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Abstract. – The temperature and magnetic field dependence of the low-energy cascade electron spin polarization is measured to determine the surface to bulk exchange interaction and the magnetic surface anisotropy on clean and chemically and physically modified surfaces of polycrystalline $Ni_{80}Fe_{20}$ and amorphous $NiFeB_{0.5}$. The surface magnetization $M_s(H, T)$ depends critically on the state of the surface.

Introduction

Magnetism is generally very different at the surface compared to the bulk. Obvious causes of surface induced alterations of magnetic properties include the inherent breaking of the symmetry at the surface, compositional and structural changes and surface adsorbates. The complex phenomena associated with magnetism at surfaces pose a great challenge to the experimentalist and require new techniques of measurement. Such techniques are presently emerging. This paper deals specifically with one branch of improvements based on spin polarized electron spectroscopies.

When asking basic questions about magnetism one can often neglect the contribution of the orbital moment to the total magnetization because the orbital moment is largely quenched in the crystal field. The magnetization is then given by $M = (n\uparrow - n\downarrow)n_B$ where $n\uparrow$ ($n\downarrow$) is the density of spin up (spin down) electrons and n_B the Bohr magneton number. The spin polarization of electrons is given by $P = (n\uparrow - n\downarrow)/(n\uparrow + n\downarrow)$. To the theorist, the measurement of M is therefore equivalent to the measurement of P. However, to the experimentalist, there are a number of differences. The measurement of M is based mainly on discoveries and inventions made in the 19th century and has been quoted in nationalistic units up to now. The definition and measurement of P, on the other hand, is entirely based on discoveries made in the 20th century, and accordingly, it is an international dimensionless quantity. It is not straight forward to measure the spin polarization of electrons in a solid. There are in fact only indirect ways to do this, for instance over the Fermi contact term to the nuclear magnetic moment, with Mössbauer spectroscopy, neutron scattering, μ-meson depolarization, positron annihilation, or similar techniques. However, one of the major achievements of the past decades is that one has learned how to extract electrons from a solid and emit them into vacuum. The energy required for electron emission is mainly supplied in the form of electric fields, and the amount of energy is small compared to the energy of the rest mass of the electron. Therefore, the nonrelativistic limit applies, and the electric fields do not couple to the electron spin. This means that the spin polarization of the electrons is conserved in the process of excitation of the electrons to an escape level. Once the electrons are in vacuo, one can form an electron beam and measure the spin polarization P in a scattering experiment. This is the basis of magnetometry with electrons. It should be noted that the experiment can also be inverted: first, a beam of spin polarized electrons is formed, for instance with a spin polarized GaAs-electron gun, and the emission of light or scattered electrons is measured when the spin polarized electron beam strikes the solid.

Unique features of magnetometry with spin polarized electrons

Magnetometry based on emission or scattering of electrons is not simple. Due to the very short mean free path of electrons in a solid, it requires structural and chemical definition of the surface of the often complex magnetic materials on an atomic scale. This implies generally that ultrahigh vacuum conditions are necessary in this type of magnetometry. Further, material specific methods have to be devised to prepare the surface prior to the measurement. However, once these difficulties are overcome, one can make use of the following unique features of magnetometry with spin polarized electrons.

1. TIME RESOLUTION. – With lasers, one can generate a short pulse of ultraviolet light. If such a pulse of say 10^{-12} s duration strikes the surface of a solid, enough electrons are emitted to perform an accurate measurement of P. Since angular momentum is conserved for the whole bunch of emitted electrons, space charge effects do not affect the spin polarization. There is no other technique that can measure the magnetization as fast as this [1].

2. SPATIAL RESOLUTION. – A primary electron beam may be focused into an extremely small spot. If the

electron beam strikes a magnetic solid, secondary electrons will be emitted from the close neighborhood of the focus. The spin polarization P of the secondary electrons is related to the magnetization of the spot from which they have been emitted. The probing depth of the secondary electrons may be a few Angstroms only, depending on their energy. Hence there exists no other magnetometer that requires less magnetic material. Good images of magnetic domains and domain walls have already been obtained with this technique [2-4].

