at RT). Assuming similar quality of all the investigated Fe films, it can be concluded that the oscillation amplitude is proportional to $H_{1,s}$, which is a measure of how strongly the anisotropy is modified by steps in a thick film limit. It shows that the oscillation amplitude scales quadratically with the step density in exactly the same way as it was observed for $H_{1,s}$ (see inset of Fig. 5). This is in agreement with our expectation that the QWS extend in the whole film volume.

In terms of oscillation amplitude and oscillation period there is no essential difference between Au-covered and uncovered Fe films on Ag(1,1,6). Since covering with Au makes H_s smaller (i.e., less positive and/or more negative), the oscillations result here in a changing sign of the anisotropy (i.e., the easy magnetization axis oscillates between parallel and perpendicular to the steps). The small difference in the oscillation amplitude between uncovered and Au-covered samples can be explained by different slopes of the uncovered and Au-covered Fe wedge and a large susceptibility of the value of the first maximum/minimum measured in the MOKE experiment to the slope of the wedge. Since the large change of H_s after covering does not affect the oscillation amplitude, it additionally confirms that the oscillations are related to the structural perturbation of the film volume and this is why the oscillation amplitude is so large. Therefore varying the step density is a convenient tool to manipulate the anisotropy strength and orientation of the easy magnetization axis of FM films.

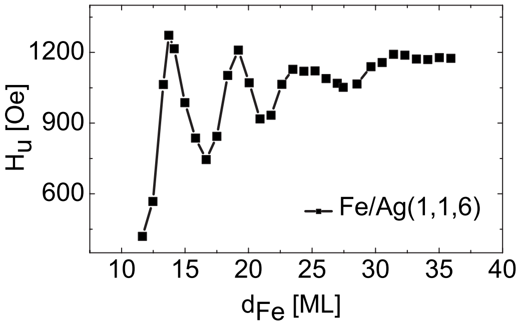

FIG. 6. H_u as a function of d_{Fe} measured at 5 K for uncovered Fe films grown on Ag(1,1,6). The period and amplitude of the oscillation are the same as for H_s (see Fig. 4).

Similar to Sec. III B, the uniaxial anisotropy field, H_u, can be calculated from the hysteresis loops measured along the harder magnetization axis at $T=5$ K.[11] This can be done for the uncovered, but not for the Au-covered sample for which the zero field slope cannot be estimated due to very small H_s values around the thicknesses at which H_s changes sign. For Fe/Ag(1,1,6), it is shown in Fig. 6 that H_u oscillates exactly with the same period and the same amplitude (of 550 Oe) as H_s does. Thus, by a proper choice of the substrate, the QWS-induced changes of H_u (which are proportional to changes of the uniaxial contribution to the step-modified anisotropy) can be made quite large.

It is worth to mention, that the modification of the anisotropy (described by H_s) could be due to a variation of either the uniaxial or the fourfold anisotropy, if the traditional description is applied (see Sec. III A). More explicitly, a decrease in H_s can be due to a decreasing uniaxial anisotropy or due to an increasing fourfold anisotropy. From the hysteresis loops measured at $T=5$ K, we can find that H_u oscillates whereas the anisotropy field of the fourfold anisotropy does not (not shown here). Thus we can conclude that the anisotropy modification due to the steps is the contribution to the film anisotropy, which oscillates as a function of film thickness at low temperature. This observation is supported by the fact that the oscillation amplitudes of H_s and H_u are the same.

In summary, we studied quantum oscillations of the magnetic anisotropy in Fe films grown on different stepped surfaces of Ag(001). We show that the step-induced modification of the anisotropy can disappear with increasing film thickness if the surface step density is sufficiently low. The oscillation amplitude scales quadratically with the step density and depends on how much the anisotropy in the film volume is modified by the steps. The anisotropy oscillations are caused by QWS which extend over the whole film volume and therefore their amplitude can be tuned by adjusting the distorted fraction of the film volume. This offers a convenient tool for anisotropy engineering which is crucial for modern spintronics devices. The largest oscillation amplitude of the shift field (H_s) is 550 Oe and was obtained for Fe films on Ag(1,1,6). The uniaxial anisotropy field (H_u) at 5 K could be calculated for uncovered Fe films only, however its oscillation amplitude is found to be the same.

ACKNOWLEDGMENTS

Fruitful discussions with M. Cinal and Y. Wu as well as experimental support from F. Yildiz, H. Menge and G. Kroder are acknowledged.

---

*Present address: Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA.

†mprzybyl@mpi-halle.de

[1] P. Bruno, Phys. Rev. B **39**, 865 (1989).
[2] G. Laan, J. Phys.: Condens. Matter **10**, 3239 (1998).
[3] R. K. Kawakami, E. J. Escorcia-Aparicio, and Z. Q. Qiu, Phys. Rev. Lett. **77**, 2570 (1996).
[4] J. Li, M. Przybylski, F. Yildiz, X.-D. Ma, and Y. Z. Wu, Phys. Rev. Lett. **102**, 207206 (2009).
[5] W. Weber, A. Bischof, R. Allenspach, C. H. Back, J. Fassbender, U. May, B. Schirmer, R. M. Jungblut, G. Güntherodt, and B. Hillebrands, Phys. Rev. B **54**, 4075 (1996).
[6] J. Schäfer, M. Hoinkis, E. Rotenberg, P. Blaha, and R. Claessen, Phys. Rev. B **75**, 092401 (2007).
[7] M. Cinal, J. Phys.: Condens. Matter **15**, 29 (2003).
[8] Y. Z. Wu, C. Won, and Z. Q. Qiu, Phys. Rev. B **65**, 184419 (2002).
[9] Z. Q. Qiu, J. Pearson, and S. D. Bader, Phys. Rev. Lett. **70**, 1006 (1993).
[10] D. M. Schaller, D. E. Bürgler, C. M. Schmidt, F. Meisinger, and H.-J. Güntherodt, Phys. Rev. B **59**, 14516 (1999).
[11] H. P. Oepen, Y. T. Millev, H. F. Ding, S. Pütter, and J. Kirschner, Phys. Rev. B **61**, 9506 (2000).
[12] F. Bisio, R. Moroni, F. Buatier de Mongeot, M. Canepa, and L. Mattera, Phys. Rev. Lett. **96**, 057204 (2006).
[13] D. Halley, O. Bengone, S. Boukari, and W. Weber, Phys. Rev. Lett. **102**, 027201 (2009).
[14] M. Cinal and D. M. Edwards, Phys. Rev. B **57**, 100 (1998).