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Thermal stability and switching field distribution of CoNi/Pt patterned media

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Abstract The thermal dependence and distribution of the switching fields of arrays of magnetic $Co_{50}Ni_{50}/Pt$ nanodots has been studied. These dots, with a diameter of 90 nm, are arranged in a hexagonal pattern with a periodicity of 300 nm. Field-dependent magnetic force microscopy was used to measure the switching field distribution of the array, which was found to range from 80 to 192 kA/m, a value which is confirmed by vibrating sample magnetometer measurements. Additionally, the temperature dependence on the collective behaviour of the switching fields of the array has been investigated. The energy barrier at zero field was estimated to have a value in between 1.8×10^{-19} and 2.1×10^{-19} J. Combining this value with the effective anisotropy determined by torque measurements, the switching volume can be estimated to lie in between 1.2×10^{3} and 1.4×10^{3} nm^3.

1 Introduction

Nanosized magnetic periodic structures have become of interest in both fundamental science and potential technological applications, such as ultra-high density information storage devices like MRAM or Probe Recording (Haginoya et al. 1999). Magnetic patterned media have been proposed as one alternative to increasing the data storage density (Albrecht et al. 2002). However, the reduction in size of such elements turns them thermally unstable. In the same way, when sizing down the patterns, it appears difficult to produce perfectly regular, identical elements. This problem specially arises because etching techniques become more critical when realising very small structures (Haast et al. 1998). As a result, there is an inhomogeneity in the geometrical shapes of the elements. Additionally there are grain boundaries inside the dots, eventual impurities and damage within the material, which also produce dispersion in the values of the switching field of individual dots (Ferré et al. 2003). When this switching field distribution (SFD) becomes too large, application in information storage becomes problematic.

In this work we present a study on the thermal dependence and distribution of the switching field of arrays of CoNi/Pt multilayered nanodots (see Fig. 1). Those structures have a thickness of 35 nm, which corresponds to 26 bilayers of $Co_{50}Ni_{50}$ and Pt, a diameter of 90 nm and a periodicity (separation from center to center of the dots) of 300 nm: This yields a bit density of 7 Gb/in^2, lower than present hard disks, but sufficient to study the possibilities of an information-storage prototype based on a patterned medium. The dots are fabricated using laser interference lithography and ion beam etching to transfer the pattern from the exposed photoresist to the magnetic film. The temperature dependence of the averaged switching field has been investigated by means of vibrating sample magnetometry (VSM), while the SFD at room temperature has been investigated by VSM and field-dependent magnetic force microscopy (MFM).

2 Experimental methods

A magnetic continuous film was deposited by magnetron sputtering on top of a thermally oxidized silicon wafer. Such a film is compound of 26 bilayers of $Co_{50}Ni_{50}/Pt$. The thickness of each individual layer is 0.5 nm (i.e. 1 nm per bilayer). Both materials were alternately sputtered at an argon plasma pressure of 1.0×10^{-2} mbar and at a constant ionising power of 30 W. The distance between the substrate and each one of the targets was fixed at 10 cm. The resulting film possesses a perpen-

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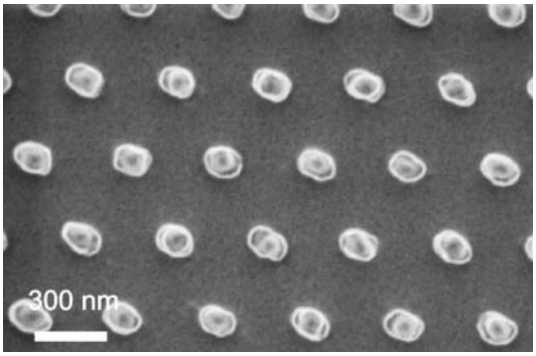

Fig. 1 The SEM top view of *CoNi/Pt multilayered dots* with a diameter of 90 nm arrayed in a *hexagonal grid*

dicular anisotropy due to the contribution of the interfaces. The typical grain diameter of the films is about 10 nm. The unpatterned (CoNi/Pt)×26 film has a saturation magnetization of 1,077 kA/m, with a coercivity of 7 kA/m and a perpendicular anisotropy of about 150 kJ/m^3, obtained by torque measurement. On top of the magnetic film a diluted positive photoresist was spin-coated, and subsequently baked at 95°C by 5 min. The final photoresist thickness is 200 nm.

