Analysis of Data Recovery Techniques for use with Patterned Media Storage

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1. Background

The continued demand for increased storage densities has resulted in unprecedented storage capabilities in today's magnetic hard disc drives. Key to the evolution of magnetic storage has been the continued development and refinement of the recording media and the read/write head. The current belief is that even following the impending move to perpendicular media, which will offer increased storage capacity, current continuous thin film media will be unable to support storage densities in excess of 1Tbit/in^2 due to the advent of thermal stability problems [1]. The use of patterned media is hailed by many as being one approach to overcome the physical limitations of current continuous media and their development as viable storage media is receiving considerable interest in both academia and the storage industry [2].

The overall purpose of this project was to investigate the issue of data recovery from patterned media storage systems. In particular we identified three (abridged) objectives and associated work packages (WP):

WP1: to identify techniques for the recovery of recorded information in storage systems incorporating patterned media by using computer simulations,

WP2: to develop extensive computer simulations of the complex readout processes from such systems,

WP3: to verify theoretical results through analysis of experimental replay signals from sample patterned media to be fabricated in-house.

The work done in completing these objectives and the results demonstrated are outlined in §2.

2. Key Advances and Supporting Methodology

We have successfully developed an accurate three-dimensional (3D) model of the replay process in magnetic systems and a model of a partial-response-maximum-likelihood (PRML) read channel, which have allowed us to investigate read channel designs for patterned magnetic media systems. As such we have satisfied our original project objectives with respect to the theoretical investigation of magnetic patterned media. Our focus shifted more towards the analysis of magnetic systems due to the current drive to commercialise such systems; although the analysis of magneto-optic systems was still part of the project aims. As a result of this shift, it was decided to concentrate solely on the analysis of experimental replay signals in magnetic systems. Our analysis has concentrated on the investigation of perpendicular media with island and head dimensions capable of supporting a storage density of 1Tbit/in^2 (island period 25nm, island length/width 12.5nm, nominal film thickness 10nm, fly height 10nm, and GMR head dimensions of W=20nm , L=4nm , G=6nm in Fig. 1).

The issue of read channel designs for patterned media has been analysed previously by Hughes for 100Gbit/in^2 [3,4] and later 1Tbit/in^2 media [5,6]. Our work differs from this analysis in a number of ways, most notably: by the use of a more accurate 3D replay model of the magnetic readout process which takes into account the shape constrained nature of both the media and the GMR read head; by more accurate modelling of noise contributions in patterned media, such as lithography jitter; by taking into account more realistic signal degradations such as inter-track interference (ITI) in the generation of the replay waveform; by considering the effects of read-head track misregistration (TMR); by using a full channel simulation (Monte Carlo analysis) to more accurately measure the read channel bit-error-rate (BER) performance; by providing a thorough analysis of how the media/island geometry affects the replay waveform properties and channel BER performance; by analysing a PRML read channel incorporating both generalised partial response (GPR) targets and powerful low density parity check (LDPC) error-correcting codes; and finally by identifying media designs which offer improved read channel performance.

i) Readout Modelling (WP2)

We have satisfied our original project objective to develop both magnetic and magneto-optic replay models.

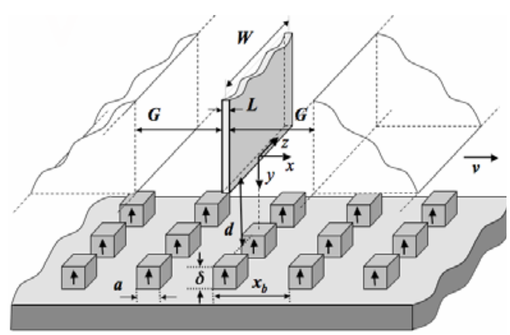

Fig. 1 Replay modelling geometry

In the case of the magnetic replay process, traditional modelling techniques, such as Potter [7] and Ruigrok [8], are based on the reciprocity integral [9]. However, such two-dimensional (2D) approaches fail to take fully into account the geometrical constraints (across and along track) of the read head and the recording medium, as well as including the presence of adjacent tracks. Whilst such models were developed, we recognised the need for a more precise simulation that takes account the 3D nature of the system illustrated in Fig. 1. In light of this, WP2 was expanded to develop an accurate replay model based on the extension of the reciprocity integral to 3D; a full mathematical analysis is presented in [10]. In order to facilitate this model, accurate representations of the potential distribution below the GMR read head were required, these were developed in collaboration with Drs. David Wilton and Hazel Shute of The University of Plymouth, who have developed 3D head field models for perpendicular magnetic recording [11].