3. ELEMENT SPECIFICITY. – If one excites electrons from specific atomic shells, one obtains a measure of the local magnetization around the atom from which the electron was emitted. That is, one can obtain element specific magnetization in an alloy or an epitaxial structure. Striking examples include results obtained with FeGd-alloys [5].

4. MAGNETIZATION OF SPECIFIC ELECTRONIC STATES. – In photoemission of spin polarized electrons, one can set the electron spectrometer to a specific energy and angle of emission. In this way, it is possible to measure the spin polarization of specific electronic states in the solid. Even if two otherwise equal electron states nearly coincide in energy they can still be separated if they have different spin polarization. This is ideal to detect the small exchange splitting in metals [6]. The results obtained on Fe, for example, contain a wealth of new information on metallic magnetism [7].

5. MAGNETISM IN UNOCCUPIED ELECTRON STATES. – If a spin polarized electron beam is directed onto the surface of a magnetic material, the spin dependence of light emission, or electron scattering, or electron absorption can be measured. This opens up the field of magnetism in unoccupied electron states [6]. Recently, a strong spin polarized feature was discovered at an energy as high as $\sim$ 20 eV above the Fermi-level in Fe [9].

It is clear that magnetometry with spin polarized electrons adds exciting new topics to magnetism.

Unresolved questions in surface magnetism

With these exciting prospects, one has to be careful not to miss a few open questions that could radically affect the interpretation of some of the above new experiments. A common feature of all electron spectroscopies is that one generally obtains information only on a very thin sheet of material at the surface due to the very short interaction length of the electrons. Therefore, there exists the danger that the observed magnetic behavior is affected by unexpected properties of the surface. In that case no answers to the fundamental questions existing in, e.g., metallic magnetism, would be obtained.

It appears that the unresolved questions can be summarized as follows:

1. what is the magnetic moment of the atoms at the surface? It is well known that the energy of core levels shifts at the surface either up or down depending on the position of the atom in the periodic table. Consequently, one expects a shift of the 3d- of 4f-states as well. This leads to a change of the occupancy of the magnetic levels and must produce a change of the magnetic moment in the atoms located at the surface. Theoretical studies have indicated that band narrowing at the surface can also lead to significant changes in surface magnetic moments;

2. what is the exchange coupling of the surface atoms? It is well known that the extension and shape of the wave functions of surface atoms are different from those of the bulk atoms. This leads to a different overlap between neighboring atoms and is bound to severely affect the exchange interaction;

3. what are the magnetic anisotropies at the surface? The occurrence of magnetic anisotropies is due to the spin-orbit interaction. In the bulk of 3d transition metals, the orbital moment is small because it is largely quenched in the crystal field. Consequently, the spin orbit coupling and the resulting magnetic anisotropy are also small. At the surface, the cubic symmetry of the crystal is broken. Therefore, the orbital moment is quenched to a lesser extent at the surface which may result in a very large surface induced magnetic anisotropy. A striking example of this phenomenon are the observations on epitaxial Fe-films [10].

Up to the present, no direct measurement of the surface magnetic moment has been possible. Some indirect methods have been proposed by Gradmann [11] and by Taborelli, Paul and Landolt [12]. It is the purpose of the following to show that the surface to bulk exchange coupling can be evaluated from the temperature dependence of the surface magnetization. The surface anisotropies may be estimated from differences between surface and bulk hysteresis loops. Both methods make use of the fact that magnetometry with spin polarized electrons is unique in that it allows one to measure the magnetization of very thin film of material at the surface, by virtue of the small probing depth of the electrons in a solid. It will be evident that reduced surface to bulk exchange coupling is very common in magnetic materials and together with special surface anisotropies can infact have a great influence on the interpretation of the magnetic data as obtained by spin polarized electron spectroscopies.