The exposure of the photoresist on top of the magnetic film was carried out with a laser interference set-up. In this set-up a 266 nm quadrupled Nd:YAG laser beam is projected onto a Lloyd's mirror and the resulting periodic fringe interference pattern with a periodicity of 300 nm is used for the exposure. By rotating the sample at an angle of 60° and performing a second exposure, we obtain after development an array of dots aligned in a hexagonal pattern.

Using the photoresist as a mask, the pattern is transferred onto the magnetic film. For this, the sample is exposed to an argon ion beam by 8 min at an angle of 0° with respect to the film surface's normal. The beam voltage is fixed at 500 V and the acceleration voltage at 100 V at an argon pressure of 3×10^{-4} mbar, which yields an ion current density of approximately 0.26 mA/cm^2. After the etching step, the remaining photoresist is stripped off using acetone in an ultrasonic bath for 3 h at 50°C. The resulting magnetic dots have a diameter of 90 nm with spacing between the dots centres of 346 nm. The dots displayed in Fig. 1 present slightly elliptical shapes. Besides that they have irregularities in their contours due to the ion beam etching conditions used in the fabrication process (Murillo et al. 2005).

Using VSM, the hysteresis loops of the array of dots were measured at different temperatures, ranging from 175 to 500 K. Each coercivity value is an average of 20 measurements. Additionally, a MFM operating in vacuum (10^{-7} mbar), which improves its sensitivity, was used to image the array of dots while applying an external magnetic field ranging from −1,353 to 192 kA/m. An example is shown in Fig. 2.

3 Results and discussion

The switching mechanism of a magnetically anisotropic particle can be described as a process in which, starting from one equilibrium state of magnetization, it is necessary to overcome an energy barrier to bring the particle into another equilibrium state of magnetization. The origin and characteristics of the energy barrier are a property of the material, but its magnitude depends on external variables, which can be experimentally controlled such as a magnetic field. In general, the energy barrier of a particle (or a group of weakly interacting particles) with uniaxial constant anisotropy is described by the following expression (Sharrock 1994):

$$\Delta E = U\left(\frac{1-H}{H_0}\right)^n, \qquad (1)$$

where U is the energy barrier at zero applied field, H is the applied field and H_0 is the field needed at zero temperature to overcome the barrier. The value of n depends on the switching mechanism within the system, $n=1$ for weak domain-wall pinning (Gaunt 1986; Chui (1997), $n=3/2$ in the case of an ensemble of particles with a Lorentzian switching-field distribution and coherent magnetization rotation (Victora 1989), and $n=2$ for single domain particles with constant uniaxial anisotropy with the external field applied along the easy axis of magnetization and antiparallel to the magnetization (Stoner and Wohlfarth 1948).

The switching probability as a function of the energy barrier and the temperature can be phenomenologically described by the Arrhenius relation (Brown 1963),

$$r = f_0 \exp\frac{-\Delta E}{kT}, \qquad (2)$$

where r is the switching probability per unit time, f_0 is the thermal attempt frequency, commonly assumed to be 10^9 s^{-1}, ΔE is the energy barrier, k is the Boltzmann's constant, and T is the temperature.

