Heat Assisted Recording Using Electron Beams

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Simulations of heat assisted recording using electron beams as a heat source were carried out. A heat flow model was combined with a micromagnetic model to calculate the recording process. The influence of underlayers on the thermal properties of the system is discussed. The results demonstrate the feasibility of heating a medium sufficiently using a low power electron beam source, allowing the use of materials with a higher uniaxial anisotropy. Additional heating of the recording layer may be achieved by patterning the medium into discrete tracks, providing access to materials with Curie temperatures of around 600 K.

Key words: heat assisted magnetic recording, perpendicular media, electron beam

1. Introduction

In order to reduce transition jitter, ultra high density recording at areal densities of several hundred gigabits per square inch (Gb/in²) requires the use of media with grain diameters less than 8 nm. To ensure thermal stability the uniaxial anisotropy K_u of the grains should be large, but the maximum usable value of K_u is limited by the recording fields which can be generated by a write head ¹⁾. To enable the use of materials with higher K_u heat assisted recording has been proposed ²⁾. Usually the heat source is electromagnetic ³⁾, however, an alternative method of heating is to use electron beams, generated from a sharp, metallic tip ^{4,5)}. The electron beam power in practical applications is limited by the physical characteristics of the tip, which may be damaged by excessive current flow. The electron beam power is unlikely to exceed 1 mW, however beam diameters of around 15 nm are attainable, which should prove advantageous at ultra high recording densities. This paper presents the results of simulations of heat assisted recording using electron beams. The effect of the thermal properties of the recording layer and underlayers on the signal to noise ratio (SNR) of recorded tracks was investigated.

2. The Model

Electron beams were assumed to be generated from a sharp tip and accelerated by a potential difference between the tip and the recording medium. The energy of the electrons was assumed to be too low to cause ionisation of the atoms in the recording layer, making all collisions elastic. The mean free path of the electrons determined the distribution of heating in the recording layer (RL) and this was calculated from kinetic theory. The electron density n_e of a solid is given by

$$n_e = \frac{N_a \rho}{M_a} n_f \quad (1)$$

where N_a is Avogadro's number, ρ the density of the recording layer, M_a the atomic mass and n_f the number of free electrons per atom. The Fermi energy is given by

$$E_f = \frac{h^2}{8m\pi^2} (3\pi^2 n_e)^{2/3} \quad (2)$$

where h is Planck's constant and m the electron mass. The mean free path λ is then calculated using

$$\lambda = \frac{\sigma m V_f}{n_e e^2} \quad (3)$$

in which σ is the conductivity, e the electron charge and V_f the Fermi velocity, which is

$$V_f = \sqrt{\frac{2E_f}{m}} \quad (4)$$

For cobalt, which often forms the bulk of a recording layer the mean free path was calculated to be 6.62 nm (assuming $n_f = 2$). For iron, the mean free path was 4.26 nm. Projected recording layer thicknesses for media able to support areal densities of 500 Gbit/in² range from 9 nm to 15 nm, this means that the majority of the electron beam energy will be transferred to the recording layer and very little direct heating of the underlayers will occur.

The electron beam intensity over the surface of the recording layer was assumed to fall off with distance from the beam centre according to a Gaussian distribution function. The beam radius was defined as the distance from the beam centre where the beam intensity fell to one half of its maximum value. The time variation of temperature was calculated by discretising the recording layer and underlayers into cuboid cells of size $2 \text{ nm} \times 2 \text{ nm} \times d \text{ nm}$, where d was the layer thickness. The specific heat capacity and thermal conductivity of each cell could be set independently. The electron beam intensity was calculated at the top and bottom surfaces of each layer and the energy transferred to the layer was assumed to be proportional to the change in intensity through the layer, assuming no reflection of electrons at the layer interfaces. A typical model included a minimum of a recording layer (RL), sandwiched by a glass substrate and an air layer. Various combinations of underlayers were placed between the recording layer and glass substrate, as required.

The change in temperature, dT , of cell i due to neighbouring cells j arising from heat conduction was

calculated using

$$dT = \frac{dt}{C_i V_i} \sum_j \frac{K_{ij} A_{ij} (T_j - T_i)}{L_{ij}} \quad (5)$$

where K_{ij} is the thermal conductivity between cells i and j , A_{ij} their common surface area and L_{ij} their centre-centre distance. C , V and T represent the specific heat capacity, volume and temperature respectively and dt is the time step.

A micro-magnetic model was used to simulate the magnetic recording process. In a real medium the recording layer grains are irregular and were modeled using Voronoi cells⁶⁾. The magnetisation of the recording layer grains was determined by the Landau-Lifshitz-Gilbert (LLG) equation, which included a random field term to represent the effect of thermal fluctuations. The heat flow and micro-magnetic models were synchronised, with the temperatures of the recording layer grains being updated from the heat flow model after every LLG time step (0.5 ps). The temperature dependence of K_u was calculated using

$$K_u(T) = K_u(T_r) \left(\frac{\cosh(\chi) - \cosh(\chi T/T_c)}{\cosh(\chi) - \cosh(\chi T_r/T_c)} \right) \quad (6)$$

where T_r is the room temperature (300 K), T_c the Curie temperature (500 K) and χ a constant that controls the variation of K_u with T . The choice of χ is somewhat arbitrary and mainly determines the rate of change of K_u with T near to the Curie temperature. In these simulations $\chi = 10$, giving a temperature dependence of K_u similar to the experimental data shown in Ref. 7.