The precise 3D replay simulation proved extremely useful in identifying how the media characteristics, such as island shape and size, as well as film thickness and presence of any soft-magnetic-underlayer (SUL) etc, affect the form of the replay pulse, and hence the BER performance of the read channel. An extensive analysis, presented in [10], has shown that the shape of the replay pulse due to an isolated island is strongly dependent upon the media characteristics. In patterned media the track edges contribute significantly to the pulse shape; however, this is not captured by the 2D models. Fig. 2 illustrates simulated pulse responses due to an isolated square island of width 12.5nm. In the case of no SUL, it is clear that the 2D approach severely overestimates the amount of undershoot present in the replay pulse, which will ultimately affect the shape of the replay waveform and the simulated read channel performance. In the no-SUL case, as the island width is increased (for a fixed GMR sensor width *W*) then the amount of undershoot increases, approaching that predicted using 2D techniques for an island width much larger than the GMR sensor width. A similar result was observed as the GMR sensor width was increased for a fixed island width. The minimum undershoot is observed when the island and GMR read sensor element are the same width; however, the pulse width is also at its greatest at this point. Hence, a compromise must be made between the pulse width required and the amount of undershoot that can be tolerated by the read channel electronics. In the SUL case, the 3D approach predicts a narrower pulse (but of similar shape) compared to that produced using 2D approaches.

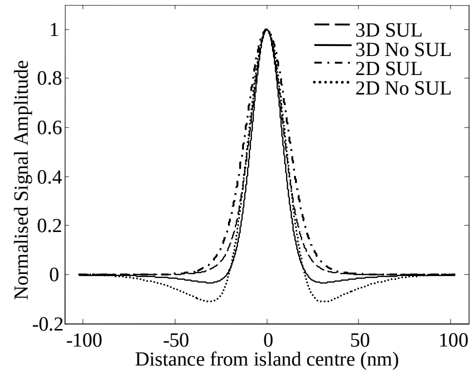

Fig. 2 Simulated pulse responses

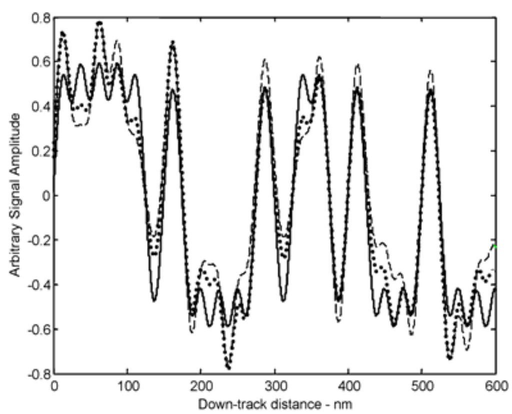

Fig. 3 Replay waveforms for a single track(solid), with ITI (dotted), and with both ITI and 25% track pitch TMR (dashed), using the 3D approach.

The replay waveform due to a track of islands is generated by the superposition of isolated island pulse/step responses. A key benefit of the described 3D model is the ability to include ITI and TMR in the generation of the replay waveform. ITI can be introduced through the linear superposition of three waveforms generated for data along the main data track and data along the two adjacent tracks, each offset from the main track centre by ±track pitch. TMR can be introduced through the addition of a constant track offset [12]. Fig. 3 illustrates the detrimental effect that both ITI and TMR (25% track pitch, 6.25nm) have on the replay waveform for a 1Tbit/in^2 patterned media.

