FEASIBILITY FOR SHINGLED WRITE RECORDING

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ABSTRACT

Super-paramagnetic effect will limit the areal density beyond 1 Tb/in^2 of the perpendicular magnetic recording in hard disk drive technology. Based on the road map predictions, the entire industry is working towards alternative technologies such as heat-assisted magnetic recording (HAMR), bit patterned media (BPM), microwave-assisted magnetic recording (MAMR) and shingled write recording (SWR) or shingled magnetic recording (SMR). Shingled write recording is based on overlapping the previous written data tracks; hence, some guard band spaces are saved. Shingled write recording appears as one of the promising candidates to extend the areal density in the future. In this study, we focus on determining the optimal shingled track pitch for the shingled write recording experimentally using the spinstand testers and also study the write ability performance on the key parameters for multiple shingled track pitches on various write width samples. The experimental results on the writability parameters measured on the spinstand testers such as reverse overwrite (ROW), signal-to-noise ratio (SNR) and bit error rate (BER) suggest that the conventional perpendicular magnetic recording could be extended using the shingle method. In addition, a wide range of the writer widths could be used for the shingle unlike the conventional perpendicular recording.

Index Terms – Perpendicular magnetic recording, shingled write recording, reverse overwrite, signal to noise ratio, bit error rate, feasibility, writability, hard disk drive technology.

Acknowledgements

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Thanks are also due to my beloved company "Western Digital Thailand" for the great moral support and also for having faith in me to complete and excellence in this data storage technology. At the same time, I would like to thank all my colleagues who supported to identify the tools and the samples for my research, the test team of Western Digital Thailand in helping me to setup and testing the samples and to my dear friends who encouraged me throughout the tenure of study and research.

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Chapter 1

Introduction

1.1 Statement and significance of the problems

In most commercial HDDs, media is coated with a thin magnetic layer or recording medium and is written with data that are arranged in concentric circles called tracks. Data are read or written with a read/write (R/W) head, which consists of a magneto resistive (MR) element, which is controlled by the voice-coil motor (VCM) actuator. Figure 1.1 shows a simple illustration of a typical hard disk with voice coil motor (VCM) actuator.

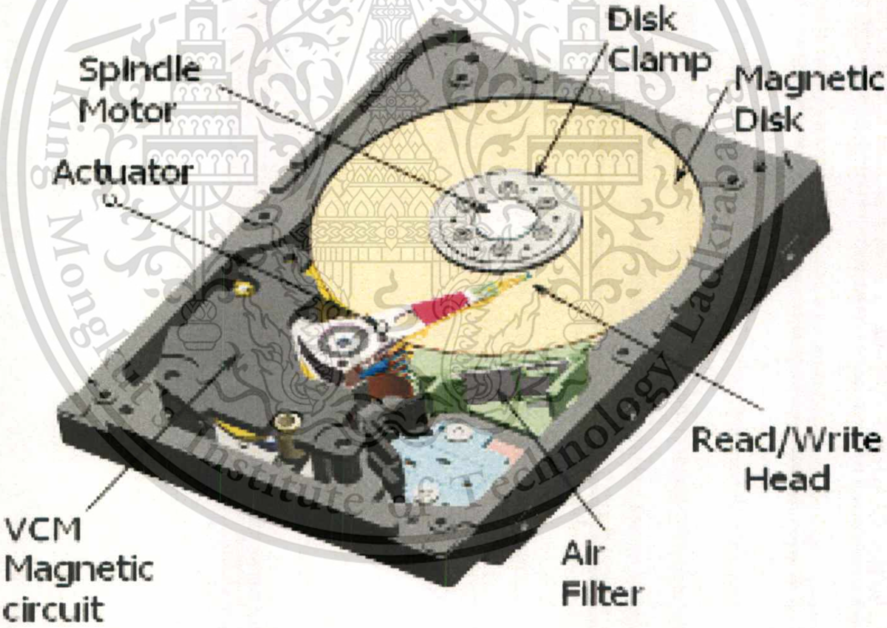


Fig 1.1 Hard Disk Drive with VCM actuator [11].

The ever expanding digital universe poses an enormous demand for data storage. There are predictions that the hard disk drive (HDD) will remain the major technology to serve this demand in the next five years on the horizon. In order to achieve the compound annual growth ratio (CAGR) of 40% year over year, some key technologies have recently been implemented and others are under consideration for the future. The HDD industry had crossed many barriers and has come all the way implementing the technologies such as giant magneto resistance (GMR), tunneling magneto resistance (TuMr) perpendicular magnetic recording (PMR), dynamic fly height (DFH) and anti ferromagnetic coupling (AFC).

Currently, the entire industry is operating with PMR technology which has the limitations due to the so called super paramagnetic effect. With the current conventional PMR technology, we are likely to increase the areal density (AD) up to 1 Tb/in^2. Beyond this limit, there are limitations due to the thermal stability.

The annual growth in the areal density is now threatened by many issues that prevailed during longitudinal recording in its waning days such as higher tracks per inch (TPI) writability, writability vs. erasure tradeoffs, adjacent track interference, wide area erasure, media thermal stability vs. harvestable BER and high data rate switching issues. To cross this barrier, a number of competing technologies have been discussed recently. The author in [2], had predicted the AD growth in the road map as shown in Fig.1.2, it states that beyond the year 2011, alternative technologies will need to be employed. Such technologies include heat assisted magnetic recording (HAMR), bit patterned media (BPM), microwave assisted magnetic recording (MAMR), and the recently proposed shingled write recording (SWR). SWR appears as a promising solution since it is an extension of the current perpendicular recording with the least limitations and investments.

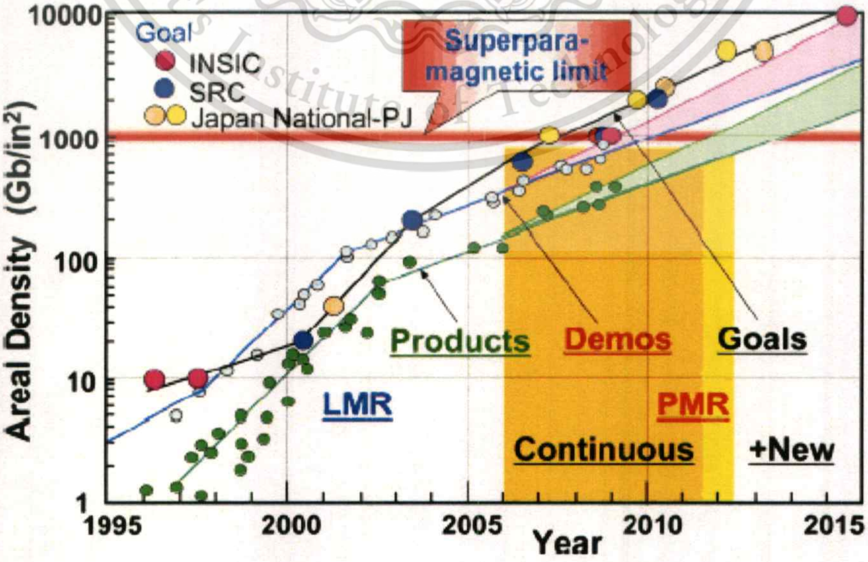


Fig 1.2 The HDD roadmap from 1995 to 2015 [2]

The current conventional perpendicular recording needs to reduce the write width in advancing towards the AD which in turn will affect the writability. In the case of shingled recording, wide writers could be used. And by overlapping the previous written tracks, the reverse overwrite (ROW) seems to be comparable; illustrating that there could be no writability issues in advancing the AD. Shingled recording effectively decouples the write width as the dependent variable in determining drive TPI capability. However, drive architecture design rules and corresponding system complexity significantly increases using SWR. Previously signal to noise ratio (SNR), bit error rate (BER) and ROW were studied at various track densities and various linear densities. In this thesis, we investigate the feasibility of the SWR at various writer widths against multiple shingled track pitches using the current TuMr heads experimentally and compare the performance between the conventional PMR and the SWR with the help of the commercially available Guzik spinstand tester. Also, we will be able to determine the optimal shingled track pitch (TP) without compromising the writability parameters. The tested head samples were fabricated using the current manufacturing process in Western Digital's Bangpa-in plant. The key writability parameters: ROW, SNR and BER of the shingled write recording are compared with the conventional perpendicular magnetic recording.

1.2 Objective

Shingled Write Recording is the new concept which enables us to use the conventional PMR technology with the granular medium to extend the Areal Density growth to decent extent, thereby extending the super paramagnetic limits too. The objectives of this research are to study:

1. The feasibility for the Shingled Write Recording with current Perpendicular Magnetic Recording heads and comparing the performance between the conventional recording and shingled write recording.
2. The performance of the recording heads against different squeeze conditions (shingled track pitch or overlapping track pitches).
3. To find and determine an optimized range of the writer width samples for shingled recording, to find an optimized shingled track pitch for wide writer design conditions without compromising the key writability parameters.

1.3 Scope of the thesis

From this study, we will focus on the performance characteristics of various writer width samples and the ability to write overlapped tracks with the optimized track pitch condition without compromising on the key parametric performances such as SNR, BER & ROW. With large variation (large sigma) of the write width samples, which is one of the critical parameter to control during the manufacturing process, the scope of the thesis are as follow.