Temperature dependence of the surface magnetization

Up to now, little progress has been made in the understanding of the temperature dependence of the

surface magnetization [13]. A classical law of surface magnetism which is valid at low temperatures was first stated by Rado [14], and later developed in more detail by Mills and Maradudin [15]. The magnetization at the surface, $M_s(T)$, should follow the $T^{3/2}$–law according to

$$M_s(T)/M_s(0) = 1 - k.CT^{3/2} \qquad (1)$$

where C is the constant describing the decrease of the bulk magnetization due to spinwaves, and $k = 2$. The factor 2 arises because the spin waves become standing waves at the surface, and the last layer is always an antinode because the surface represents a free end. Therefore, for spinwaves of any wavelength, the spin deviation at the surface is twice as large as the average in the bulk. One might expect that the surface induces new spin wave states below the bulk band and that these states reduce $M_s(T)$ even further than the classical law predicts. This is not the case because the total number of spin-waves in the bulk and at the surface is fixed. Therefore, each surface spin wave leaves a hole in the bulk band. Since the surface and bulk modes are approximately degenerate in energy, both effects cancel and the density of spinwaves at the surface remains unchanged, leading to the simple classical law under all circumstances.

For the "ideal" surface with Heisenberg exchange and bulk values of the exchange constant right up to the last layer, the probability of finding a reversed spin at a distance x from the surface is given by

$$p(x, T) \propto \int_0^\infty dq.\left(q^2.\cos^2(qx)\right) / \left(e^{E/k_BT} - 1\right) \qquad (2)$$

where q is the magnon wave number, k_B the Boltzmann constant, and $E = Dq^2$. The spin wave stiffness D is known from neutron scattering in the bulk [16, 17], or from Brillouin scattering [18], or may be estimated from C in equation (1) [18] obtained from bulk measurements.

Figure 1 shows $p(x, T)/(p\infty T)$ for $T = 150$ K and 300 K, for the case of $D = 150$ meV.Å^2 which applies to the amorphous glass $NiFeB_{0.5}$. It is seen that the classical law with $k = 2$ can only be observed with a very small probing depth $\ell \cong 0$. The actual spin polarization $P(T)$ expected if $P(T) \propto M(T)$ and with a finite probing depth of the electrons $\ell > 0$ can be calculated for the ideal surface from:

$$P(T)/P(0) = 1 - CT^{3/2}.(1/\ell) \times \times \int_0^\infty p(x, T)\, e^{-x/\ell} dx. \qquad (3)$$

Hence, to interpret the spin polarization measurements in detail, one has to know the actual value of the magnetic probing depth ℓ, and, quite importantly, one has to verify that $P(T) \propto M(T)$ does indeed apply. However, it is clear that k in equation (1) must be < 2. This is not found experimentally. Elastic scattering of spin polarized electrons from the surface of the amorphous ferromagnet $FeNiB_{0.5}$ showed that $M_s(T)/M_s(0)$ decreased with $T^{3/2}$ but with $k > 2$ [14]. Mathon and Ahmad [19] proposed a solution to this paradox. They found that equation (1) with $k = 2$ holds only for $T/T_c \leq 0.01$ under all circumstances, even when the magnetic moment changes at the surface and even when the exchange coupling on a path perpendicular to the surface becomes arbitrarily weak. However, for weak perpendicular exchange $J_\perp$ and at higher temperatures, a law of the form of equation (1) is still valid approximately, yet the effective k can now be larger than 2 depending on the value of $J_\perp/J$, where J is the exchange interaction in the bulk. This theoretical prediction was recently confirmed for the case of $FeNiB_{0.5}$ [20]. We shall show in the next chapter that it also applies to polycrystalline $Ni_{80}Fe_{20}$ (permalloy). Hence the measurement of the temperature dependence of the surface magnetization offers unique possibilities to study the exchange interaction at surfaces.

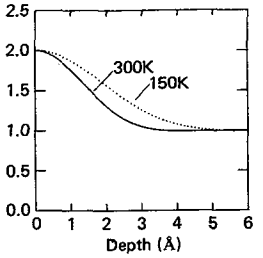

Fig. 1. – The magnetization profile created by the reflection of spinwaves at the surface of a Heisenberg ferromagnet with bulk values of the exchange up to the last layer. Plotted is the probability $p(x, T)$ to find a reversed spin at depth x (Å) from the surface at $T = 150$ and 300 K, normalized by the bulk probability $p(\infty, T)$.

