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ABSTRACT
The selective switching of dual-structure magnetic dots under the influence of the stray field from a spin torque oscillator was investigated. A configuration was found which allowed selective switching of either structure when subject to ac magnetic fields oscillating at 9 GHz and 20 GHz. No other external magnetic fields were needed to switch the magnetisation of the structures.

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I. INTRODUCTION

Microwave-assisted magnetic recording (MAMR) makes use of high frequency (HF) magnetic fields which, when oscillating at, or near, the resonance frequency of a magnetic material, reduce the switching field of the magnetic material. When the HF field is applied in conjunction with the field from a write head magnetic grains with much higher uniaxial anisotropy, \( K_u \), can be switched than when using the head field alone.

The HF field is usually generated by a spin torque oscillator (STO). However, it is difficult to obtain stable STO oscillation when the STO is integrated into a write head due to the large fields acting on the STO. In some cases it is possible to switch the magnetisation of a recording medium or magnetic dot using only the field from the STO and with no other external field sources. This is true even if the coercivity or switching field of the magnetic dot is much higher than the strength of the HF field from the STO. The sense of rotation of the HF field, or chirality, determines the direction of magnetisation switching, e.g., from up to down, or vice-versa, and this can be controlled by the direction in which the current flows through the device.

Another advantage of MAMR is the ability to record on media or dots with multiple recording structures. If each structure has a different ferromagnetic resonance frequency the magnetisation of each structure can be switched independently. For media or dots with two structures this theoretically allows the recording density to be doubled. In this work we investigate the possibility of selective recording on dual structure magnetic dots using only the field from a STO. No write head or any other external applied fields were used.

II. THE MODEL

A simplified model of a spin torque oscillator consisting of just a field generating layer (FGL) was used in this work. The FGL was modelled as a uniformly-magnetised cuboid with a thickness \( z \) of 10 nm and in-plane \( x, y \) dimensions of 20 nm \( \times \) 20 nm. The FGL had \( M_s \) of 1591 emu/cm\(^3\) and the magnetisation was assumed to rotate in the \( x-y \) plane at a constant angular velocity. The stray field arising from the FGL was calculated underneath the FGL and varied as a function of position and time.
were used.\textsuperscript{12,13} These comprised of magnetically hard and soft layers exchange coupled together with a strength of 5 $\times$ 10\textsuperscript{-7} erg/cm. The Landau-Lifshitz-Gilbert damping constant, $\alpha$, was 0.02 for all structures.

The switching probability of the structures was calculated at a temperature of 300 K. At the start of the simulations the magnetisation of the structures was pointing up ($\vec{M}$ along the positive z axis). After waiting for 0.25 ns in zero field the STO was turned on for 2 ns. Once the STO was turned off the simulation continued in zero field for a further 1 ns after which time the magnetisation of the structures was evaluated. The main variables were the frequency of the HF field, the spacing between the structures and the STO ($dz$), and the uniaxial anisotropy of the structures. The switching probabilities given here were evaluated after 100 trials.

III. SINGLE STRUCTURE DOTS

First the switching of single structures was investigated. The HF field from the STO decreased rapidly with distance from the STO surface. The structure nearest to the STO (RL2) experienced higher HF fields and should therefore have higher $K_u$ than the structure further away from the STO (RL1). If two recording structures are to be switched by the same STO both structures should be as thin as possible. However, a minimum structure thickness of 3 nm was imposed in order that thermally stable structures could be realised using realistic values of $K_u$.

Fig. 1 shows the switching probabilities of single phase structures with various values of $K_u$ where the spacing between the STO and the structures was 1 nm. Switching probabilities of 1 were achieved for $K_u$ values from 4.6 $\times$ 10\textsuperscript{6} erg/cm\textsuperscript{3} to 8.1 $\times$ 10\textsuperscript{6} erg/cm\textsuperscript{3}. The switching probability curves shifted to higher STO frequencies as $K_u$ increased as the resonance frequency of a single phase structure is proportional to the anisotropy field $H_k$.

For selective switching of two structures to be possible the left edge of the switching probability curve for RL2 should reach zero at a sufficiently high STO frequency, e.g., 10 GHz. Fig. 1 shows that to achieve this condition $K_u$ should be at least 7.1 $\times$ 10\textsuperscript{6} erg/cm\textsuperscript{3}. A design for RL1 is then needed which switches at a STO frequency below 10 GHz.