1. This would help the design team and the process teams in designing and manufacturing the best suitable recording heads for the SWR technique to increase the AD growth.
2. This study will determine the suitable shingled track pitch for the future areal density predictions.
3. Also this study will help in determining the best or optimal writer width samples to be used for the SWR.

1.4 Limitations of the thesis

1. Since the recording heads are fabricated in WD US plant, it is not feasible to change the design to study different aspects for the SWR feasibility.
2. Since this study is based on the Guzik spin stand testing, the values that are used are not the end values of the HDD system. Future integration with the HDD is necessary to find the integration between the recording heads and the recording channel. This one is just the characterization of the recording head.
3. The recording medium used is only the current available PMR media, not, specific to the SWR (which might need a separate study).
4. The sample sizes selected are limited to 20 to 25 samples due to the availability of the specific writer width samples.

Chapter 2

Literature Review

First of all I would like to thank all the six paper's authors from which I could attain the knowledge to develop my thesis. There are total of six papers reviewed for this study to understand the topic. The papers are organized as

1. Conventional Recording limitations [1]
2. Future Options for the Data storage [2] & [3]
3. Estimation and Experimental analysis on Shingled writing [4], [5] & [6].

The works in [1] helps us to understand the limitations of the conventional perpendicular recording with granular media. This paper explores the feasibility of implementing conventional magnetic recording technology at densities up to one Terabit per square inch. The key limiting physical factor is the superparamagnetic effect (thermal stability) in the recording medium. Ambient thermal energy can cause the magnetic signals to decay. The requirement for thermal stability over periods of years dictates a lower limit to the size of magnetic grains (switching units) in the recording medium.

In [2], it describes several promising technology options to increase the areal density beyond the limit such as bit patterned magnetic recording (BPMR), heat assisted magnetic recording (HAMR), and microwave assisted magnetic recording (MAMR). In addition to these three technology options, there is recent interest in a fourth approach that has the advantage of staying with a relatively conventional perpendicular medium and head. This combines shingled write recording (SWR) and/or 2-D read back and signal processing, whereby the term two-dimensional magnetic recording (TDMR) is used to represent a super-dense SWR that works together with 2-D signal processing. Although the targeted areal density above 4 Tb/in2 based on this technology is still far away, SWR itself is perceived as a viable option before the realization of the HAMR and BPMR systems. This paper reviews the technology options ahead and the pros & cons for each option and also a brief introduction to SWR.

In [3], the authors propose a new approach to magnetic recording based on shingled writing and two-dimensional read back and signal processing. This approach continues the use of conventional granular media but proposes techniques such that a substantial fraction of one bit of information is stored on each grain. Theoretically, areal-densities of the order of 10 Terabits per square inch may be achievable. In this paper we examine the feasibility of SWR and TDMR and identify the significant challenges that must be overcome to achieve this vision.

In [4], it describes the need of head and media designs for shingled recording by targeting areal recording densities of 2–3 Tbit/in^2. The potential of the designs was evaluated using micro magnetic simulations. The possibility of achieving multiple Tbit/in^2 is demonstrated using a continuous, perpendicular recording medium. The effects of write head skew, inter-granular exchange coupling and read head offset are understood when using the shingled recording.

In [5], systematic experimental studies ROW process in the SWR scheme has been conducted in conjunction with characterization of corresponding recording performances from recording heads with different geometries. It was found that not only is there no ROW reduction as the track density increases, but also ROW is, in fact, slightly increased from 3000 track per inch (TPI) to 6000 TPI or beyond by using the same writing conditions. These data suggest that the conventional magnetic recording technology might be able to extend all the way beyond an areal density of one Tbit/in^2 by using the SWR scheme.

In [6], the feasibility of two-dimensional magnetic recording is discussed from the viewpoint of high track density. The 747 curves of shingled track were measured using existing heads and media and were interpreted with a squeezing model dominated by the SNR of the read head output. As long as a reader can be placed on the median line of the squeezed data area, wider OTC than that of conventional writing will result. The modeled 747 curves were in good agreement with the experimental data for both conventional writing and shingled writing. The feasibility of narrow track pitch shingled writing was shown; however, write-to-write misregistration should be minimized to maximize the track density.

2.1 The Feasibility of Magnetic Recording at 1 Terabit per Square Inch

The study from [1], explores the feasibility of implementing relatively conventional magnetic recording technology at the densities up to one Terabit per square inch. A conventional magnetic recording system is taken to be one that operates at around room temperature and employs a uniform featureless medium. In the physics of magnetic recording there are two key factors of concern in achieving very high areal densities. These are the superparamagnetic effect (thermal stability) in the recording medium and the finite sensitivity of the read back head.

In both cases, the limitations arise because the signal energy becomes comparable with the ambient thermal energy. In addition to the basic physics, there are a number of practical engineering factors that must be considered. In particular, these factors include the ability to manufacture accurately the desired head geometries, the ability to closely follow the written tracks, and the ability to maintain a very small, stable magnetic separation.

In order for the magnetization in a recording medium to be stable over long periods of time, the energy barrier required to switch an individual magnetic “grain” or switching unit must be much larger than the thermal energy. We know and understand from the author that the grains cannot be narrowed down due to the thermal effect and the super paramagnetic effect. Also the author explained the impact of the SNR against different bit aspect ratio. For the future system, a need of 3-dB gain in SNR is required and it could be achieved by proper signal processing techniques as per the simulation and modeling study from the author.

For one Tbit/in^2 system, the author clearly explained the key requirements based on his simulated calculations. The design of the mechanical characteristics of a 1 Terabit per square inch hard disk drive is probably even more speculative. A hard disk drive storing 1 Terabyte of data will require about 16 sq in of storage area.

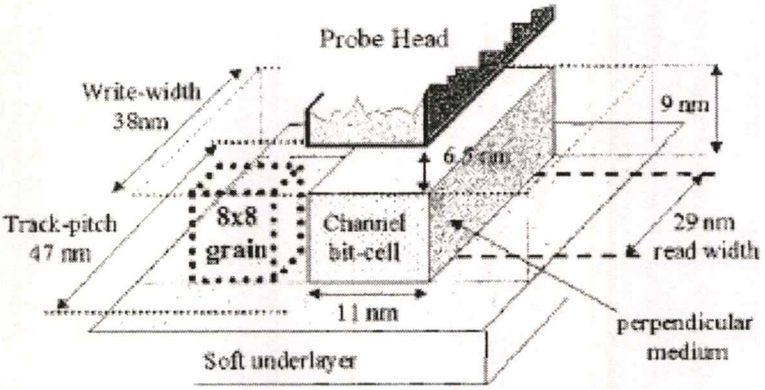


Fig 2.1 Key dimensions of 1 TB/sq in magnetic recording system [1].

Figure 2.1 illustrates the key requirements for the Tbit/in^2 magnetic recording systems. The example does manage to approach a density of 1 Terabit per square inch without apparently violating any physical laws. The biggest lever in achieving this density is a signal processing scheme capable of operation at very low SNR (very few grains/bit). The proposed system is designed with a 3-dB margin against sources of system degradation including thermal decay.

The HDD industry is at a critical technology crossroads and it is paramount that we quickly establish comprehensive paths to push beyond the superparamagnetic limit while mitigating the R&D and tooling investment risks.

2.2 Future Options for HDD Storage

In [2], it described the HAMR, BPM, MAMR and Shingled Recording/Two Dimensional Magnetic Recording technologies that are feasible to overcome the super paramagnetic limits as shown in Fig 2.2.

For SWR, a wide write-pole is used to write a series of overlapping tracks. Of the initial wide track that is written, only a narrow portion along one edge of the track remains after the track adjacent to it is written. The write head needs to have a side-shield only along that edge. Although in recent study, the wrapped around shields are preferable [Ref. Intermag 2011].