Experimental method and results with $FeNiB_{0.5}$

The amorphous ferromagnet $FeNiB_{0.5}$ with a Curie point $T_c \simeq 700$ K is particularly suited for a first test of the predictions [19]. The main prerequisite of the theory is that the bulk magnetization $M_B(T)$ follows equation (1) with $k = 1$. By measurement of $M_B(T)$ in a Josephson magnetometer, this was found to apply at $T \leq 300$ K, and $C = 17.8 \times 10^{-6}$ deg$^{-3/2}$ was obtained in close agreement with earlier results [16]. Furthermore, one basic prediction of the general approach [14, 15, 19], namely that $M_s(T)$ also follows equation (1) but with $k > 1$ has already been convincingly demonstrated by the electron scattering experiments [16].

We have chosen to measure the spin polarization $P(T)$ of the low energy cascade electrons excited with an unpolarized beam of primary electrons. $P(T)$ is believed to reflect the average magnetization over a

probing depth of $\ell \simeq 5$ Å from the surface [21]. P is however not equal to M_s; we shall show below that $P \rightarrow 21$ % for the cleanest surface we could prepare as $T \rightarrow 0$ K. From the Bohr magneton number n_B= 2.40 Bohr magnetons/$NiFeB_{0.5}$–molecule at $T = 0$ and the average number n of valence electrons one would expect $P = n_B/n \simeq 13$ %. Enhancement of P over M_B is a common observation in most magnetic materials, yet its origin is at present still under discussion. Therefore, we shall only assume here that $P(T) \propto M_s(T)$ which means that the enhancement factor is independent of T. To prove the validity of this assumption it is sufficient to show that $P(T)/P(0)$ follows the $T^{3/2}$–law as it is already known that the law is valid for $M_s(T)/M_s(0)$ with the same material [16]. To specifically test the predictions of Mathon and Ahmad [19], one has to demonstrate further that k in equation (1) increases as $J_\perp$ weakens while the $T^{3/2}$–law is still preserved.

The sample [23], a ribbon 3 mm wide and 0.025 mm thick, was glued with silver paint across the 2.0 mm gap of a horseshoe electromagnet. The primary beam with an energy of 3 keV was focused into a spot of 0.1 mm in the middle of the sample. The low energy secondary electrons emerging from the sample were imaged with an extraction lens system onto the entrance diaphragm of a medium energy (40 keV) Mott polarization analyzer as described by Gray *et al.* [22]. To permit the observation of the small changes of $M_s(T)$, the relative accuracy in the measurement of P has to be very high. This accuracy can be measured by employing the fact that $NiFeB_{0.5}$ exhibits square magnetization loops with magnetic saturation occurring in external magnetic fields $H \geq 1$ Oe. It follows that $P(H)$ must be constant at $H \geq 1$ Oe which provides an internal relative standard against which the precision of the apparatus can be verified for every hysteresis loop. On the basis of this test, the systematic errors are estimated to be of the order of $\Delta P = \pm 0.1$ %. Hysteresis loops were recorded at each T and the data taken in magnetic saturation yet at different values of H were averaged.

The sample was bombarded with Xe ions at an energy of 500 eV with a dose equivalent to the removal of $\simeq 25$ Å. After each treatment, and before and after each temperature cycle, an Auger spectrum was taken. The spectra showed that within the accuracy of a few percent, the surface had the bulk composition. C and O could be removed with a few of the above Xe-treatments to less than 5 % of a monolayer each. We shall name the surface obtained after a large number of cycles a "clean" surface. We observed that $P(T)$ depends critically on spurious contamination caused by absorption of residual gas molecules. Only under excellent UHV conditions was it possible to return to the starting polarization after completing a cooling and warming cycle in $\simeq 1$ hour.

Figure 2 shows $(P(0) - P(T))/P(0)$ *vs.* the observed relative change of the bulk magnetization $(M(0) - M(T))/M(0)$ for $T/T_c \leq 0.4$. According to [19] and equation (1), we expect $\Delta P/P = k\ \Delta M/M$. It is evident that the predicted linear relationship is indeed observed for both the clean and the chemically modified surface. For the clean surface, one obtains $k = 2$, and for the surface with 1/2 monolayer of Ta, $k = 5.4$. There is a dramatic dependence of the surface magnetization at, e.g., room temperature on the chemical state of the surface. A closer examination of the dependence of $M_s(T)$ on the concentration of Ta showed that the maximum lowering occurs actually with 1/2 monolayer of Ta. A full monolayer seems to be less effective, at least if the Ta-atoms sit on top of the surface [20]. Yet all the surfaces obeyed the $T^{3/2}$–law, even when contaminated with various amounts of C and/or O which shows that [19] is generally applicable to $NiFeB_{0.5}$. The maximum value of $k = 5.4$ corresponds to approximately $J_\perp/J = 0.1$, where $J_\perp$ is the exchange interaction on a path perpendicular to the surface, and J the exchange in the bulk [9]. This might be explained by the donation of electrons from Ta to the Ni and Fe-atoms which both have higher electronegativities. The occupancy and shape of the 3d-functions obviously has a dramatic effect on the exchange interaction.

