High-Frequency Effects in Perpendicular Recording Media

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We investigated switching speed effects in perpendicular media, using micromagnetic simulations. Hysteresis loop calculations show that for field sweep rates greater than 2×10^{13} Oe/s the measured coercivity increases sharply. The switching speed of individual grains was calculated as 18 ps to 38 ps, with a strong dependence upon the medium thickness and the magnetisation state of surrounding grains. A simulation of recording over a range of frequencies determined that writing of bits at data rates of up to 5 Gbit/s in media thicknesses of up to 180 Å is possible before loss of output occurs.

Key Words: switching speed, perpendicular media, time dependence

1. Introduction

A finite time is required for the magnetic moment of a grain to be reversed, therefore an upper limit to the frequency at which data can be recorded exists. With data rates approaching 1 Gigabit per second (Gb/s) an understanding of high frequency phenomena in recording media is necessary. Previous studies have been mainly concerned with longitudinal media.¹⁻⁴⁾ Experimental measurements of switching speeds in longitudinal NiFe films⁵⁾ and Pt/Co multilayers with perpendicular anisotropy⁶⁾ show that magnetisation reversal times of less than 100 picoseconds (ps) can be attained if the switching field rise time is of the order of 1 ps. In this paper the results of three sets of simulations examining phenomena related to high frequency magnetic switching in perpendicular media will be discussed: field sweep rate dependence of coercivity, switching time of individual grains and the effect of recording at high frequencies.

2. Simulations

Simulations were carried out using a micromagnetic model based on the Landau-Lifshitz-Gilbert equation. The saturation magnetisation, M_s , of 300 emu/cc, uniaxial anisotropy, K_u , of 1×10^6 erg/cc, oriented perpendicular to the film plane, and damping constant, α , of 0.05 were the same in all simulations. Thermal fluctuations were introduced by means of random field terms added to the effective field at each time step. For the hysteresis loop simulations the magnetisation of each grain was represented by one moment, i.e. the magnetic cell size was the same as the grain size. For the other simulations each

grain was subdivided into several cells each with its own magnetic moment. The other parameters for each of the three sets of simulations are shown in table 1.

Table 1 Parameters used in the simulations

Hysteresis loops at various sweep rates			
Time step	0.568 ps	Temperature	300 K
Exchange constant	Zero to 1×10^{-6} erg/cm		
Cell size (grain size)	$100 \text{ \AA} \times 100 \text{ \AA} \times 300 \text{ \AA}$		
Field sweep rate	3.5×10^{10} to 3.5×10^{14} Oe/s		
Individual grain reversal time			
Time step	0.0114 ps	Temperature	0.1 K
Exchange constant	Zero between grains 1×10^{-6} erg/cm in grains		
Cell size	$14 \text{ \AA} \times 14 \text{ \AA} \times 14 \text{ \AA}$		
Grain size (d=length)	$98 \text{ \AA} \times 98 \text{ \AA} \times d \text{ \AA}$		
Grain length, d	56 \AA to 504 \AA		
Recording of tracks at various frequencies			
Time step	0.284 ps	Temperature	300 K
Exchange constant	Zero between grains 1×10^{-6} erg/cm in grains		
Cell size	$100 \text{ \AA} \times 100 \text{ \AA} \times 60 \text{ \AA}$		
Grain size (d=length)	$100 \text{ \AA} \times 100 \text{ \AA} \times d \text{ \AA}$		
Medium thickness, d	60 \AA to 300 \AA		
Head dimensions	Width 2100 \AA Length 700 \AA		
Head-disc spacing	200 \AA		

3. Results

Hysteresis loops were calculated for constant applied field sweep rates i.e. the applied field was incremented by a fixed amount at each time step. Fig. 1 shows the calculated coercivities versus sweep rate for media with a range of exchange coupling constants, A . To analyse the results we define granular media as those with exchange coupling constants from zero to 5×10^{-8} erg/cm and exchange coupled media as having A values from 5×10^{-7} erg/cm to 1×10^{-6} erg/cm.