3. Results

Initial simulations used a static electron beam and a glass / 9 nm RL / air structure. The recording layer was assumed to be a (Co₉₀Cr₁₀)Pt₂₅ alloy with a thermal conductivity of 0.92 W/cmK and a specific heat capacity of 3.42 J/cm³K. Prerequisites for a heat assisted recording system are a rapid heating time, to allow for high data rates, and localised heating to avoid data loss in adjacent tracks. The diameter of the electron beam was 14 nm and the maximum temperature of the recording layer was monitored during and after heating. Fig. 1 shows the time dependence of the recording layer temperature for various electron beam powers. The electron beam was turned on for 1 ns and then switched off. If the Curie temperature of 500 K is to be reached in 1 ns or less the results show that an electron beam power of around 0.4 mW should be sufficient.

The diameter of the electron beam was also varied to determine the allowable tolerance. For an electron beam power of 0.4 mW the medium could be heated to, or above, the Curie temperature in 1 ns when the electron beam diameter was less than 16.8 nm.

The recording layer thickness was varied from 5 nm to 13 nm and heated by an electron beam of 14 nm diameter and 0.4 mW power. A peak was observed in the maximum recording layer temperature for a

Fig. 1 Temperature of the recording layer vs. time for various electron beam powers. Inset: Maximum temperature after 1 ns.

recording layer thickness of 10 nm. For thicker recording layers a combination of heat conduction in the film plane and higher thermal mass reduced the maximum temperature. Reducing the recording layer thickness below 10 nm allowed an increasing number of electrons to pass through into the substrate and the maximum temperature of the recording layer decreased. The Curie temperature was attained or exceeded for recording layer thicknesses from 7.5 nm to 12.5 nm.

A typical recording medium does not contain only a recording layer, there are also seed/intermediate layers (IL) and, in the case of a perpendicular medium, a thick, soft-magnetic underlayer (UL). These layers are typically metallic alloys with high thermal conductivity. Fig. 2 shows how the number of these layers affects the maximum attainable temperature for a glass / $n \times 9$ nm RL / air structure. The conductivities and specific heat capacities were the same for each of the RL layers. The maximum achievable temperature decreased rapidly as the number of layers increased and was predicted to fall below 400 K for a combined recording layer and underlayer thickness of 37 nm.

Since typical intermediate layer thicknesses are currently in the 10 nm to 20 nm range this result highlights a major difficulty that will be encountered when trying to heat a medium. A possible solution would be to place an intermediate layer material with a low thermal conductivity between the recording layer and the underlayer. The heating simulations were repeated for a glass / 45 nm UL / 4 nm IL / 9 nm RL / air structure. The intermediate layer had a thermal conductivity of 0.01 W/cmK (the same as glass). This arrangement increased the maximum temperature of the recording layer by around 70 K, to 457 K. If the electron beam power were also increased to 0.5 mW the Curie temperature could be attained within 1 ns.

Recording simulations were carried out by moving the electron beam heat source along the medium at a constant velocity of 20 m/s. The electron beam power

Fig. 2 Temperature of the uppermost recording layer vs. time and number of layers. Inset : Maximum recording layer temperature vs. combined recording layer and underlayer thickness.

was 0.5 mW and the beam diameter was 15 nm. An unshielded, single pole head, 80 nm wide and 150 nm long provided the magnetic field to write the tracks. The spacing between the head and the recording layer was 12 nm and the maximum vertical head field in the recording layer was 17.1 kOe. The recording layer had a saturation magnetisation of 500 emu/cm³, intergranular exchange coupling of 1×10^{-7} erg/cm and uniaxial anisotropy, K_u , at room temperature (300 K) from 3×10^6 erg/cm³ to 7×10^6 erg/cm³. The layer structure was glass / 45 nm UL / 4 nm IL / 9 nm RL / air, as described above. The linear recording density was 635 kfc (40 nm bits) and the electron beam was turned on for 1 ns, then turned off for a further 1 ns during the writing of each bit. The centre of the electron beam was coincident with the centre of the write pole.