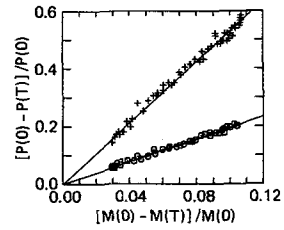

Fig. 2. – Amorphous $FeNiB_{0.5}$: dependence of the relative change of the cascade electron spin polarization $\Delta P(T)/P(0)$ on the relative change of the bulk magnetization $\Delta M(T)/M(0)$ for the clean surface (circles) and a surface with 1/2 monolayer of Ta (plusses).

Pierce *et al.* [16] observed $k = 3$ by elastic electron scattering on $NiFeB_{0.5}$. However, the Auger spectra showed a surface concentration of C comparable to that of B which means that $\simeq 20$ % of the surface could have been covered with C. With approximately the same relative Auger signal from C, we found $k = 3$ as well but from the spin polarization of the cascade. Therefore, it appears that the probing depth for elastic electron scattering at an energy of 100 eV is not much different from the probing depth of the low energy cascade, and/or that the recovery of the magnetization with distance from the surface is slow compared to ℓ. Both possibilities are in sharp contrast to earlier beliefs yet consistent with [21]. It would of course be very desirable to compare M_s obtained with differ-

ent techniques on the same surface to obtain more information on the magnetization profile created by the spinwaves on a real surface.

Of particular interest is the question of whether $k = 2$ as observed with the clean surface indicates that $NiFeB_{0.5}$ obeys the classical law if the surface is properly prepared. Equation (3) shows that this is not the case. When assuming the lowest possible estimate of $\ell = 4$ Å, one is still able to fit $P(T)/P(0)$ to the $T^{3/2}$–law, but one obtains k_{eff}=1.3 from equation (3). Hence the observed larger value of $k = 2$ shows that even with "clean" material, the exchange interaction on a path perpendicular to the surface must be reduced.

Experimental results on $Ni_{80}Fe_{20}$ (permalloy)

The incoherent generation of the cascade electrons averages over effects of diffraction in the case of crystalline materials. In contrast to the spin dependence of the elastic scattering of electrons, the spin polarization $P(T)$ of the cascade electrons is then expected to be proportional to $M_s(T)$ even with crystalline materials. We find that this is indeed the case, at least at low T. Permalloy films were deposited in ultrahigh vacuum onto a Cu-band 4 mm wide through which an electric current could be passed to produce a homogeneous magnetic field H. A beam of Xe-ions from a plasma gun was used for sputter deposition. A film of $\simeq$ 500 Å of Ta was deposited onto the Cu-band to provide a substrate on which low coercivity permalloy films can be obtained. The permalloy films were deposited on top of the Ta in the presence of a magnetic field. Film thicknesses were monitored by a quartz microbalance, and the atomic composition of the near surface region was analysed by rotating the sample to the Auger-spectrometer. The beam of a He-Ne laser could also be reflected from the sample surface. This enabled us to measure the magneto-optic Kerr effect *in situ* and to compare the hysteresis loops obtained from the Kerr measurements to the loops obtained from the measurement of the spin polarization $P(T)$ of the low energy cascade electrons.