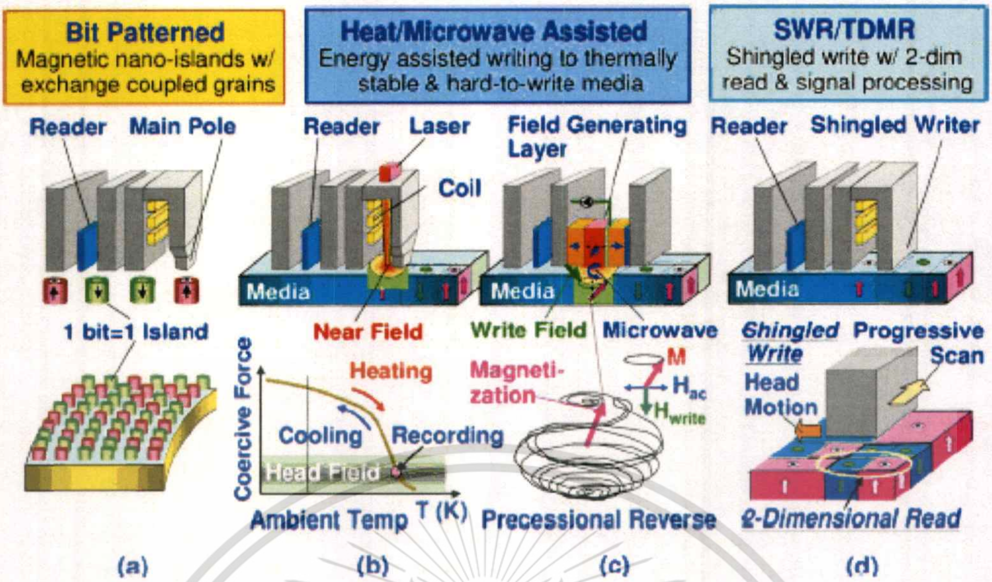


Fig 2.2 Future Technology Options for HDD Storage [2]

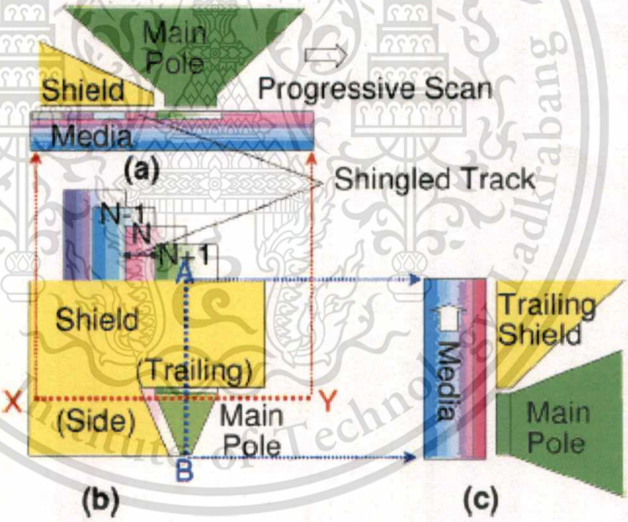
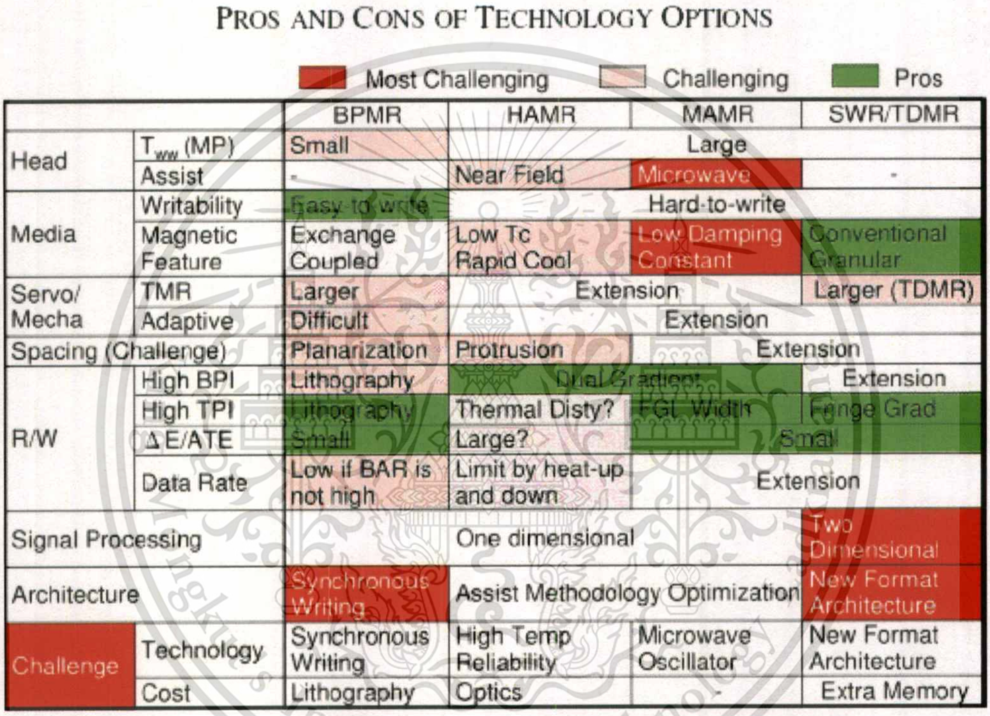


Fig 2.3 Shingled writer and shingled write process [2]

The concept of shingled writing is to heavily overlap tracks written sequentially by a much wider writer. Because of the overlap, the resulting tracks are much narrower than the original written width as shown in Fig 2.3. Although this complicates writing operations, read back (with a suitably narrow reader) is unconstrained and random-access reads work just as in a conventional drive. SWR has advantages of much stronger write field due to larger pole and sharp corner-edge field allowing a narrower erase band, which by itself enables us to increase areal density up to around 2 Tb/in^2.

Adjacent track erasure (ATE) will also not be an issue. Reading a sector from a shingled written surface may have conventional recording performance. A huge disadvantage is that "update-in-place" is no longer possible. Tracks are written sequentially in one direction cross track. Therefore, a single track or portion of a track cannot be altered without first recovering many tracks of subsequently written data. After the target track is updated, the recovered tracks must be rewritten back onto the disk. This is a great challenge in SWR.


PROS AND CONS OF TECHNOLOGY OPTIONS

🟥 Most Challenging ▨ Challenging 🟩 Pros

		BPMR	HAMR	MAMR	SWR/TDMR
Head	T_{ww} (MP)	Small	Large		
	Assist	-	Near Field	Microwave	-
Media	Writability	Easy-to-write	Hard-to-write		
	Magnetic Feature	Exchange Coupled	Low Tc Rapid Cool	Low Damping Constant	Conventional Granular
Servo/ Mecha	TMR	Larger	Extension		Larger (TDMR)
	Adaptive	Difficult	Extension		
Spacing (Challenge)		Planarization	Protrusion	Extension	
R/W	High BPI	Lithography	Dual Gradient		Extension
	High TPI	Lithography	Thermal Disty?	FGL Width	Fringe Grad
	ΔE/ATE	Small	Large?	Small	
	Data Rate	Low if BAR is not high	Limit by heat-up and down	Extension	
Signal Processing		One dimensional			Two Dimensional
Architecture		Synchronous Writing	Assist Methodology Optimization		New Format Architecture
Challenge	Technology	Synchronous Writing	High Temp Reliability	Microwave Oscillator	New Format Architecture
	Cost	Lithography	Optics	-	Extra Memory

Fig 2.4 Pros and Cons of technology options [2]

Figure 2.4 and 2.5 summarize possible technology transition paths to push beyond the superparamagnetic limit. Recording with energy assist on BPM or 2-D signal processing will theoretically enable areal densities beyond around 5 Tb/in^2. Furthermore, areal densities of about 100 Tbit/in^2 could be achieved based on the thermal stability of known magnetic materials.

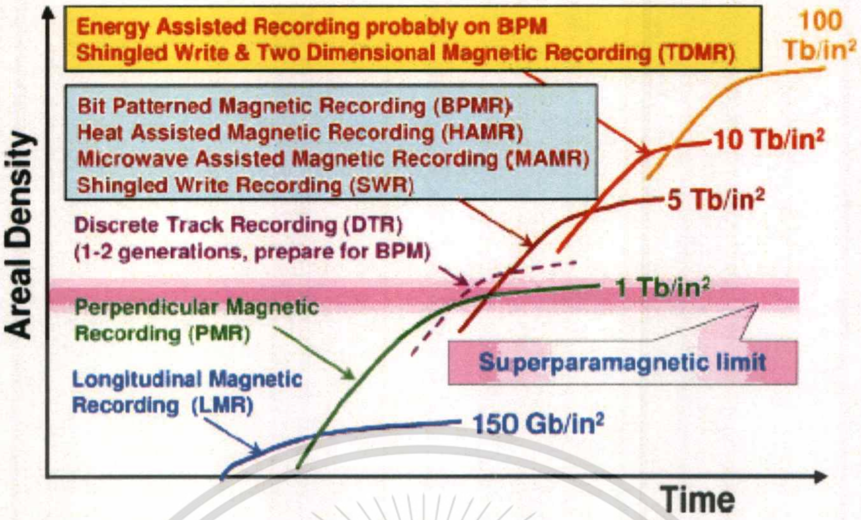


Fig 2.5 Predicted Future Technology Options [2]

However, none of these options show a clear problem-free solution at this moment. Their pros and cons are summarized in Fig.2.4. Considerable carefully-coordinated pre competitive research will strongly be encouraged to completely assess the viability of these options. The best option without major investments would be the SWR, whereas this technology uses the same conventional perpendicular granular media. If combined with the TDMR, SWR could even be pushed until 10 Tb/in^2.

2.3 The Feasibility of Magnetic Recording at 10 Terabits per Square Inch

A pole-tip of 5 nm square may be able to generate a reasonable field at the top of a 5 nm diameter grain, but the fields (and gradients) say 15 nm further away at the bottom of the grain will be much smaller. Shingled-write with a specially designed "corner writer" overcomes this problem since there is no longer a narrow pole-tip that has to match the track-pitch [3]. Here the fields are constrained only on one edge down-track and one edge cross-track. The vertical fields will be more uniform through the thickness of the medium. Also, with a head of this design, there are no constrictions limiting the amount of flux approaching the corner. Because of these two factors, much higher fields can be obtained that can penetrate the medium to much greater depths. The implication is that field magnitudes and thus grain sizes and thermal stability can be maintained much better as we push to these ultimate storage densities.

