Magnetic force microscopy studies of the domain structure of Co/Pd multilayers in a magnetic field

A. W. Rushforth, P. C. Main, and B. L. Gallagher
School of Physics and Astronomy, University of Nottingham, University Park, Nottingham NG7 2RD, United Kingdom

C. H. Marrows and B. J. Hickey
Department of Physics, University of Leeds, Leeds LS2 9JT, United Kingdom

E. D. Dahlberg and P. Eames
Department of Physics and Astronomy, University of Minnesota, 116 Church Street, S.E. Minneapolis, Minnesota 55455

We have measured the magnetic domain patterns in Co/Pd multilayers of varying thickness using magnetic force microscopy in the presence of an external magnetic field applied perpendicular to the multilayers. We find that the domain patterns evolution is in qualitative agreement with existing theories for single layer thin films. Our results are in reasonable agreement with a theoretical model of domains appropriate to multilayer films. © 2001 American Institute of Physics.

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Ferromagnetic thin films with perpendicular anisotropy have been the subject of intense research due to their potential application as magnetic storage media. In particular, cobalt-based multilayers, with either palladium or platinum as the nonferromagnetic spacer layer, have attracted much interest recently since they offer the possibility of high storage density. The magnetic properties of the multilayers can be manipulated easily by varying the number of layers, the thickness of the layers, and the growth conditions. We describe a study of Co/Pd multilayers which are known to have perpendicular anisotropy when the Co layer thickness is less than 8 Å. We use magnetic force microscopy (MFM), in the presence of an external magnetic field applied perpendicular to the plane of the multilayers, to study the evolution of the domain patterns. The MFM technique offers certain advantages over other techniques that have been used previously to study thin ferromagnetic films, such as Lorentz force microscopy and the Faraday effect. For example, it allows imaging of films of varying thickness, it can resolve features down to 10 nm in principle, and there are no special requirements for the substrate.

The multilayer films were grown on GaAs substrates by dc magnetron sputtering at an argon pressure of 0.4 Pa. The nominal layer thickness was 4.7 Å for the Co layers and 14.2 Å for the Pd layers. The thickness of the films was measured using a Daktek profilometer capable of measuring the step height to an accuracy of 12 Å. The measurements indicate that the thickness of the layers was approximately 30% greater than the nominal thickness. Therefore we have assumed a thickness of 6.2 Å for the Co layers and 18.6 Å for the Pd layers in the calculations presented below. Three samples (S1, S2, and S3) were produced with 200, 300, and 400 bilayers, respectively. The bulk magnetic properties were measured by vibrating sample magnetometry (VSM). The MFM images were obtained using a Digital Instruments Dimension 3000. The scan height of the tip was 100 nm above the sample surface, which will limit the resolution for our measurements to ~100 nm. The external magnetic field was controlled by adjustment of the position of a NdFeB magnet positioned beneath the sample holder. This arrangement produced a maximum field of 0.3 T, as measured using a commercial gaussmeter.

Figure 1 shows MFM images of sample S1 as the external field is swept from −0.3 to 0.3 T. The black areas represent domains oriented in the direction of the positive applied field and the white areas represent domains with magnetization pointing in the opposite direction. At −0.3 T there are many isolated bubbles and short stripes oriented in the opposite direction to the applied field. Domains pointing in the direction of the applied field surround these. As the external field is swept to 0 T the domain pattern evolves. There is an increase in the length of the black domains, which eventually coalesce with the bubble domains to form a pattern at 0 T that consists mainly of stripe domains. At this point there are equal areas of domains oriented in the two

[FIG. 1. MFM images (10 μm square) of S1 for external magnetic fields of (a) −0.3 T, (b) −0.2 T, (c) −0.1 T, (d) 0 T, (e) 0.2 T, and (f) 0.3 T.]
directions. As the external field is increased from 0 T we see the gradual formation of bubble domains as the stripes break up and contract in length.

Figure 2 shows a magnetic hysteresis loop for sample S1 obtained using VSM. The shape of the hysteresis loop is similar to that observed by Barnes et al.\textsuperscript{5} who studied CoPd multilayers similar to our own. They identified point $A$ ($A'$) as the point at which the domain structure changes from a uniform magnetization to a random domain pattern due to the nucleation of domains oriented in the opposite direction to the applied field. The domain pattern then saturates to a uniform magnetization at point $B$ ($B'$). The low value of the magnetization at zero external field is consistent with our observation that the number of domains pointing in each direction is roughly equal when the external field is removed. The MFM and VSM measurements on samples S2 and S3 produce results that are qualitatively similar to those obtained for S1.