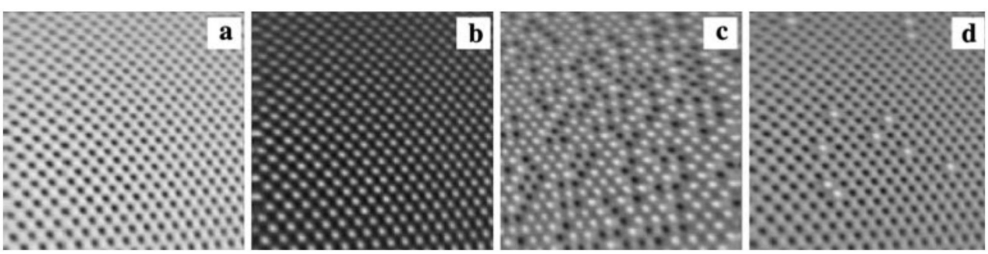

Fig. 2 Magnetic force microscopy (*MFM*) images of a patterned CoNi/Pt after application of −1,350, +4, +127, and +183 kA/m

In the case of a set of uniaxial particles it is possible to define the coercivity as the applied field at which the probability of being already switched after a time t is 1/2 (i.e. $rt = 1/2$).

Combining Eqs. 1 and 2 and using the definition above it is possible to express the coercivity as

$$H_c(t,T) = H_0\left(1 - \left(\frac{kT}{U}\ln(2f_0t)\right)^{1/n}\right). \quad (3)$$

The temperature dependence of the switching field for the array of dots is shown in Fig. 3. The experimental data was fitted to Eq. 3 by using the three different values of n related to the different switching mechanisms, and a value of $f_0t = 10^9$. These fitted curves are also displayed in Fig. 3. However, based solely on this information it is not possible to determine which is the most suitable value for n, since on the range of temperatures studied the three functions behave very similar. From the fits, the values for H_0 and U were estimated for $n = 1$, 3/2 and 2, and listed in Table 1. U, the energy barrier at zero field, can be written as $K_{\mathrm{eff}}V_{\mathrm{s}}$, where V_{s} is the switching volume. By using the value of the effective anisotropy, determined by torque measurements (Meng et al.1996), as 150 kJ/m^3, it is possible to estimate the values of the switching volumes, which are also displayed in Table 1.

Using a MFM, a series of measurements were made to study the reversal of the individual dots. For each measurement the field was increased to a certain value and taken back to zero. All the images were made over the same area of the sample covering a surface of about 5.5×5.5 μm^2, which contains a total of 365 dots. The first image in Fig. 2 shows the magnetization after applying −1,353 kA/m perpendicular to the sample. The tip and the medium are saturated in the same direction so only attractive forces occur (black dots). When the field is increased to +4 kA/m, the tip reverses magnetization and all forces become repulsive, so the contrast reverses (white dots). At 127 kA/m almost 50% of the dots are reversed (Fig. 2c) and at 183 kA/m almost all dots are reversed (Fig. 2d). The first dots switch already at 80 kA/m, but the last at 192 kA/m. The graph on Fig. 4 shows the relative remanent magnetization of the array of dots as a function of the applied field. Figure 5 shows a histogram of the fraction increment of switched dots after applying a new field. It is possible to approximate the

Table 1 Estimated values for the switching field (H_0), energy barrier (U) and switching volume at zero temperature (V_s) for the different values n

Value of n	H_0 (kA/m)	U (J)	V_s (nm^3)
1	246.9	1.8×10^{-19}	1.2×10^3
3/2	307.9	2.0×10^{-19}	1.3×10^3
2	368.8	2.1×10^{-19}	1.4×10^3

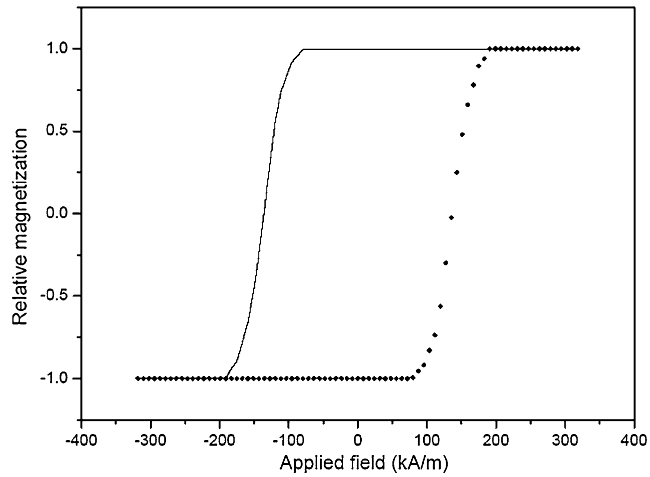

Fig. 4 Remanence hysteresis loop obtained by MFM (the *dots* are the measured values, the *continuous line* is just a mirror reflection of the experimental data)