The effectiveness of thermally assisted recording was investigated by writing tracks with and without thermal assistance in media with various values of K_u . The signal to noise ratio (SNR) of the tracks was calculated from the magnetisation of the recording layer grains over a 60 nm trackwidth. Fig. 3 shows examples of such tracks; the write head started at the bottom of the image and moved upwards. For K_u values of 5×10^6 erg/cm³ and lower the SNR was similar for tracks written with and without thermal assistance. For $K_u = 6 \times 10^6$ erg/cm³ (figs. 3a and 3b) the SNR was 1.8 dB higher when thermal assistance was used. Without heating it was difficult for the head to saturate the medium, this is evident from the number of reversed grains under the write pole at the top of fig. 3a. When K_u reached 7×10^6 erg/cm³ it was impossible to write clear bits using the head field alone, whereas heating the medium reduced K_u sufficiently to allow the head to saturate most of the grains in the recording layer. The difference in SNR was over 11 dB for the tracks shown in figs. 3c and 3d.

Fig. 3 Tracks written with and without thermal assistance in media with different K_u .

In perpendicular recording the transitions are written at the trailing edge of the main pole. This means that if the heat source is located at the centre of the main pole the medium will have cooled down somewhat before it reaches the trailing edge of the main pole. To improve the writing efficiency of the head, the location of the heat source was moved along the down-track axis towards the trailing edge of the main pole. Fig. 4 shows that a significant improvement in the SNR can be expected if the heat source is moved nearer to the trailing edge of the main pole, which is located at $y = -75$ nm in the fig. The optimum SNR was obtained for a heat source offset of around -40 nm. Transition jitter, calculated from 0.1 nm wide microtracks, is also shown in fig. 4 and shows an inverse correlation with SNR.

As the heat source was moved backwards along the down-track axis, the location of the transitions was also shifted backwards, but by less than the shift of the heat source. At the same time, the temperature of the recording layer at the time of writing the transition increased, reaching a maximum of 490 K for a heat source offset of -60 nm. However, this did not coincide with the maximum SNR, where the temperature at the transition at the time of writing was 445 K.

If the recording layer temperature is too high, and K_u too low when a transition is written the transitions will be formed by a head field gradient which is lower than the optimum value, reducing the SNR. This being the case, it is not necessary to heat the medium to its Curie temperature: to reduce K_u such that the anisotropy

Fig. 4 SNR and transition jitter vs. offset of electron beam from centre of main pole.

field, H_k , matches the field at which the head field gradient is a maximum is sufficient. Analysis of the data revealed that the SNR was maximised when the recording layer H_k was slightly less than the effective head field H_{eff} , at the point where the transition was written. The effective head field is given by

$$H_{\text{eff}} = (H_x^2 + H_y^2 + H_z^2)^{1/2} (\cos \theta^{2/3} + \sin \theta^{2/3})^{3/2} \quad (7)$$

where H_x , H_y and H_z are the Cartesian components of the head field and θ is the angle of the resultant head field from the perpendicular. For heat source offsets of -50 nm and -60 nm the recording layer H_k was around 1/3 of H_{eff} , resulting in increased jitter and transition noise.

Finally, the impact of an increased Curie temperature on the recording performance was investigated. The Curie temperature was increased from 500 K to 750 K. This resulted in an almost linear increase in transition jitter and a rapid reduction in SNR. It will be difficult to control the magnetic and thermal properties of the recording layer independently, and the electron beam power is limited to around 0.5 mW. One of the main factors limiting the temperature rise of the recording layer is conduction within the layer itself. The effect of patterning the recording layer into discrete tracks was calculated. In the model the discrete tracks were formed by making 10 nm wide grooves through the depth of the recording layer in the down-track direction. The grooves were given the conductivity and specific heat capacity of air, almost eliminating cross-track heat conduction across the grooves. The spacing between the grooves (the land width) determined the maximum temperature of the recording layer when the land width was sufficiently small.

Heat assisted recording was simulated for a medium with a Curie temperature of 600 K and K_u of 7×10^6 erg/cm³. The width of the land region between the grooves was varied from 80 nm to 300 nm. For a land width of 300 nm the maximum temperature of the recording layer was 500 K. This increased rapidly once the land width became less than 180 nm and reached

(a) Unpatterned

(b) 80 nm land

Fig. 5 Tracks written in media with a Curie temperature of 600 K by heat assisted recording. The grey, vertical bands are the grooves.

555 K for a land width of 80 nm. At the same time the SNR increased from 9.3 dB to 15.6 dB as the anisotropy of the recording layer fell to writable values. The effect of the patterning can clearly be seen in fig. 5. The track written in the unpatterned medium (fig. 5a) was very indistinct. The written bits were made much clearer by patterning the recording layer into discrete tracks, as shown in fig. 5b. Patterning of the recording layer allows the use of materials with Curie temperatures too high to use in a continuous medium.

4. Conclusions

The feasibility of heat assisted magnetic recording with an electron beam heat source was demonstrated using micro magnetic simulations. Recording layer temperatures of around 500 K could be attained in unpatterned media. The use of an interlayer with low thermal conductivity is one way to increase the maximum temperature of the recording layer. Another method is to pattern the recording layer into discrete tracks, or islands. The results also showed that the optimum location for the heat source was near the trailing edge of the magnetic write pole, where the head field gradient was a maximum. To manufacture a durable, integrated write head and heat source will be the main challenge in realising heat assisted recording.

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