Two models have been proposed to describe the most stable domain structures for ferromagnetic thin films. Both involve minimization of the total energy, which includes contributions from the domain wall, demagnetization, and magnetostatic energies. Thiele\textsuperscript{7} proposed that, above a certain critical field, the most stable domain configuration consists of bubbles oriented opposite to the applied field. Kooy and Enz\textsuperscript{4} dealt with the situation where the external field was small and they predicted that a system consisting of stripe domains would form the most stable configuration in this case. There is qualitative agreement between these models and the domain patterns in our multilayers. At low external fields we see stripe domains and at higher fields we see the stripes contracting in length and breaking up to form bubbles. Thiele’s model predicts that, for single thin ferromagnetic films with the same thickness as ours, bubble domains will form when the external field is above approximately 0.2 T.

Draaisma and de Jonge\textsuperscript{8} proposed a model, which is similar to the stripe domain model of Kooy and Enz, but which was modified for a multilayer system consisting of alternating layers of ferromagnetic and nonferromagnetic material. The model considers a system of stripe domains with alternating orientation perpendicular to the plane of the multilayers. The repetition length $d$ is defined as the total width of two adjacent stripes oriented in opposite directions. The other parameters in the model are the thickness of the layers, the number of bilayers, the external field, the magnetization of the ferromagnetic material, and a material dependent characteristic length, $\tau = \sigma_w/0.5\mu_0M_s^2$, where $\sigma_w$ is the domain wall energy per unit area and $M_s$ is the saturation magnetization per unit volume of the ferromagnetic material.

Barnes et al.\textsuperscript{5} compared this model to MFM images of multilayers similar to our own, but without the presence of an applied field. They varied the number of bilayers in their samples and measured repetition lengths up to 450 nm. They obtained good agreement with the theory for $\tau = 55$ Å. Our measurements allow us to test the model in the presence of an applied magnetic field.

Figure 3 shows the experimentally measured repetition lengths of our samples and a theoretical fit as a function of the magnetization normalized to the saturation magnetization. To measure the repetition lengths we take advantage of the fact that the stripes tend to align in a preferred direction. The reason for this is not clear, but it could be due to the small magnetic field, which is present during the sputtering process. For each image, the average number of times the contrast changed sign along a line perpendicular to the preferred direction of the stripes was determined. This effectively counts the number of domain walls, from which the repetition length can be deduced. This was done for 256 cross sections on each image. The points in Fig. 3 represent the average, and the error bars represent the standard deviation of the measurements. We see that the agreement between theory and experiment is reasonable for values of $\tau$ in the range 200–250 Å. Table I shows the measured values of the field required to saturate the multilayers, $H_s$, and the value predicted by the model. We obtain the saturation field by averaging the up and down arms of the hysteresis curve, since hysteresis is not included in the model. The agreement between the model and these measured values is reasonable when $\tau$ is in the range 130–170 Å depending on the number of bilayers. The discrepancy between the two methods is probably due to the fact that our measurement of the repetition length is an overestimate. This will occur because the
stripes are not perfectly aligned in a direction perpendicular to the cross sections. Our values of \( t \) are large in comparison to the value of \( t = 8 \) Å obtained by Barnes et al. and \( t = 55 \) Å used by Draaisma and de Jonge. However, Draaisma and de Jonge used vapor deposition to produce their samples. Such films tend to have a higher perpendicular anisotropy than sputtered films because the interfaces are smoother. This leads to smaller values for the saturation field, which is consistent with a smaller value of \( t \).

The model gives a reasonable fit to our data despite certain assumptions, which are not strictly valid for our multilayers. The model assumes that only the cobalt layer is magnetic. However, it is known that the palladium layers are also polarized. The model also assumes that the domains have perfect perpendicular anisotropy, that they are arranged in infinitely long parallel stripes, and that the domain walls can move freely due to the absence of any pinning sites. We have already mentioned that multilayers produced by sputtering are unlikely to have perfect perpendicular anisotropy. Also, the random pattern of domains indicates that there are many pinning sites present.

In summary, magnetic force microscopy shows the evolution from stripe domains to bubble domains as the external field is increased. This is consistent with existing theories for single layer thin films. We have measured the domain repetition lengths and found reasonable agreement with the model developed by Draaisma and de Jonge. We obtain values of \( t \) which are larger than the values obtained by previous authors who have studied similar multilayers in the absence of an external field. This discrepancy may be due to the difference in the perpendicular anisotropy, which results from the method used to produce the multilayers.

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### Table I

<table>
<thead>
<tr>
<th>Sample</th>
<th>No. of bilayer</th>
<th>( H_s(T) ) measured ( +/- 0.02 ) T</th>
<th>( H_s(T) ) theory ( \tau = 130 ) Å</th>
<th>( \tau = 150 ) Å</th>
<th>( \tau = 170 ) Å</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>200</td>
<td>0.47</td>
<td>0.49</td>
<td>0.47</td>
<td>0.45</td>
</tr>
<tr>
<td>S2</td>
<td>300</td>
<td>0.55</td>
<td>0.55</td>
<td>0.53</td>
<td>0.51</td>
</tr>
<tr>
<td>S3</td>
<td>400</td>
<td>0.55</td>
<td>0.58</td>
<td>0.57</td>
<td>0.55</td>
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