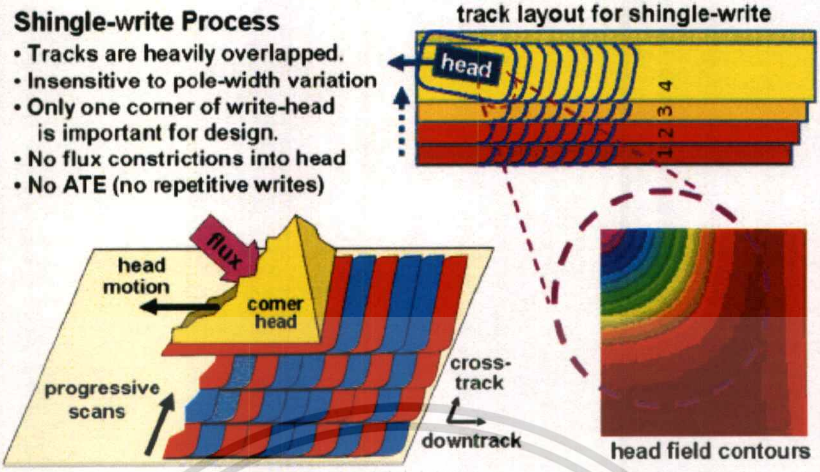


Fig 2.6 Illustration of shingled write recording [3]

Advantages and Disadvantages of Shingled Writing

There are a number of positive advantages of shingled writing and of the corner writer (Fig. 2.6). The advantages include the higher fields (and thus higher field gradients) that can be obtained as well as the freedom from the effects of most process tolerances (pole-tip width, flare-point, shield throat-height, etc.). In addition, because tracks must be written sequentially, ATE, which occurs when a single track is written repetitively and damages an immediately adjacent track, is no more an issue on the SWR. This allows a relaxation in the design constraint on the maximum head field that is allowed to fringe onto the adjacent tracks.

A significant disadvantage is that “update-in-place” is no longer possible. Tracks are written sequentially in one direction on the cross-track. Therefore a single track or a portion of a track cannot be altered without first recovering many tracks of subsequently written data. After the target track is updated, the recovered tracks must be rewritten back onto the disk.

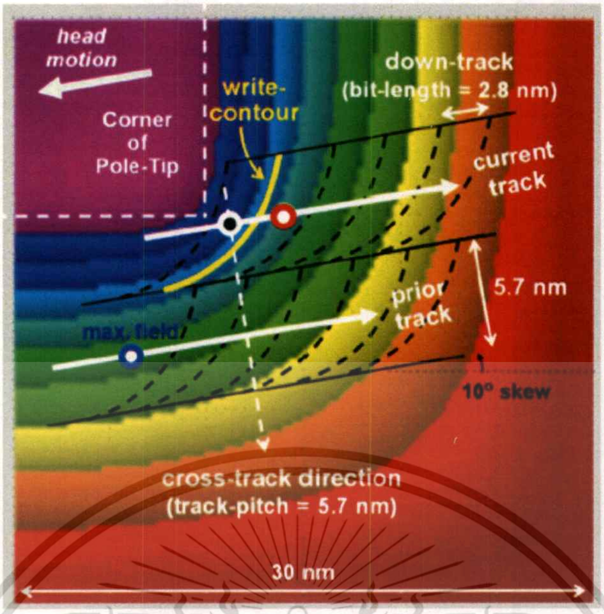


Fig 2.7 Shingled write process super imposed on contours [3]

Figure 2.7 is the superimposed of the shingled writing process. “Channel” bit density of 40 Tbit/in^2 (corresponding to 10 Tb/in user bits) is possible with SWR with the bit aspect ratio of 2:1. The write-contour is drawn at 12.5K Oe reflecting the medium’s switching field assuming it as a continuous medium. The writing has a skew of 10 Deg throughout the write process.

2.4 Shingled Recording for 2–3 Tbit/in^2

The SNR of the shingled tracks was calculated using the sensitivity function of a 14 nm wide MR Head with a shield gap of 25 nm. Cross-track profiles of the SNR were calculated and the maximum SNR for each shingled track was determined as shown in Fig 2.8. The results of several simulations were averaged to obtain the SNR curves and error bars. The peak SNR fluctuated with a standard deviation of 2–3 dB among the simulations. Each of the shingled tracks could be clearly identified in the cross-track profiles by a distinct peak in the SNR. The SNR of the final, 1104 kilo flux changes per inch (KFCI) track fluctuated significantly across the track as the width of the read head was much smaller than the width of the final, non-shingled track. A comparison of the maximum SNR values of the two 1104 KFCI tracks shows that the shingled track had about 5.4 dB lower SNR, despite the shingled track being twice the width of the read head.

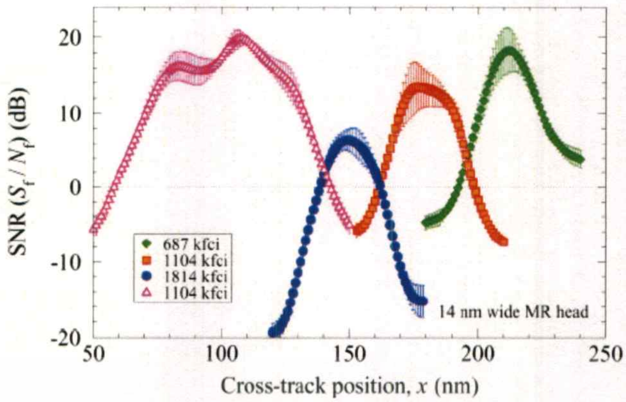


Fig 2.8 SNR versus cross track position of read head with a 30 nm TP [4]

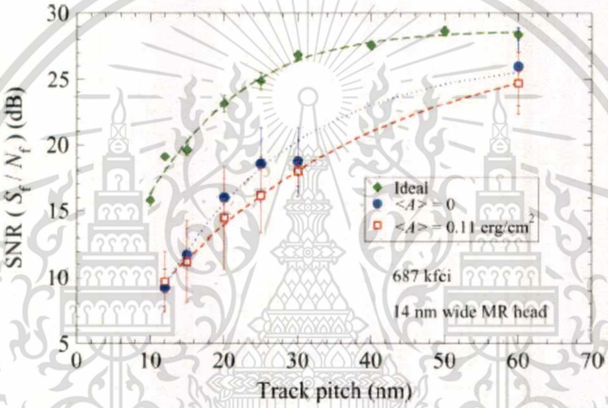


Fig 2.9 SNR versus Track Pitch [4]

The SNR of the shingled tracks was calculated using the MR Head and is shown in Fig. 2.9, together with data for tracks written by the SPT head. Ideal tracks are programmed. Other tracks were written by SPT head. 60 nm is without shingle.

The “Ideal” data represent the SNR that could be obtained if the head field gradient were infinite, the temperatures were zero and there were no dispersions of Ku. The noise in the “Ideal” case arises from the grain size distribution. The calculation was repeated for “Ideal” tracks without transition curvature and the SNR values were almost unchanged; therefore, it can be said that transition curvature by itself does not decrease the SNR, but the lower head field gradient that causes it does reduce the SNR. The results for tracks recorded in media with and without exchange coupling show an SNR reduction of around 6 dB from the “Ideal” data, indicating the potential for improvement.

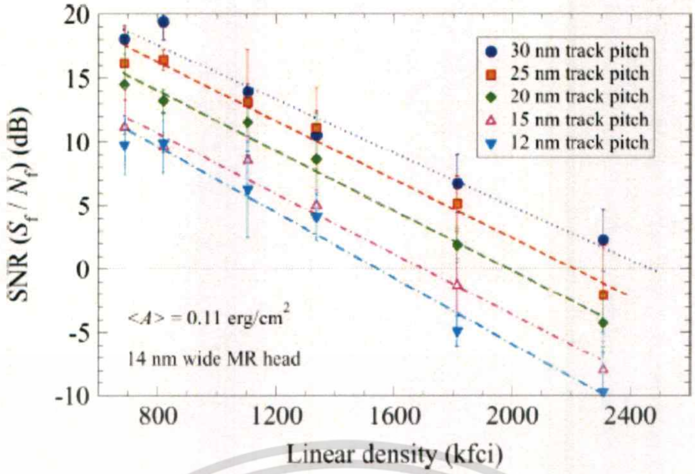


Fig 2.10 SNR versus linear density for various TP [4]