In the case of magneto-optical replay model, our aim was to develop an accurate simulation of the readout process in a near-field system adopting a solid immersion lens (SIL), as illustrated in Fig. 4. Accurate modeling of the interaction of a focused field distribution and the media structure was performed using a finite difference time domain (FDTD) model. Here, the input to the FDTD simulator was the propagating optical field distribution below the flat bottom surface of the SIL, which was calculated using a pseudo-vector diffraction (PVD) replay model [13], modified to permit the analysis of SIL near-field imaging. The choice of the PVD and FDTD models was made to enable accurate modeling in the presence of complex multilayer magnetic structures and to permit the rapid generation of replay signals via the removal of the SIL from the FDTD simulation space. The scattered-field formulation of the FDTD approach permits the incident optical field distribution to be calculated separately (i.e. in the absence of any interaction object) from the FDTD calculation, which speeds up the simulation. The model has been used successfully to analyze the recording light distribution in a SIL-based MAMMOS recording system [14], and has been adapted to permit the generation of replay waveforms from arbitrary disc structures. Fig. 5 illustrates step responses due to a

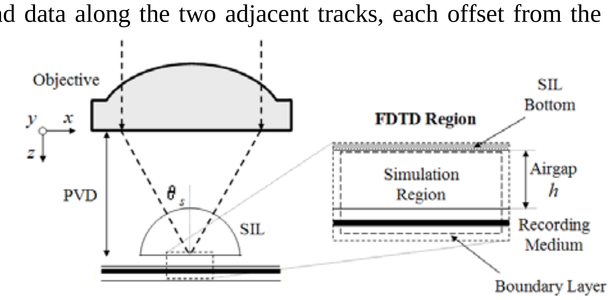

Fig. 4 Magneto-optic model FDTD simulation space

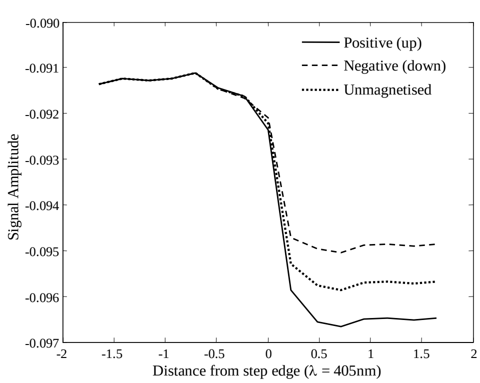

Fig. 5 MO Step Responses

magnetic island of height 60nm for different magnetisation states. Here, it is clear that the magneto-optic signal is dominated by a phase step introduced by the patterned island, regardless of the orientation of the film magnetisation; this may have an effect in the recovery of data, particularly in the presence of jitter, when the phase step will become more evident in the sampled waveform. This work is ongoing, in particular with respect to read channel analysis, and we hope to disseminate our results soon.

In conclusion, a significant result of our work is recognising the need for an accurate 3D model of the replay process in magnetic storage systems in order to accurately predict the correct form of the replay pulse at such small dimensions; as far as we are aware, we are the first group to recognise this need. Waveforms produced using these models can be easily fed into the read channel simulation developed as part of WP1.

ii) Read channel analysis (WP1)

We have successfully satisfied our objective to investigate read channel designs for patterned magnetic recording systems. The analysis of read channel BER performance was achieved using a developed PRML read channel simulation, whereby the performance of the read channel is evaluated via plots of BER against system Signal-to-Noise Ratio (SNR), where an Additive White Gaussian Noise (AWGN) contribution is assumed. The system simulation allows the investigation of a variety system conditions, such as choice of PR (or GPR) target and the application of advanced error correcting schemes (LDPC codes) and run-length-limited (RLL) encoding schemes; a full system description can be found in [15,16]. The input data to the read channel simulation is generated by sampling replay waveforms (due to pseudo random data), which in the case of the 3D magnetic replay model contains signal degradations arising from both ITI and TMR. In addition, the effects that jitter noise, due to variations in geometries of the islands introduced by the patterning process [17], can be introduced.