At low sweep rates the coercivity of the exchange coupled media is less than that of the granular media, which is in accordance with experimental measurements. The coercivity of the granular media is close to H_k ($2K_u/M_s$), or 6.66 kOe at low sweep rates. The exchange coupled media show a much larger variation of H_c with sweep rate than the granular media for sweep rates of up

Fig. 1 Effect of field sweep rate on coercivity for various exchange coupling constants.

to 2×10^{13} Oe/s. This is because the exchange coupling leads to cooperative reversal and square hysteresis loops, whereas the granular media have sheared hysteresis loops with a slope of $1/4\pi M_s$. This makes the exchange coupled media more susceptible to thermal fluctuations in the vicinity of H_c , resulting in a larger sweep rate dependence of H_c . For sweep rates in excess of 2×10^{13} Oe/s we find a sharp increase in H_c for all media. This increase is due to the switching speed of the media rather than a result of thermal fluctuations of magnetisation. Over this range of sweep rates the difference in coercivity among the media is small with the exchange coupled media having the highest coercivity.

In the hysteresis loop calculations the applied field has a triangle waveform with time with a slope equal to the sweep rate, R . For each sweep rate we calculated the time required for the applied field to reach $H_c(R)$, $t(H_c(R))$, this is plotted in fig. 2. The write frequency ($1/2t(H_c(R))$) is also shown. Despite the steep increase in H_c for sweep rates larger than 2×10^{13} Oe/s, the time required for the applied field to reach H_c continues to decrease even as the sweep rate increases further. If we assume a maximum head field of around 20 kOe then the maximum write frequency for a head field with a triangle waveform is approximately 10 Gbit/s.

Simulations of the reversal of individual grains were carried out using a small time step to improve accuracy and also because the exchange coupling field increases rapidly as the size of the cells in the model is decreased. An array of nine grains magnetised in three initial configurations as shown in fig. 3 was investigated. The grains were discretised into cubic cells and the length of the grains was varied by adding extra cubes. A 9 kOe field was applied to the centre grain only, indicated by the 'X' in the fig. and the switching time of that grain calculated. We define the switching time as that required for the magnetisation to change from +90% of M_s to -90% of M_s .

Fig. 2 Time for applied field to reach H_c versus applied field sweep rate. The equivalent write frequency is also shown.

Fig. 3 Magnetisation configuration of grains prior to application of a pulsed field.

The results of the switching time simulations for the three configurations are shown in fig. 4. For the saturated case (fig. 3(a)) the switching time is proportional to the medium thickness, or length of the grain. This implies slower reversal in thicker media. The grain magnetisation reverses in 18 ps to 25 ps, depending upon the length. For cases (b) and (c) in fig. 3 the switching times are somewhat longer, with the reversed case being the slowest. The magnetostatic fields in the reversed case favour the initial configuration and oppose reversal of the centre particle.

Fig. 4 Switching speeds for grains subjected to a 9 kOe pulsed field. The surrounding grains are magnetised as shown in Fig. 3.

The results shown in fig. 4 were calculated at a temperature of 0.1 K to make it easy to determine accurately the reversal times. If the temperature is increased the switching times become distributed about the values shown in the fig., but the average value remains the same. If the definition of switching time is changed to +99% to -99% of M_s , the switching times for a 504 Å long grain increase to 60 ps, 92 ps and 144 ps for the saturated, chessboard and reversed cases respectively.

Hysteresis loops of the centre grain are shown in fig. 5 for the saturated and reversed cases. The magnetostatic field of the surrounding grains has the effect of shifting the hysteresis loops and increasing the coercivity to around 9 kOe on one side of the loop.

Fig. 5 Hysteresis loops of the centre grain with the surrounding grains in the reversed and saturated configurations of Fig. 3.

Fig. 6. shows the rate of magnetisation switching, dM/dt , versus time for the 504 Å long grains. The external field is applied at $t = 11.4$ ps, after which there is a latent time before reversal begins. This latent time increases with medium thickness and also depends upon the state of magnetisation of the surrounding grains, but the switching always takes place in the order shown in the fig. Raising the temperature of the grains reduces the latent time and the order in which the grains switch is randomised. The peak value of dM/dt is always greatest

Fig. 6 dM/dt (divided by M_s) versus time for the 504 Å long grains. The field is applied at $t = 11.4$ ps.

for the saturated case and lowest for the reversed case, although these values converge as the medium thickness increases.