Fig. 2 shows the effect of the spacing between the STO and the recording structure on the switching probability when $K_u$ was 6.6 $\times$ 10\textsuperscript{6} erg/cm\textsuperscript{3}. The switching probability dropped below 1 once $dz$ exceeded 3 nm. Given the minimum structure thickness of 3 nm and a minimum spacing between structures of 1 nm, the smallest possible value of $dz$ for the structure furthest from the STO (RL1) is 5 nm. The switching probability could be increased by reducing $K_u$, e.g., the switching probability was 1 at 8 GHz when $dz = 5$ nm and $K_u = 4.6 \times 10^6$ erg/cm\textsuperscript{3}, but a more flexible approach is to use an ECC structure for RL1.

Fig. 3 shows switching probabilities of single phase and ECC structures for $dz = 6$ nm and hard layer $K_u$ of 6.1 $\times$ 10\textsuperscript{6} erg/cm\textsuperscript{3}. Adding a soft layer with $K_u$ of 1 $\times$ 10\textsuperscript{7} erg/cm\textsuperscript{3} and a thickness of 2 nm, or more, shifted the switching probability curves to lower STO frequencies whilst maintaining a maximum switching probability of 1. The right edges of the switching probability curves for soft layer thicknesses of 2 nm and 3 nm reached zero at a frequency of around 15 GHz. This can be below the peak in the switching probability curve of RL2 if RL2 has $K_u$ of 7.6 $\times$ 10\textsuperscript{6} erg/cm\textsuperscript{3}, or more.

IV. DUAL-STRUCTURE DOTS

Based on the results in section III the two structure design shown in Fig. 4 was adopted. RL1 had an ECC structure with a 3 nm thick hard layer and 2 nm soft layer. The spacing between the two structures was 2 nm.

Fig. 5(a) shows hysteresis loops of a dual structure dot calculated at 4.2 K and 300 K. The loops show that the magnetisation...
of the two recording structures reversed independently at distinctly different applied fields, both at low temperature and at room temperature. Fig. 5(b) shows the magnitude of the in-plane component of the HF field from the STO at various distances from the STO surface. The fields shown were those at the centre of the dot and at the edge of the dot (10 nm from the centre), and were much smaller than the switching fields indicated by the hysteresis loops in Fig. 5(a).

The switching probabilities of RL1 and RL2 in a dual-structure dot as a function of the STO frequency are shown in Fig. 6. In this calculation the magnetisation of the two structures was initially parallel. The thin lines show the switching probabilities for single structure dots whilst the bold lines and points are the results for a dual-structure dot. Compared with the single structure dots the switching probability curves of the dual-structure dot were narrower and the maximum switching probability decreased from 1 to 0.97 for RL1 and to 0.95 for RL2. The reduction was a consequence of the magnetostatic interaction between the two recording structures which favoured the initial, parallel magnetisation alignment.

Fig. 6 shows that for a dual-structure dot the maximum switching probabilities for RL1 and RL2 occurred at STO frequencies of 9 GHz and 20 GHz, respectively. Fig. 7 shows some typical magnetisation dynamics for RL1 and RL2 under HF fields at these frequencies. When the HF field was turned on the magnetisation of the target structure decreased and began to oscillate around $M_z = 0$ after about 0.5 ns. Subsequently the magnetisation gradually became increasingly negative over the following 0.5 - 1 ns. The magnetisation of the non-target structure was slightly disturbed by the HF field in both cases but no correlation between the oscillation of the magnetisation of the two structures was observed. As can be seen in Fig. 7, the oscillation frequencies of the two structures when subjected to the same HF field were quite different.

Magnetisation reversal took place via domain wall nucleation and motion. In addition to lateral motion of the domain wall, which was responsible for the magnetisation oscillations shown in Fig. 7, the domain wall also rotated multiple times during the reversal process. The speed of rotation was not constant, but the average frequency of rotation was about 12 GHz for RL1 when the HF field frequency was 9 GHz. For RL2 the domain wall rotation frequency was about 22 GHz for a 20 GHz HF field.
The effect of the HF field pulse duration was examined, varying the pulse length from 0.5 ns to 4 ns. Fig. 8 shows the results. For pulse durations of less than 2 ns the switching probabilities decreased rapidly. For pulses longer than 2 ns the maximum switching probability slowly increased, reaching 1 for a pulse length of 4 ns. As the pulse length increased the probability of RL1 switching at higher STO frequencies also increased. For example, when the STO frequency was 15 GHz the switching probability of RL1 increased from zero to 0.03 when the pulse length was extended from 2 ns to 4 ns.

In a storage system the switching error rate (SER) determines the ultimate capacity of the system. The SER of RL1 and RL2 at 9 GHz and 20 GHz was calculated for 1000 trials using 4 ns pulses. The SER was 0.001 for RL1 and 0.01 for RL2. Thus, the capacity of a system of N dots would be 0.99N for RL1 and 0.92N for RL2.

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