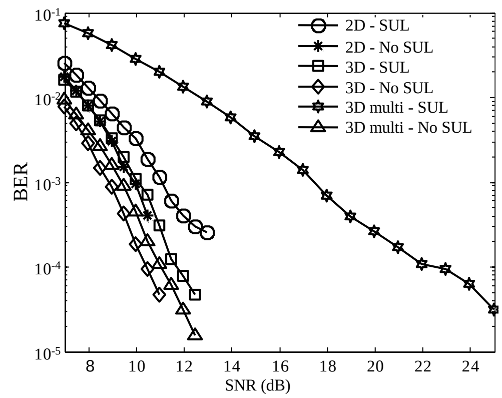

Fig. 6 BER curves using different replay models

One of our original aims was to identify PR schemes suitable for use in the patterned system under investigation, the results of our investigation are outlined in [15,16]. A key result from our analysis was that the use of a GPR target offers optimum performance, whether a SUL is present or not. Interestingly, in the case of an isolated track of data, i.e. no ITI, the optimised GPR target is identical to the simple dicode channel (1, -1). A surprising result, considering the use of a perpendicular medium, is that the PR4-type targets offered acceptable performance [16].

The 3D replay simulation has been shown to produce different pulse shapes compared to conventional 2D approaches, most notably in the absence of a SUL. In order to gauge the impact that these differences have on the channel performance, BER curves were generated, as illustrated in Fig. 6, using the two approaches (2D and 3D), for media with and without a SUL. In addition, in the case of the 3D simulation, a BER curve was generated including ITI (3D multi). In all cases an optimised GPR target (at an SNR of 20dB) has been used. These results demonstrate that the use of the conventional 2D approach has a tendency to underestimate the read channel performance, due to the pulse shape differences described previously. The use of our more realistic 3D approach indicates a more accurate read channel performance. ITI in the replay waveform results in a reduced BER performance, particularly for the SUL case, as would be expected due to the increased signal degradation [16]. A key result of our work is that to achieve optimum BER performance a patterned medium without a SUL is ideal, even in the presence of ITI [16]; this would be beneficial to media designers due to the problems of fabricating patterned media with a continuous soft magnetic underlayer. In addition, in this case the island period can be reduced from 25nm to 20nm, permitting an improved storage density of 1.6Tbit/in^2, whilst still maintaining a BER performance comparable to the SUL case at 1Tbit/in^2 [16]. Further analysis shows that the channel performance is strongly dependent on the geometry of the islands, in particular island width [16]. In addition, if the islands are hexagonally packed then significantly improved read channel performance is observed, particularly in the case of a SUL-based medium, as illustrated in Fig. 7, where the minimum SNR to achieve a BER of 10^{-4} can be reduced by approximately 6dB [12].

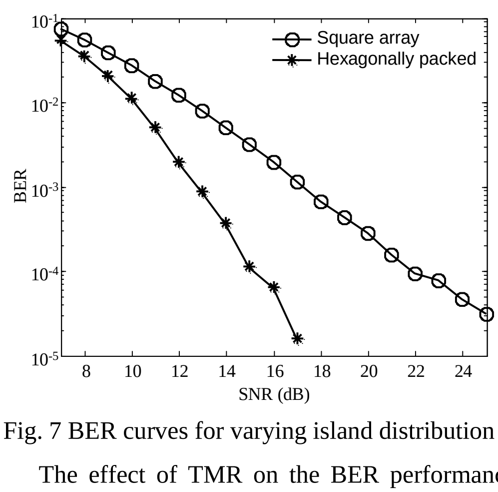

Fig. 7 BER curves for varying island distribution

The effect of TMR on the BER performance has been investigated and has been shown to severely affect the performance of the read channel, particularly in the case of SUL-based media [12]. The severity of the performance degradation depends upon the island distribution. When the islands are distributed over a square array, it is difficult to achieve a BER<10^{-5} with 6.25nm TMR, here the BER performance is largely independent of SNR. However, when the islands are hexagonally packed, a modest increase in SNR of 3dB is required in order to maintain a BER<10^{-5} with 6.25nm TMR [12]. Fig. 8 illustrates off-track BER performance against TMR (at an SNR of 17dB) for the case of a SUL-based medium. In the case where the islands are hexagonally packed, the on-track BER performance is improved by almost 2 orders of magnitude over that of a square array; in addition, the read channel is able to tolerate the presence of TMR whilst still maintaining an acceptable BER.