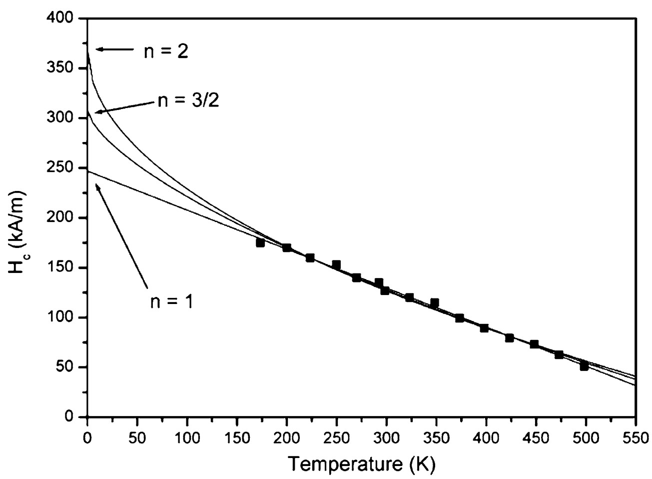

Fig. 3 Temperature dependence of the coercivity in the *array of dots*. Three different fittings for the experimental data are shown, by using different values of n

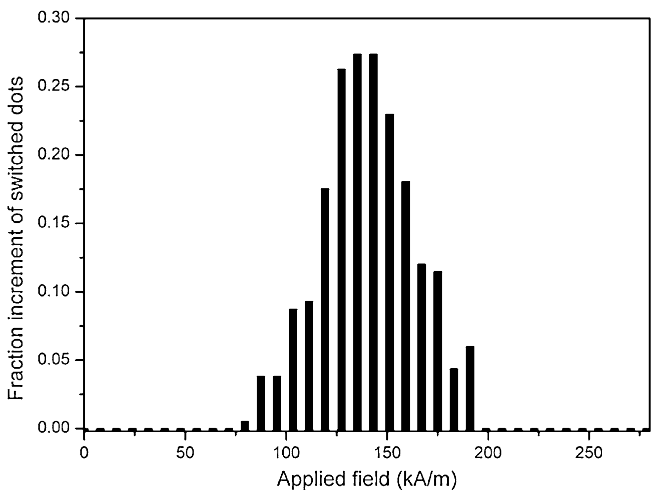

Fig. 5 *Histogram* showing the fraction increment of the switched dots after applying a new external field

dispersion in the switching field value of the dots with a Lorentzian distribution. This could suggest that the switching mechanism can best be represented by $n = 3/2$. However, the dots are still relatively large, and most likely switch incoherently. Clearly, further thermal-dependent measurements at lower temperatures are needed.

4 Conclusions

Different temperature dependent VSM measurements ranging from 175 to 500 K were made on hexagonal arrays of dots with perpendicular anisotorpy. By using Sharrock's equation the energy barrier at zero field was estimated to lie in between 1.8×10^{-19} and 2.1×10^{-19} J. Using the former result and the value of effective anisotropy determined by torque- and VSM measurements, the switching volume was estimated to lie between 1.2×10^{3} and 1.4×10^{3} nm^{3}. This volume is comparable to the size of the grains observed in the film. It has been shown that the individual dots in the patterned medium switch in a field range from 80 to 192 kA/m. The presence of grain boundaries in the dots and their edge roughness are thought to be the origin of the large SFD.

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