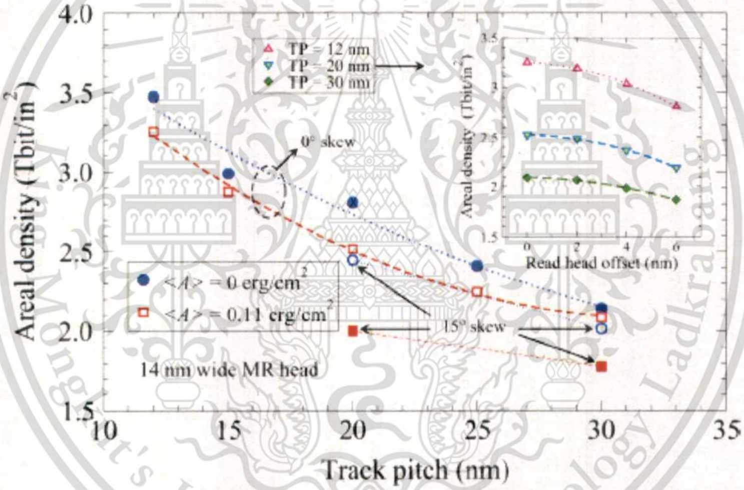


Fig 2.11 AD versus Track Pitch of read head offset from track center on maximum AD [4]

To determine the areal density limit, the maximum SNR values for each medium and shingled track pitch were plotted against linear density. Fig. 2.10 shows the maximum SNR values for media with [A] = 0.11 erg/cm and track pitches from 12 nm to 30 nm. The SNR of the highest frequency, 2309 KFCI track (11 nm bit length), was 2.2 dB for a 30 nm track pitch, with a standard deviation of 2.5 dB, indicating that tracks with a bit length of two grains could be supported by the media, given a sufficiently large head field gradient. As the track pitch decreased, the SNR of the shingled tracks decreased. This was because the down-track head field gradient varied across the track width and was lowest at the edges of the written tracks. The maximum usable linear density was assumed to be that where the SNR reached 0 dB. By fitting the data in Fig. 2.10, the maximum linear density, Linear Density 0 was obtained. If higher SNR values are required, the maximum linear density will be reduced.

The average slope of the fitted curves in Fig 2.10 was -0.1174 dB/KFCI, so the maximum linear density should be reduced by about 85 KFCI to gain 1 dB of SNR. The maximum areal density is given by LD (0)/TP. The results are plotted in Fig. 8 (b) for media with [A] = 0 and [A] = 0.11 erg/cm^{2}where [A] = inter-granular exchange coupling field. At zero skew, the maximum areal density was greater than 2 Tbit/in^2 for all combinations of track pitch and exchange coupling that was simulated. The maximum areal density increased as the track pitch reduced, despite the reduction in LD (0) at smaller track pitches, and exceeded 3 Tbit/in^2 for a 12 nm track pitch. The maximum areal density was reduced by 5% to 10% as the average inter-granular exchange coupling increased from zero to 0.11 erg/cm^2. When the skew was 15 degrees, the maximum areal density was less than 2 Tbit/in^2 in some cases. The wider erase bands on the shielded side of the write head at 15 deg skew significantly reduced the maximum areal density as the track pitch decreased, relative to the zero skew results.

In a real disk drive the read head would not be able to follow the written tracks exactly and there would be an offset between the read head and the written track. The inset to Fig. 2.11 shows how the maximum areal density would be decreased if the read head were offset from the track center. The points were calculated using the average SNR values 2 nm, 4 nm and 6 nm from the peak SNR position in the cross-track SNR profiles and re-calculating LD (0). Even with a read head offset of several nm, areal densities of 2 Tbit/in^2 should be possible

2.5 Reverse Overwrite Process in Shingled Recording Process at Ultrahigh Track Density

The obtained ROW dependence on shingled track density or track pitch is plotted in Fig. 2.12. As can be seen clearly, not only is there no ROW reduction as the track density increases, but also the ROW is even slightly increased from 3000 TPI to 7000 TPI in certain cases. It is believed that the fundamental mechanism of such ROW improvement could be mainly attributed to an inherent successive and multiple writing process in the shingled recording scheme. This experimental finding further confirms that conventional magnetic recording technology might be able to extend all the way beyond an areal density of one Tbit/in^2 by using shingled recording scheme since insufficient writability currently is the bottleneck for next few generations of drive products. Fig. 2.13 plots the SNR as a function of the shingled track density or track pitches (TP). It was found that the SNR initially does not decrease much if the track density increase is at a moderate level. However, as the track pitch further increases to a higher level (>4000 TPI), the SNR drops drastically. Two aspects should be mentioned here. Firstly, the heads with several different writer designs were employed in this study and, secondly, it is not clear that any particular design would be the best for the shingled recording among them.

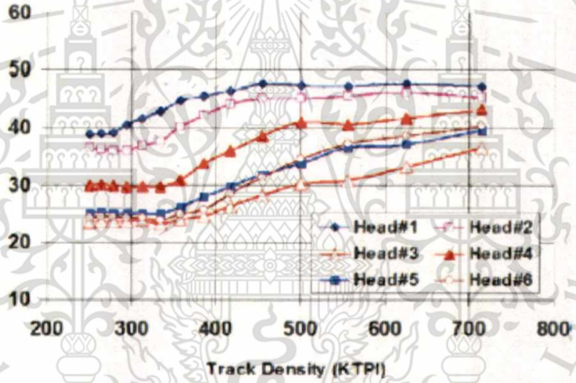


Fig 2.12 Measured ROW versus track density in shingled recording scheme [5]

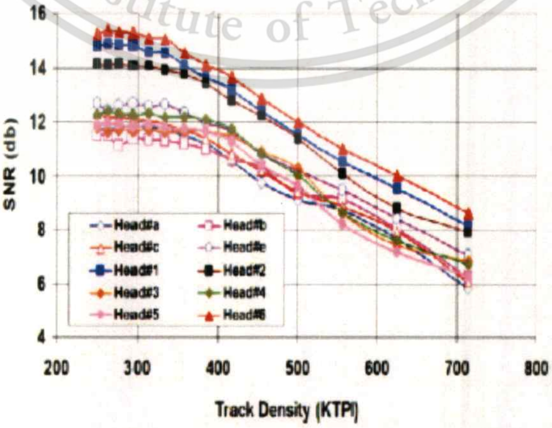


Fig 2.13 SNR dependence of the shingled track density (1650 KFCI) [5]

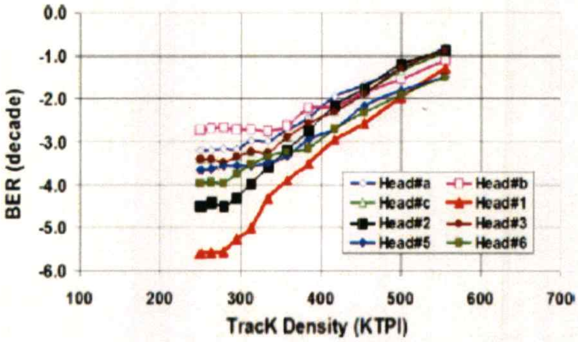


Fig 2.14 BER dependences of the shingled track pitches for two writer designs [5]

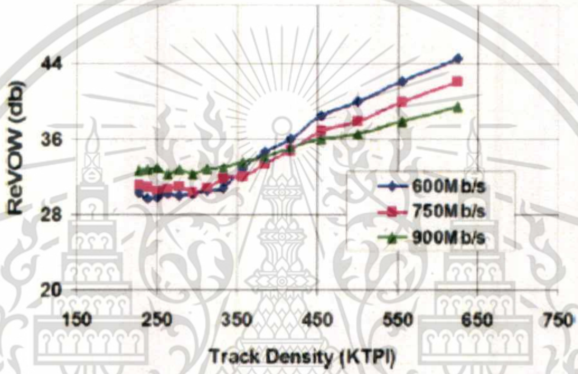


Fig 2.15 ROW dependence on the shingled track pitches at different data rates [5]

Many design features could influence the cross-track field gradient and on track recording performances simultaneously. The writer heads only for the shingled recording purpose should be specially designed. Unlike the conventional recording situation, here the trend of SNR dependence on the TP is not proportional to the ROW dependence of the TP. Furthermore, the BER dependence on the shingled TP is illustrated in Fig. 2.14, showing a similar trend of TP dependence as the SNR dependence on the track pitch. The linear relationship between SNR and TP is due to the fact that as the TP is increased resulting lower number of magnetic grains, the SNR will decrease linearly. The frequency dependence of ROW versus shingled track pitch is presented in Fig. 2.15, showing that the ROW in fact is slightly reduced at the higher linear density if the track density becomes quite high.

2.6 Estimation of Maximum Track Density in Shingled Writing:

The maximum track density is governed by the tolerable on track capability (OTC) to ensure sufficient error rate performance, or signal to noise ratio. Herein, it is assumed that noise emanates only from the adjacent tracks. A squeezed track model was used to formulate the OTC in shingled writing. Fig. 2.16(a) and (b) are schematics showing the difference between shingled writing and conventional writing. The adjacent tracks are placed close together to represent the squeezed condition. Three tracks data, center and adjacent are shown below.