A significant result of our analysis is that we have shown that the use of hexagonally packed islands leads to a vastly improved read channel performance, particularly in the presence of TMR; this result indicates that the use of self-assembled fabrication techniques may be the method of choice because invariably such approaches produce hexagonally packed arrays of islands.

Figure 9 illustrates the effect that lithography jitter (measured as a percentage of the island period) has on the read channel performance, in the case of a medium without a SUL and the islands distributed over a square array. The BER increases by an order of magnitude at an SNR of 12dB in the presence of 6% jitter. A similar degradation in BER performance is observed in the SUL case. The inefficiency of the read channel to recover user data in the presence of lithography jitter will have a considerable effect on the commercial viability of magnetic data storage on a patterned medium, particularly at ultra-high storage densities in excess of 1Tbit/in^2. Such extreme dependency on the amount of lithography jitter present will ultimately determine the manufacturing process used to produce patterned media.

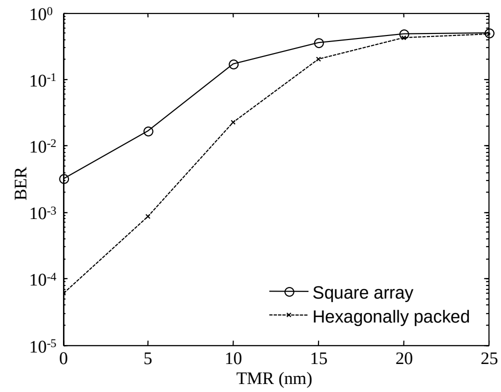

Fig. 8 Off-track BER performance v. TMR

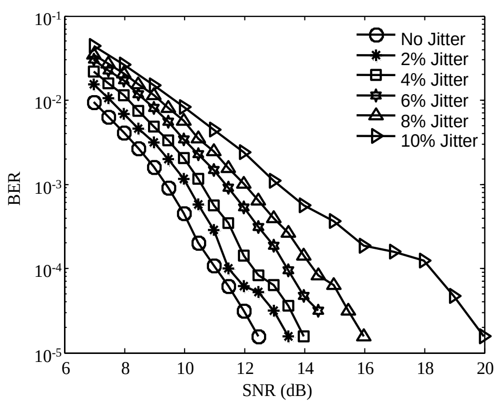

Fig. 9 BER curves with varying amounts of jitter (% of island period of 25nm)

We have demonstrated that hexagonal packing of islands offers vastly improved read channel performance, even in the presence of lithography jitter. An additional result we have demonstrated is that a further improvement in read channel performance is observed through the use of LDPC error correcting codes. The analysis of LDPC coding techniques in patterned media systems has been achieved through the development of a close working relationship with Dr Mohammed Ahmed of the University of Plymouth who has experience in the field of error-correcting codes. Fig. 10 illustrates BER curves with and without LDPC codes for a patterned medium with a SUL where the islands are hexagonally packed. The improvement in BER when using LDPC codes is impressive, especially in the presence of realistic lithography jitter. With 10% jitter, the BER performance of the uncoded channel is severely affected, however, using LDPC codes, an SNR of 12dB can be tolerated whilst maintaining a BER of 10^{-5} [18].

The use of both LDPC codes and hexagonally packed islands permits the reduction of island period whilst still maintaining an acceptable BER. For example, with no SUL, a BER performance $<10^{-5}$ can be achieved at an SNR of 10dB, even when the island period is reduced to 20nm (giving an areal density of 1.6Tbit/in^2). The use of LDPC codes provides a BER$<10^{-5}$ even in the presence of 20% jitter.