Fig. 7 shows the z component of magnetisation (along the grain major axis (504 Å long grains)), M_z , for the saturated and reversed cases at various times during the switching process. The time interval between each curve is not constant. For the saturated case (fig. 7, left) the reversal process is initiated by rotation of the magnetic moment at both ends of the grain. The magnetisation at the top and bottom of the grain always leads the magnetisation in the centre during the reversal process. In the reversed case, magnetisation reversal is again initiated at the ends of the grain, as in the saturated case, although in the reversed case the lag between the magnetisation in the centre of the grain and at the ends is much less. When M_z becomes less than $-0.5 M_s$, the magnetisation in the centre of the grain takes the lead over that at the ends and continues to lead until saturation.

Fig. 7 Z component of magnetisation with depth in the centre grains of figs. 3(a) and 3(c) during the switching process. Left: saturated case, right: reversed case. The time is increasing from the top to the bottom of the figures although the contours are not equally spaced in time. Grains are 504 Å long.

Recording simulations in media with thicknesses from 60 Å to 300 Å were carried out to determine the effect of high frequency recording on media performance. The media were composed of cells with a thickness of 60 Å and the media thickness was varied by adding extra layers of cells. The exchange coupling constant between adjacent layers was 1×10^{-6} erg/cm, and zero between cells in the film plane. This represents a granular medium with the number of cells in each grain varying according to the film thickness. The simulated media covered an area of $2 \mu\text{m} \times 0.6 \mu\text{m}$ with cyclical boundary conditions. Recording was implemented by assuming an unshielded single pole head made of iron. Since each grain of the thicker (>60 Å) media was subdivided into two or more magnetic cells the head field varied through the media thickness as shown in fig. 8. The head field in the upper layer of the media (nearest to the head) was about 6.4 kOe

and dropped to 3.8 kOe in the lower layer of the 300 Å thick media. The writing frequency was varied by altering the head-media velocity whilst keeping the linear density at a constant 254 kfc/i.

Fig. 8 Peak vertical head field in media, H_z , with distance from head for recording simulations. The points indicate the centres of the cells forming the grains of the media, the vertical lines indicate the boundaries of the cells.

Two tracks for 60 Å and 300 Å thick media are shown in fig. 9, written at a frequency of 1.76 Gbit/s. In the 300 Å medium the track width is reduced compared with the 60 Å medium. Also, within the bits there are many reversed grains which are not present in the thin medium. The number of these reversed grains increases with medium thickness and leads to a loss of output. The reversed grains are not distributed uniformly throughout the written bits but tend to be concentrated in the centre of the bits where the magnetostatic field is a maximum.

60 Å media

300 Å media

Fig. 9 Written tracks for media with thicknesses of 60 Å and 300 Å. Depicted area = $0.6 \mu\text{m} \times 2 \mu\text{m}$. Write frequency = 1.76 Gbit/s. The head moves from left to right.

The output was calculated by considering the average magnetisation of the bits and is shown in fig. 10. As both the writing frequency and medium thickness increase the output decreases. For the single layer 60 Å medium the output is stable up to frequencies of 10 Gbit/s. For thicker media the decrease in output begins at lower frequencies. However, for frequencies up to 5 Gbit/s the difference in output between media of 60 Å and 180 Å thickness is small. The output decreases to zero at around 30 Gbit/s which corresponds to a switching time of about 33 ps, in good agreement with the switching times for single grains calculated in the previous section.

Fig. 10 Output versus write frequency for various media thicknesses.

4. Conclusions

The switching speed of individual grains was found to be as fast as 18ps in a thin, 56Å medium. Recording simulations show that a perpendicular medium of up to 180Å thickness can be written to at frequencies of up to 5 Gbit/s without a significant loss of output. This assumes a square wave head field, the output is likely to decrease further as the rise time of the head field increases.

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