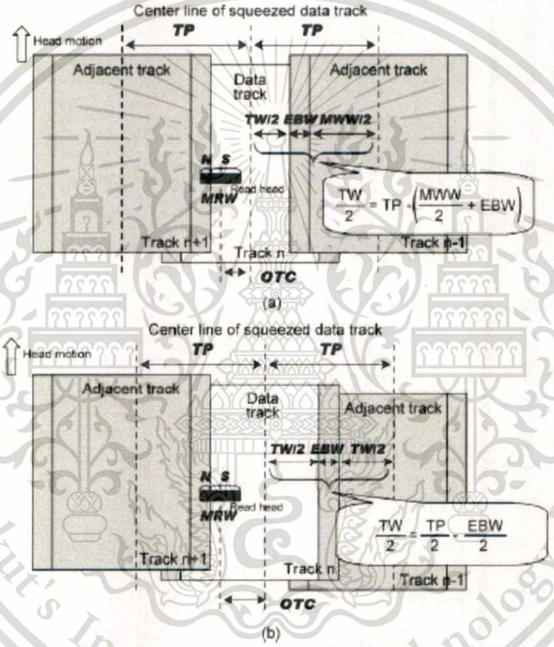


Fig 2.16 Schematic representation of magnetic tracks and read element for (a) conventional writing and (b) shingled writing [6]

Center line of data track is changed according to TP in shingled writing. A read head is also shown to indicate the maximum OTC. The portion of the left end of the read head above the neighboring track must be less than a certain width, because the erase-band is a significant noise source in PMR, as is the cross-talk noise from neighboring data tracks. The OTC is defined as the displacement from the center line of the data track to the off-track position where the SNR deteriorates due to noise from the adjacent track. The OTC obviously corresponds to half the data track width. In Fig. 2.16(a) the half track width of the squeezed track (TW/2) is obtained by subtracting half of the written track width plus erase band width (MWW/2 + EBW) from the TP. In contrast, as shown in Fig. 2.16(b), the half track width in shingled writing is obtained by subtracting half of the erase-band width (EBW) from half of the TP. For the same track pitch, the data track width or OTC is proportional to TP in conventional writing and TP/2 in shingled writing. The distinct difference means that the OTC decreases less quickly in shingled writing than in the conventional writing. It is noted that the center line of the data track does not change when by the squeezing from both sides in conventional writing. In contrast, with the shingled writing, the read head can be centered on the tracks to obtain a wider OTC than that of conventional writing. Because the data track is squeezed from only one side, the track center positions can be optimized according to the pitch of the two data tracks, n-1 and n, in shingled writing.

2.7 Conclusion

In this chapter, recent works on the shingled have been reviewed. Previous studies were really helpful in understanding the principles and the advantages of the SWR. The key writability parameters such as ROW, BER and SNR performances are described for the SWR. The parameters against linear densities and the track densities are discussed. Based on theoretical calculations, it is observed that the SNR drops around 5 dB compared to the conventional recording. Based on the previous studies, it is understood that the AD increases when the track pitches are reduced. The read head plays the major role in advancing the AD. Also the advantages and the disadvantages of the SWR are clearly understood. Globally, to advance the areal density, the only way is to have some sort of energy assisted magnetic recording to overcome the super paramagnetic effect which might be a bit expensive. SWR has an advantage of using the wide writers and the current conventional PMR could be well extended to a decent limit (within 3 Tbit/in^2) and if combined with the 2-D signal processing, it could be further extended until 10 Tbit/in^2.

Chapter 3

Research Methodology

In this thesis, SWR is based on the concept of overlapping the previously written tracks and thereby estimating the recording head performance experimentally based on overlapping track pitch or the shingled track pitch using various write width heads. Currently available TuMr/PMR recording heads are used for the study. This chapter describes the research methodology and is organized as follows.

Section 3.1 describes the concept of conventional perpendicular magnetic recording. Section 3.2 describes a need for Shingled Write Recording & its basic concepts. Section 3.3 will describe the evaluation sample selection and measured performance of key parameters for the pre selected samples on conventional recording. Section 3.4 illustrates the list of materials, specs and research tools used in this thesis experimental work. Finally in section 3.5, we conclude this chapter with the experiment structure and data analysis method to meet the goal.

3.1 Conventional Perpendicular Magnetic Recording

For the past few years back, the longitudinal recording was replaced by the entire HDD industry to the PMR in order to overcome the super paramagnetic effect due to the thermal stability towards incremental areal density to support the global data storage. In PMR, the recording bits are recorded to the medium in perpendicular to the plane unlike longitudinal recording where it used to be horizontal to the plane. PMR was a great break through for the recording industry and is being used until date. The predictions and the literature review indicate the limitations of the PMR, which could handle only until 1 Tb/in^2 theoretically. In Fig. 3.1, the basic head design of both LMR and PMR is shown. LMR uses the ring-type head and the PMR uses the single-pole-type head for recording. PMR uses the additional SUL on the medium for the return pole function.

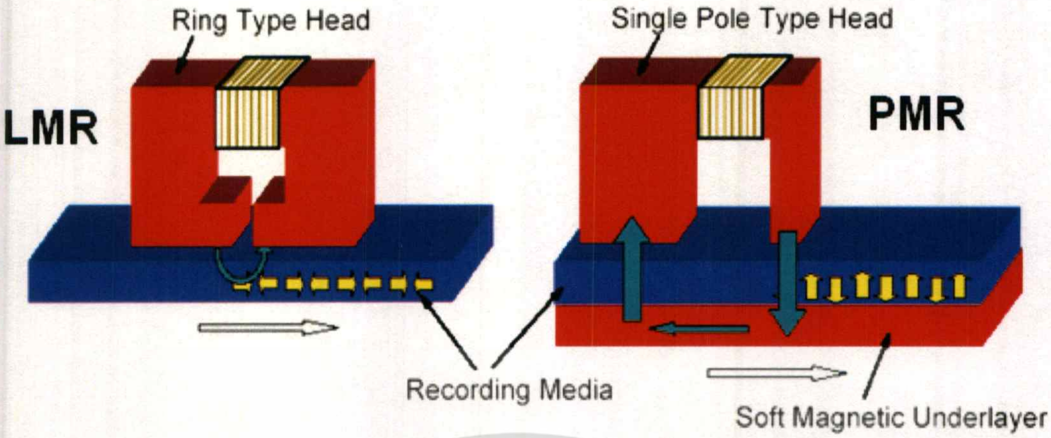


Fig 3.1 LMR Vs PMR basic head design [11]

For understanding the conventional PMR recording, a basic track profile is shown in Fig. 3.2. The basic recording concept of the conventional recording on the medium is self explained. There are simulations of three written tracks shown as Track N colored as pink, Track N+1, colored as yellow and Track N+2 as blue. Each written track is simulated with a track pitch of 4 μin. Each and every track has a clear separation. In this simulation, it is assumed that a writer width of 4 μin is used for recording every track sequentially in one direction. From the fig 3.2 the direction is from the left view to the right view of the picture. The y-axis denotes the amplitude level of the recording (also can be assumed as the circumferential direction of recording). The x-axis is assumed to be the radial direction.

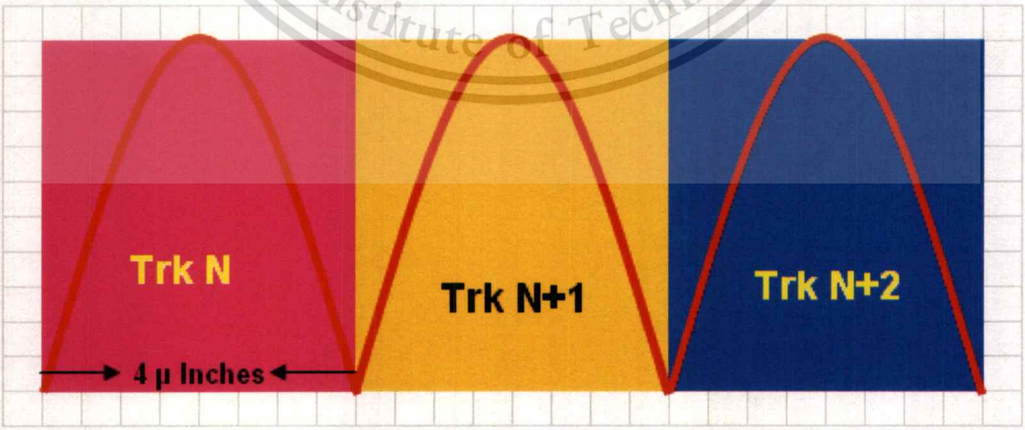


Fig 3.2 An understanding of the conventional PMR track profile.

3.2 A need for Shingled Write Recording and its basic concepts

In general, the entire industry reduces the write width to enhance the AD. There forth based on the estimation the Reverse Overwrite would be around 10db at 2 μin, as shown in Fig. 3.3 which might not be enough to sustain the read back. The projected Re-OVW gap could be as high as 20db which will not be enough to sustain the writability for the conventional recording. Shingled recording concept is getting familiarized and the entire industry is eyeing this concept to sustain the AD growth without a drastic change in the head technology. SWR would be an extension of the PMR technology to extend the super paramagnetic limits beyond 1 Tb/inch^2.