An investigation of the application of RLL encoding in patterned media has shown that it may not be required, mainly because a replay pulse is generated each time the read head scans an island which provides a recoverable clock regardless of the recorded data pattern [18].

Work on the development of read channel designs and BER studies in magneto-optic systems is ongoing and we hope to be in a position to publish results in the near future.

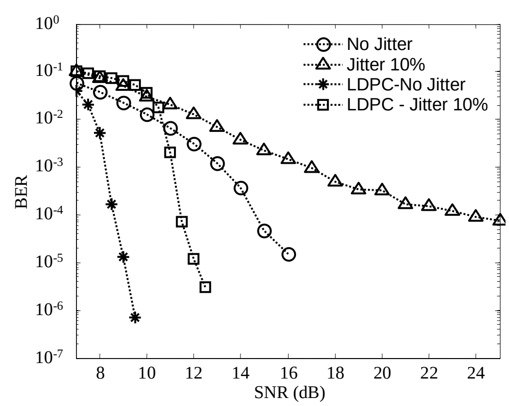

Fig. 10 BER curves using LDPC codes with 10% jitter

iii) Analysis of experimental results (WP3)

The goal of this work package was to fabricate patterned media and validate the results of the simulated replay pulses/waveforms generated via WP2. The magnetic films chosen for the fabrication of patterned media are Pt/Co multilayer thin films (1nm Pt seed layer + 15×[0.4nm Co/1nm Pt] bi-layer) due to their large perpendicular anisotropy and square hysteresis loops. The films were produced by vacuum deposition using an electron beam source at a average pressure of 4-5x10^{-7} mbar, and a substrate temperature of 200°C in order to achieve adequate {111} texture in the Pt seed layer and to induce high perpendicular anisotropy. In addition, we have developed a process for fabricating such multilayer structures on a thick (100nm) Permalloy (Ni_{81} Fe_{19} alloy) soft underlayer (SUL). These films have been characterised using both alternating gradient field magnetometer (AGFM) and magneto-optical Kerr effect (MOKE) techniques and have been shown to exhibit the desired characteristics of square hysteresis loops and high coercivity (2-4kOe).

Work on the patterning of these films was delayed due to the late inception of the Manchester Centre for Mesoscience & Nanotechnology, and the change of technical staff responsible for the operation of the e-beam facility in the centre. A PhD student was recruited (ORS funded) to continue this work one year into the project resulting in a delay in the projected work plan of approximately 12-18 months.

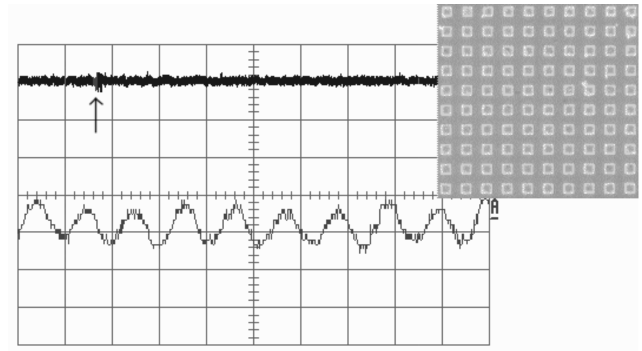
Fig. 11 Experimental media (inset) and replay signals

Fabrication of large scale patterned islands (>200nm) has been performed in order to develop stages of the lithographic process, initially using optical lithography then e-beam lithography, with the pattern being transferred to the Pt/Co multilayer by ion-milling. The inset in Fig. 11 illustrates sample Pt/Co islands of diameter 200nm. Replay waveforms from such media have been produced using our in-house contact recording system configured with commercial GMR read heads. Fig. 11 illustrates a sample waveform due to a track of 200nm islands with period 400nm (the arrow indicates the position where the expanded waveform is taken from the main experimental waveform).