Figure 3 shows the temperature dependence of the cascade electron spin polarization $P(T)/P(0)$ for 3 different chemically modified surfaces and the temperature dependence of the bulk magnetization $M(T)/M(0)$ according to Weber and Tannenwald [24]. In the 3 surfaces, the modification consisted of inserting an interlayer of 0.5, 1.0, and 1.5 monolayers of Ta between the surface layer of 5 Å thickness and the bulk. In this way, a controlled reduction of the surface to bulk exchange coupling $J_\perp$ on a path perpendicular to the surface was produced as required to test the theory of Mathon and Ahmad [19]. The results displayed in figure 3 show that $P(T)$ is proportional to the surface magnetization $M_s(T)$ also for crystalline materials, and furthermore that the prefactor k in equation (1) is a measure of $J_\perp/J$. From the fitting of equation (1) to the data we obtained $k = 2.3$, 4.1, and 5.3 for the surfaces with 0.5, 1.0, and 1.5 monolayers of Ta between surface and bulk respectively.

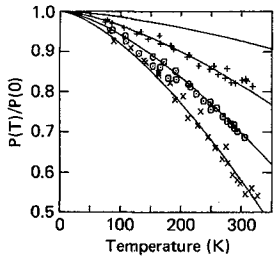

Fig. 3. – $Ni_{80}Fe_{20}$: temperature dependence of the cascade spin polarization $P(T)/P(0)$ for 3 modified surfaces. A sheet of $Ni_{80}Fe_{20}$ of 5 Å thickness is separated by 0.5 (plusses), 1.0 (circles), and 1.5 monolayers of Ta (crosses) from the bulk of $Ni_{80}Fe_{20}$. Full lines are calculated from equation (1) with $k = 2.3$, 4.1, and 5.8 respectively. The upper line is the temperature dependence of the bulk magnetization from Weber and Tannenwald [24].

Figure 4 shows the temperature dependence of $P(T)/P(0)$ for more or less clean surfaces of unmodified pure permalloy. In the case of the cleanest surface, $P(T)/P(0)$ follows very closely the bulk magnetization with $k \cong 1$. This indicates that the permalloy surface is quite close to the "ideal" surface of a Heisenberg ferromagnet. $P(0) = 21$ % was obtained with this surface. From the Bohr magneton number n_B=1.07 and the average number of electrons $n = 9.6$ one would expect $P = n_B/n = 10.4$ %. Hence permalloy shows an even larger enhancement factor of P over M than amorphous $NiFeB_{0.5}$; we can conclude that whatever the reason for this enhancement, the enhancement factor is independent of temperature for $T/T_c \lesssim 0.4$.

The next cleanest permalloy surface showed $P(0) =$ 19.5 %, but the fit to equation (1) yields already $k \cong 1.5$. The Auger-spectrum shows some C and O, of the order of a few % of a monolayer, but nothing more.

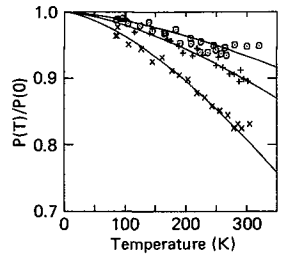

Fig. 4. – $Ni_{80}Fe_{20}$: temperature dependence of the cascade spin polarization $P(T)/P(0)$ for a clean surface (circles), a surface with $\sim$ 5 % of a monolayer of C and O each (plusses), and a surface with $\sim$ 10 % of a monolayer of C and O each (crosses).

As soon as more contamination is present, of the order of 10 % of a monolayer of C and O, $P(0)$ was reduced to 15 % and $k \cong 3$. This extreme sensitivity of the surface magnetization can only be understood when the preferential oxidation of Fe as well as its much larger magnetic moment than that of Ni, approximately by a factor of 4, is taken into account [25]. As the 20 % Fe atoms in the surface are the main source of the magnetization, their preferential oxidation produces a dramatic effect.

When $P(0)$ has decreased to $\sim$ 12 % , it is quite stable even in a vacuum of 10^{-6} Torr. Passivation must therefore occur with permalloy once the surface is oxidized.

These observations demonstrate that the surface magnetization and its temperature dependence is severely affected even by submonolayer adsorbates. Therefore, experiments in which the surface contaminants can not be controlled to a level of a few percent of a monolayer would be unreliable.