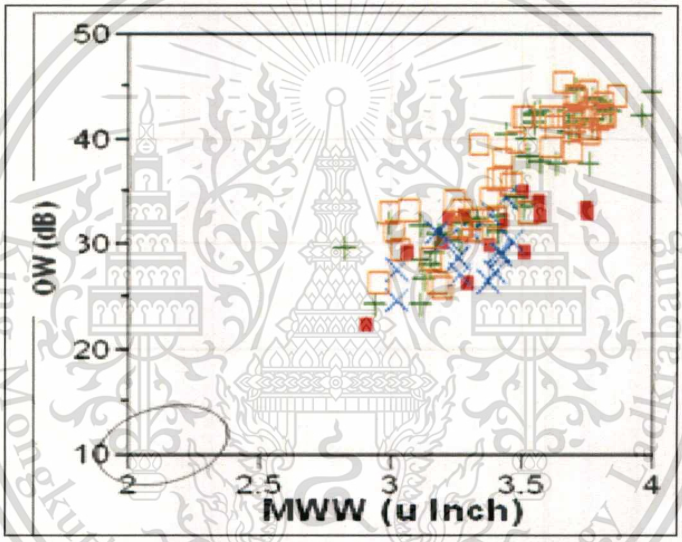
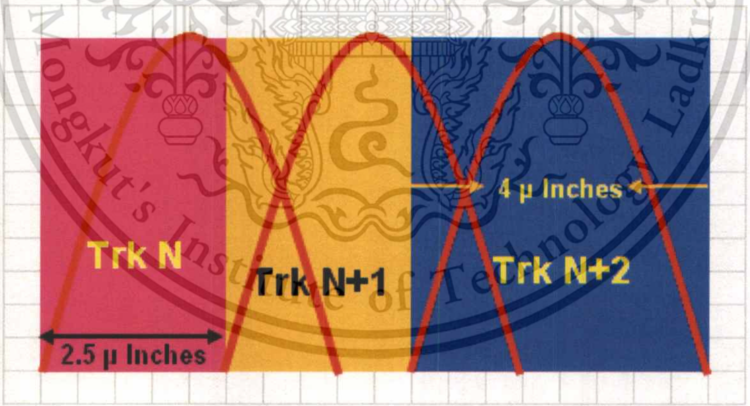


Fig 3.3 Writability Deficiency on Conventional recording [10]

Fig 3.3 explains the ROW to the MWW correlation on the current conventional PMR. Based on the prediction (respect to the current data output), the ROW would be around 10 dB which is almost 15 to 20 dB lower than what we achieve today with the current designs. This 10 dB would not be sufficient for the writability and for the read back by the reader sensor. In order to sustain the AD growth with the current PMR, SWR is a feasible option. Shingled write method for ultra-high track density application was proposed in 2001 and many patents have been filed and the entire industry is aggressively investigating this approach. The concept of SWR technology is based on overlapping the previously written tracks with a relatively wide writer when writing successive tracks sequentially on the disk. This results in a much narrower track than the originally written full track. The only constraint in Shingle recording is to know how much writability is required for overlapping the previous written tracks which will be answered in this thesis.

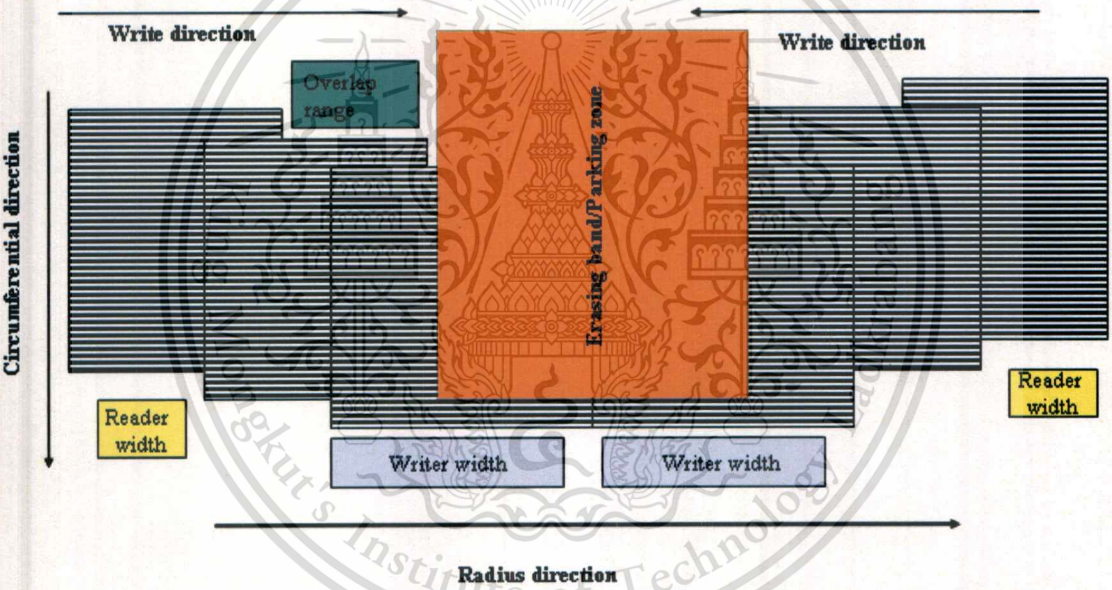
The advantages of SWR are:

a) Sufficient writability beyond 1 Tb/in^2 AD which is projected to be the maximum limit of the conventional PMR technology.
b) Cost reduction effectiveness by higher yields.
c) Minimal investments for the AD increment when compared to other energy assisted techniques.
d) No adjacent track interference.
e) No issues for magnetic write width sigma control and side wall angle control.
f) Ability to use rectangular pole or other type of pole (which will potentially give a higher recording field).
g) The resultant higher field from a relative wide writer head will allow using the higher anisotropy material on the medium, which will increase the AD.



Figs 3.4 An understanding of the Shingled write recording track profile.

Fig. 3.4 is the simple concept for the SWR. In the conventional recording, every track profile is separated based on the writer width, whereas in SWR, the tracks are overlapped with a fixed TP. It is assumed that the writer width to be 4 µin and the shingled overlapping is assumed to be a constant track pitch of 2.5 µin. The rightmost track (3rd track – blue colored) is the full track, while the preceding left tracks (2 tracks – pink and yellow colored) are the shingled tracks. In the conventional recording, all the tracks will be separated when it is written sequentially based on the writer width and the specified product track pitch. In SWR, the concept is to overlap the previously written tracks and the data will be read based on the remaining track information. The shingled recording writes the information in the sequential manner overlapping the previously written track. This will be particularly helpful in the case of storing bulk information such as pictures or movies. For random storage, the disadvantage lies in the update-in-place issue which means the recorded data in a particular track could not be erased as it used to be in the conventional recording. To erase a single track, the entire block of data should be erased. Some system-level changes similar to flash storage technology will be required to overcome this.

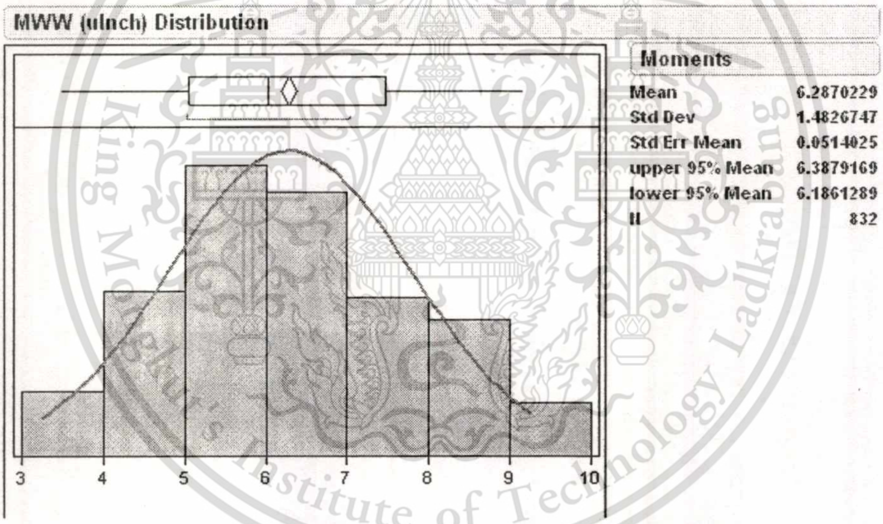


Figs 3.5 A basic understanding on the concept of shingled write recording [10]

Fig 3.5 explains the basic understanding on the overlapping. In the conventional recording there are erase bands or guard bands on every track which could be minimized while using the shingled recording. The x-axis is the radial direction and the y-axis is the circumferential direction. The shingled sequential writing is shown in two different directions in the figure. We can see that the writer width is quite wide and the reader width is narrow. In conventional recording, the trend used to be on the reverse side. In addition, a wide writer could cause adjacent track interference issues whereas in shingled recording it helps to concentrate the amount of field at a particular point which might enhance the AD as well (need further study on this topic).

3.3 Sample selection for thesis study and key parametric performances

For any experimental evaluation, the sample selection is one of the key criteria and so for this evaluation too. The samples used in this thesis study were all from regular manufacturing process from the Western Digital Bangpa-in plant. Although these samples are from regular manufacturing process, they were all fabricated to test the SWR, as the writer width are quite larger which will not suit the current areal density demands. To represent the full distribution and to avoid the bias of the sample, the entire samples were selected based on the write width criteria with nominal parametric values.