The next stage in this process is to develop a lift-off process, using gold as the dot mask, to transfer the exposed patterned to the underlying Pt/Co multilayer thin film using ion-milling. Fig. 12 illustrates an SEM image of a fabricated dot array of island width ≈50nm and period ≈100nm. This fabrication process is currently being developed in order to improve the quality of the dot array, as well as producing smaller scale structures. Once this fabrication process has been refined, we hope to use it to produce islands of diameter and period <50nm, and use the experimental signals produced using this media to validate the theoretical observations obtained due to WP2. However, experimental replay analysis using island dimensions below 200nm is currently difficult due to the limitations of the GMR read heads we currently have available. We have obtained new higher resolution read heads from an industrial partner that we are currently fitting to our contact recording system. In addition, the current contact recording system is limited in resolution and we are currently preparing a proposal to seek funding for the development of a replacement system in order to continue this work.

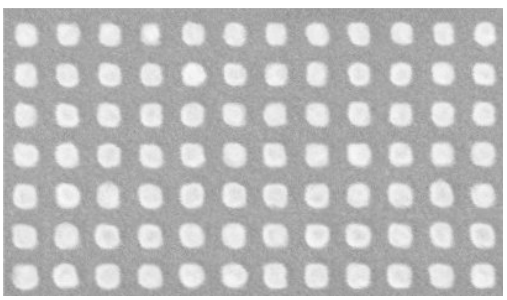
Fig. 12 50nm diameter patterned islands

In parallel to the fabrication of patterned media, we have partially developed a new MOKE system, based upon an existing x-y scanning laser microscope, in order to fully characterise our media. It is envisaged that we will start to generate results form this work by early 2006. We also believe that this system can be used to perform the near-field optical analysis, using a SIL, as described in the original proposal. Finally, once we have fabricated small scale (ideally single domain, <50nm diameter) islands, we hope to both characterise the patterned media, using the MOKE facilities developed and other in-house facilities, as well as verify the magnetic replay modelling in order to satisfy the primary objective of this work package.

3. Project Plan Review

Apart from those few changes to the original project highlighted, there has been little further change to the proposed programme of work. Due to the necessity to develop the 3D replay model, there were delays in the analysis of the read channel; this also involved a shift of focus of the PI from the experimental analysis to the development of the replay model.

In total 3 PhD students have been involved directly with this project: Ioannis Ntokas to work on the development of the read channel simulation (funded directly), Matthew Manfredonia to work on the development of the MO replay model (EU/University funded) and Branson Belle to work on the experimental work (ORS funded).

4. Research Impact and Benefits to Society

This programme of research has been considerably more extensive than originally planned, encompassing novel work in replay modelling and an extensive study of how the island geometry and distribution affects the read channel performance. Such an analysis is novel and we are the first to investigate how island geometry/distribution can be made to influence and improve the read channel performance. Further, the ongoing analysis of experimental results and verification of theoretical observations would be hugely beneficial to the development of patterned media as a viable storage medium.

Significant outcomes of this research that will be used to determine which technologies are used in patterned media are summarised briefly below.

1. The demonstration that 3D reciprocity-based magnetic replay models are essential in order to take into account the 3D nature of the storage medium and the read head and thus accurately design and analyse such systems.
2. Recognising that GPR targets offer optimum read channel performance in patterned media systems.
3. Identifying that the optimum read channel performance is observed for a patterned medium with no SUL.
4. Identifying that the use of hexagonally packed media offers improved read channel performance, particularly in the presence of jitter noise and TMR.
5. Demonstrating that the use of LDPC codes offers vastly improved BER performance, particularly in the presence of lithography jitter, and in addition a potential increase in storage density.

Papers have been presented at two major international conferences for magnetic data storage, PRMC 2004, Sendai, Japan (2 papers) [19,20], and Intermag 2005, Nagoya, Japan (3 papers) [21,22,23], all were received extremely well. A total of six journal papers have been submitted for publication (currently five have been published [10,12,14,15,16] one is currently being reviewed [18]). Overall, the published work will undoubtedly be of great interest to both media and read channel designers working on the development of patterned media as a viable storage medium, and also the general magnetic storage community as a whole. The work has already received attention from representatives of major hard disc manufacturers working on the development of patterned media, which has led to a collaborative EPSRC proposal, which is in preparation.