Surface hysteresis loops

For a first insight into the process of magnetization reversal near a surface it is advantageous to develop a simple model with few parameters. The model structures of the permalloy surface in figure 3 have one magnetic sheet of 5 Å thickness at the surface which may have its own surface magnetization M_s, and uniaxial surface anisotropy K_s, and which is coupled over a link of adjustable strength to the underlying bulk permalloy. If the external magnetic field H is applied in the easy direction of magnetization of the bulk, the anisotropy keeps the bulk specimen in a single domain state even when H is removed. If H is reversed and reaches the value of the coercive field H_c, a reversed magnetic domain nucleates. The reversed domain expands by domain wall movement which results in a sudden reversal of M at $H = -H_c$. Therefore, bulk magnetization loops for H along the easy direction are square loops. Whether or not the surface sheet follows the bulk depends on the energy of the exchange coupling across the interface, on the direction and magnitude of the anisotropy K_s of the surface, and on M_s. If K_s has a direction different from the one in the bulk and if its energy is large, the surface will be magnetized in its own easy direction and a fractional magnetic domain wall may form in the bulk if the surface to bulk exchange interaction is sufficiently strong. Even the simplest possible model is complex enough to require computing to find the minimum of the energy; this is discussed in more details in references [26, 27].

The experimental results shown in figure 5 illustrate some important features of the simple model discussed above. Figure 5 shows, on the left hand side, hysteresis loops of a 5 Å thick permalloy film at various temperatures. This film is not coupled to any magnetic

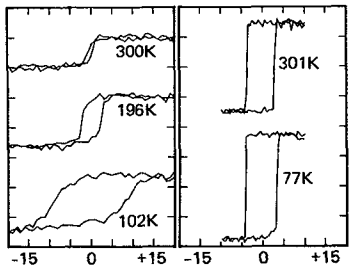

Fig. 5. – $Ni_{80}Fe_{20}$: hysteresis loop of a 5 Å thick film at various temperatures; the film on the left side is on a thick Ta substrate and therefore not coupled to any bulk magnetic material. The film on the right side is coupled over an interface of 0.5 monolayers of Ta to bulk permalloy. Plotted is the spin polarization $P(H)$ of the cascade electrons in % (distance between adjacent marks 10 %).

substrate as the underlying Ta is very thick. On the right of figure 5 are the loops of the same type of film coupled over a quite strong exchange link of 0.5 monolayers of Ta to bulk permalloy. The hysteresis loops are obtained *via* the spin polarization of the low energy cascade electrons P hence they represent the magnetic behavior of the surface sheet alone as the magnetic probing depth is about equal to the thickness of the surface film.

It is seen that the free standing film on the left exhibits hysteresis loops that are not square and change with temperature. Hence the strength of K_s depends on T and its direction is not exactly collinear with the direction of the applied field H. The coupled film on the right shows exactly the same square loops as the underlying bulk permalloy. This demonstrates clearly that the surface magnetization has to follow the bulk magnetization if the energy associated with M_s and K_s are small compared to the energy of the exchange coupling across the interface. An additional point is that a fractional domain wall extending into the bulk is not formed unless the surface anisotropy energy is sufficiently strong which is not the case here.

Figure 5 shows clearly what is expected for a strong surface to bulk exchange coupling: the surface must show the same hysteresis loops as the bulk. If, on the other hand, the exchange coupling is weak, the surface sheet may show hysteresis loops different from the bulk loops. To demonstrate this feature as well, one needs to measure the bulk hysteresis loops in addition to the surface loops. It can conveniently be done by employing the magneto-optic Kerr effect, which has a probing depth of $\sim$ 160 Å with the light from a He-Ne-laser and with permalloy. Hence it can measure the bulk hysteresis loops by reflecting the light beam from the surface even in the presence of a thin film of magnetically different material at the surface.

Figure 6 shows the results of experiments on a permalloy film which has a strong exchange coupling to

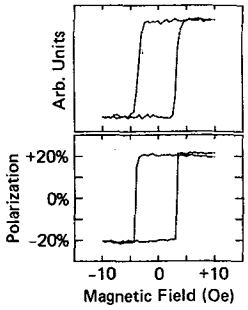

Fig. 6. – $Ni_{80}Fe_{20}$: film of 5 Å thickness coupled over 0.5 monolayers of Ta to bulk $Ni_{80}Fe_{20}$. Upper hysteresis loop from Kerr-elliplicity and lower hysteresis loop from the cascade spin polarization.

the bulk over a 0.5 monolayer Ta interface. The upper part of figure 6 shows the hysteresis loop as observed with the magnetooptic Kerr effect, and the lower part the loop obtained from a measurement of the spin polarization P. Hence the upper part shows the back loop and the lower the surface loop. These loops are very similar as expected. The remaining differences are due to the fact that the light spot used in the Kerr-measurement probed an area of 3×12 mm, whereas the electron beam employed in the P-measurement had a focus of ~ 0.1 mm^2, that is it probed a much smaller area of the sample. H and the sample properties are not expected to be homogeneous over the full area of the light spot. This explains the somewhat reduced squareness of the Kerr-loop.