The ongoing experimental work (supported by both this proposal and the EPSRC proposal in preparation) concentrating on the fabrication and patterning of Pt/Co multilayer films, will be of benefit not only in the development of patterned media storage systems, but also in perpendicular magnetic storage systems and magneto-optical storage systems.

5. Explanation of Expenditure

Some funds were transferred between cost headings mainly to cover an anticipated overspend in staff costs, due to increased PhD studentship overheads, (within 20% of staff costs). As a result, there was a reduced spend under the consumables and travel headings. An overspend under the equipment heading arose due to the need to upgrade the computing facilities. Overall, the project came in on budget.

6. Further Research or Dissemination Activities

As previously mentioned, experimental analysis of patterned media, as driven by this programme of work, will continue at Manchester, via a current PhD student in the short term and the development of industrial collaborations and anticipated further EPSRC funding in the long term. Some of the work is still ongoing and remains to be disseminated, and we hope to take the opportunity to present and publish this work in the near future.

A follow on collaborative research project with a major hard disc manufacturer is being prepared for submission to EPSRC.

References

1. B D Terris et al., J. Phys. D: Appl. Phys. 38(2005) R199-R222.
2. Digests of the IEEE International Magnetic Conference (Intermag 2005), Japan, April 2005.
3. G F Hughes, IEEE Trans Mag, vol. 35, pp. 2310-2312, Sept. 1999.
4. G F Hughes, IEEE Trans Mag, vol. 36, pp. 521-527, March 2000.
5. G F Hughes, IEEE Trans Mag, vol. 39, pp. 2564-2566, Sept. 2003.
6. G F Hughes, Chapter 7, The Physics of Ultra-High-Density Magnetic Recording, Plumer, van Ek, Weller (Eds), Springer Varlag, 2001.
7. R I Potter, IEEE Trans Mag, vol. 10, pp. 502-508, Sept. 1974.
8. J J M Ruigrok, Shirt Wavelength Magnetic Recording, Elsevier Science, UK, 1990.
9. H N Bertram et al., IEEE Trans Mag, vol. 36, pp. 4-9, Jan 2000.
10. P W Nutter et al., IEEE Trans Mag, vol. 40, pp. 3551-3558, Nov. 2004.
11. D T Wilton et al., IEEE Trans Mag, vol. 40, pp. 148-156, Jan 2004.
12. P W Nutter et al., IEEE Trans Mag, vol. 41, pp. 3214-3216, Oct. 2005.
13. C D Wright et al., IEEE Con Elec, vol. 46, pp. 586-596, Jan. 2000.
14. M M Manfredonia et al, IEEE Trans Mag, vol. 41, pp. 2866-2868, Oct. 2005.
15. I T Ntokas et al., J Magn Mag Mat, vol. 287, pp. 437-441, 2005.
16. P W Nutter et al. IEEE Trans Mag, vol. 41, pp. 4327 - 4334, Nov. 2005.
17. M M Aziz et al., IEEE Trans Mag, vol. 38, pp. 1964-1966, Sept. 2002.
18. I T Ntokas et al., submitted to IEEE Trans Mag, Oct 2005.
19. I Ntokas et al., Paper 01pE-04, PRMC 2004 Technical Digest, Sendai, Japan, pp. 213-214, May 2004.
20. I Ntokas et al., Paper 02pA-02, PRMC 2004 Technical Digest, Sendai, Japan, pp. 237-238, May 2004.
21. M Manfredonia et al., Paper BP 04, Intermag 2005, Technical Digest, Nagoya, Japan, pp. 237 – 238, April 2005.
22. I Ntokas et al., Paper EP 06, Intermag 2005, Technical Digest, Nagoya, Japan, pp. 987-988, April 2005.
23. P Nutter et al., Paper FR 05, Intermag 2005, Technical Digest, Nagoya, Japan, pp. 1377-1378, April 2005.