Figure 7 shows the case of a weakly coupled permalloy film. The coupling to the bulk is through 1.5 monolayers of Ta. The Kerr loop in the upper part shows that the bulk exhibits a square magnetization loop, whereas the loop of the film at the surface as observed *via* the spin polarization P shows a slanting particularly near the coercive field. This indicates that the surface sheet starts to be governed by its own individual M_s and K_s as soon as the coupling to the bulk weakens. The slanting of the square hysteresis

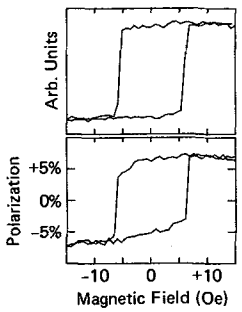

Fig. 7. – Same as figure 6, but with a thicker Ta-interlayer (1.5 monolayers of Ta between surface film and bulk).

loops at the surface follows from the complete mathematical expression when the exchange energy is comparable to the anisotropy and field energy of the surface [27].

Slanted surface hysteresis loops have also been observed on the Fe(100)-surface [28] and with amorphous FeB [29]. This then indicates that a weak surface to bulk exchange coupling and a direction of the surface anisotropy different from the bulk occurs quite frequently in magnetic materials. The value of K_s can be estimated on the basis of the simple model [26] by fitting the observed hysteresis loop to the computated ones as demonstrated in [27].

Conclusion

Spin polarized electron spectroscopies provide unique possibilities to investigate magnetic phenomena at surfaces. Magnetometry with spin polarized electrons has the highest possible time and spatial resolution, it can be made element specific, it can measure the contribution of specific electron states to the total magnetization, and it opens up for the first time the phenomenon of magnetism in unoccupied electron states. Although magnetism at surfaces is a very active field, the following problems are still unresolved and could affect the interpretation of spectroscopy with spin polarized electrons.

1) What is the size of the magnetic moments of atoms located at the surface?

2) What is the strength of the bulk to surface exchange coupling?

3) What is the size and direction of the surface anisotropy?

It is shown that an answer to 2) and 3) may be obtained from measurement of the temperature dependence of the surface magnetization in the spin wave regime and from a comparison of surface and bulk hysteresis loops. This experimental approach is based on the surface sensitivity of spin polarized electron magnetometry, and on recent theoretical findings of Mathon and Ahmad [19]. We show that a weakening of the exchange interaction on a path perpendicular to the surface may be induced by traces of adsorbates and is a frequently occurring phenomenon even with the cleanest surfaces one can prepare with present day vacuum technology and instrumentation. The surface magnetization depends strongly on the physical and chemical properties of the surface; at room temperature, for instance, it can decrease by as much as 50 % with a below submonolayer coverage of a nonmagnetic metal such as Ta in the case of amorphous $FeNiB_{0.5}$. For permalloy, M_s (300 K) decreases by 20 % with C and O contaminats of less than 10 % of a monolayer each.

By preparing an artificial surface consisting of a surface layer coupled to the bulk through an interface of variable thickness, we demonstrate some simple phenomena induced by a surface anisotropy K_s which is different in direction and magnitude from the K of the bulk. In the case of strong exchange coupling to the bulk, surface and bulk loops are identical. As the exchange coupling weakens, the surface loop shows characteristic differences which can lead to an estimate of the direction and strength of K_s. Surface hysteresis loops with characteristic slanting of the edges have been observed with several materials. Therefore, special surface induced anisotropies combined with a weak surface to bulk exchange coupling occurs with many common materials. This can lead to an extremely complex behavior of magnetic surfaces and must carefully be considered when interpreting the results of the surface sensitive spin polarized electron spectroscopies.

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