Moments	
Mean	6.2870229
Std Dev	1.4826747
Std Err Mean	0.0514025
upper 95% Mean	6.3879169
lower 95% Mean	6.1861289
N	832

Fig. 3.6 MWW distribution of the samples before selection

Fig 3.6 illustrates the normal distribution of the evaluation samples before selection. From the graph we could see that the magnetic writer width (MWW) population varies from 3 to 10 μin for 832 samples. From the population, the evaluation samples were cherry picked based on MWW values to range from 3.5 μin to 9 μin in step of 0.5 μin. For every step size 20 to 25 samples were selected for the entire evaluation and for every step size a tolerance of +/- 0.05 μin was set as the criteria for selection. For e.g., for 3.5 μin the samples ranged from 3.45 to 3.55 were selected.

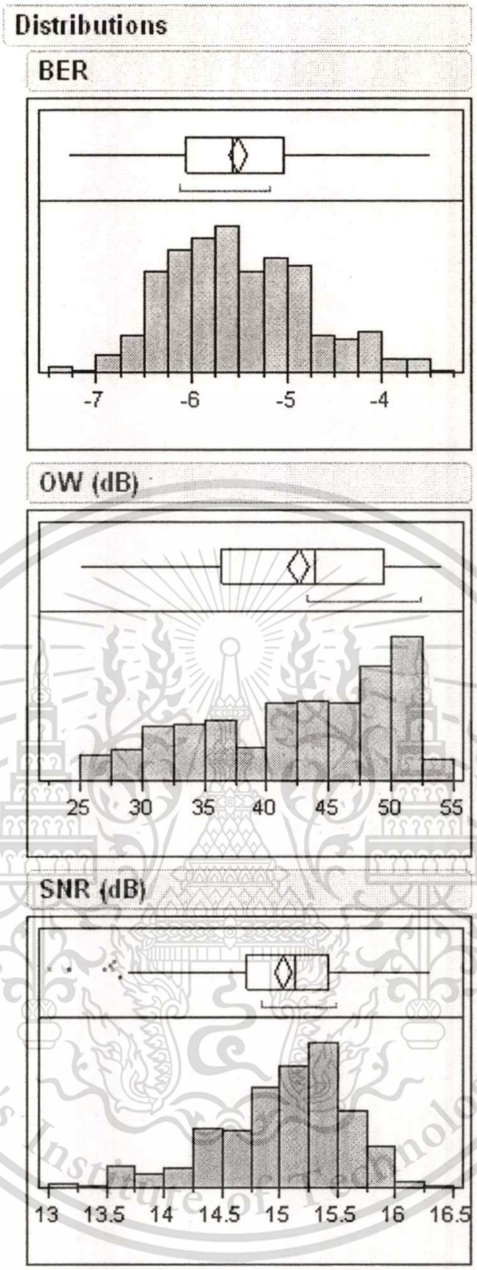


Fig. 3.7 Parametric performance of the cherry picked samples

Fig 3.7 explains the key parametric performance (BER, ROW & SNR) of the cherry picked evaluation samples. From the parametric measurements, the performance of the cherry picked samples were nominal and to the center of the regular product distribution. For BER, we could see the values are ranging in the order of -8 to -4.5. For ROW, the values are in between 25 to 55 dB and for the SNR the values are in the range of 13 to 16 dB.

3.4 List of materials, specifications and research tools used for research

Following is the list of the materials and research tools that were used to perform the experiment of this thesis.

1. Head gimbal assembly using Perpendicular Magnetic Recording writers with the MWW values in the range of 3.5 μin to 9 μin in step of 0.5 μin. Each step has 20 to 25 HGA samples. The tested head samples were all fabricated using the current manufacturing process to obtain a wide range of writer width. These samples could not be used for current products as the writer width is wide.
2. MgO based TuMr reader. The reader width is in the range of 1.1 μin to 1.5 μin.
3. Perpendicular recording granular Medium with the reference soft under layer (SUL) thickness of around 2 μin and the recording layer coercivity of 4500 to 5000 Oe.
4. Commercially available Guzik spinstand testers (HGA based dynamic electrical tester as shown in Fig 3.8) and a 2004-series read-write analyzer (RWA) with the high-performance servo improvement package (SIP).

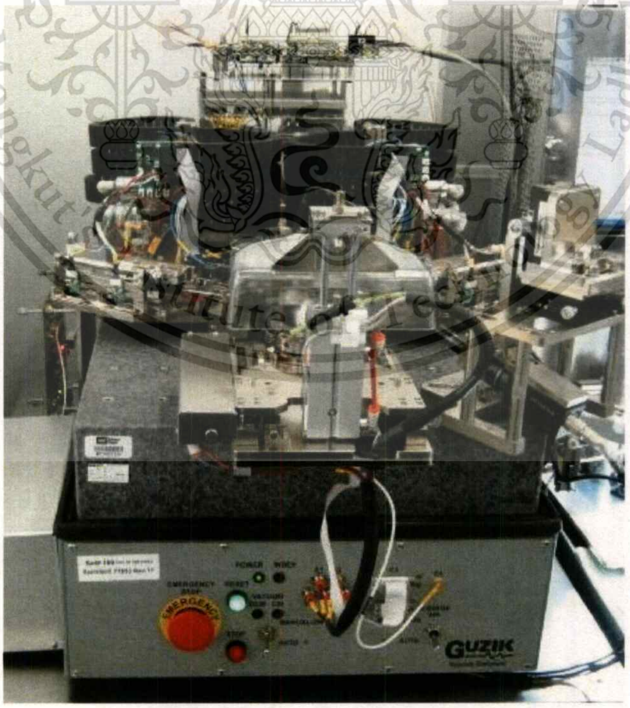


Fig. 3.8 Guzik spin stand tester

5. The commercially available iterative channel (integrated to the Guzik spinstand testers) is used for the BER measurement.
6. Shingled test module (designed by Western Digital Test team) is used for shingled testing.
7. High power & low power microscope (for visual inspection of the experimental samples before testing).
8. Statistical analysis tool "JMP" software is used for the analysis.
9. Middle zone is used for the entire testing and data collection.
10. A linear density of 1875 KFCI is used for the entire testing.
11. For multiple overlapping shingled TPI, we used 1.5 to 3.5 μin at a step of 0.5 μin.

3.5 Experiment structure and data analysis

The experiment for this thesis and the data analysis is performed at Western Digital Bangpa-in plant and KMITL. All experiments related to conventional recording and shingle recording is performed on commercially available Guzik HGA based dynamic electrical tester and the statistical analysis is done using the commercially available "JMP" software.

The experiment structure and data analysis is as follows:

1. The pre selected HGA samples based on the conventional recording data will be subjected to the shingle testing with a fixed shingled track pitch of 2.5 μin. Key parameters such as ROW, SNR and BER are measured. The test results are compared to the conventional recording data.
2. The results from step 1 are analyzed. This result will help us in understanding the feasibility of the SWR. The details are covered in Chapter 4.
3. The same samples from step 1 are again subjected to test on multiple squeeze tests or multiple overlapping shingled TPI in the range of 1.5 μin to 3.5 μin. The same key parameters ROW, SNR and BER are measured. Also the AD is also calculated.
4. The results from step 3 are analyzed. This result will help us in determining the optimal track pitch and the optimal write width for the SWR. Also the AD could also be determined based on the optimal selection point.

5. Based on the different criteria of the selected writer width and the multiple shingled TP, the ratio will be obtained based on the write width and the squeeze/overlapping shingled TP (Shingled TP/MWW). The optimal shingled ratio will be determined based on the desired AD.

Chapter 4

Shingled Recording Feasibility

This chapter describes the feasibility of the shingled write recording using the wide range of writers. In this chapter we evaluate the performance of the normal conventional results on the key parameters such as BER, ROW & SNR based on the perpendicular magnetic recording and shingled recording and finding the difference between the two techniques to see the feasibility. In Section 4.1, the conventional PMR experimental results are explained. In Section 4.2, the SWR experimental results on the same set of samples are explained. The difference between the conventional recording and the SWR are explained in Section 4.3. In Section 4.4 at the end of this chapter, based on the experimental results, we conclude that the SWR is feasible to be extended.

4.1 Conventional Perpendicular Magnetic recording results

Conventional perpendicular recording has been used in the industry for almost a decade now. The entire industry is operating with the perpendicular recording to suit all the demands of the data storage. Currently 600 Gb/in^2 is the areal density that is being produced in the globe. As described before a wide range of write width samples are subjected to the conventional perpendicular recording testing using the commercially available Guzik testers. The key parameters are measured to see the performance of the selected samples in order to facilitate the samples for further experimental works.

Fig 4.1 shows the BER performance for the selected wide range of writer width samples. From the figure, the x-axis represents the writer width (μin) and the y-axis represents the raw BER (in order). Every y-axis data point is the average data of 20 to 25 samples. In this graph, the writer width varies from 3.5 μin to 9 μin in step size of 0.5 μin. The BER tested results vary from -4.6 orders to -5.7 orders. For the lower range of the writer width samples i.e. from 3.5 μin to 4.5 μin, the BER performance is almost observed to be flat maintaining at the value of -5.7 orders. In other words, the samples smaller than 4.5 μin experiences the lower BER performance compared to those of higher widths. This is due to the deficiency of the writability for the lower write width samples.

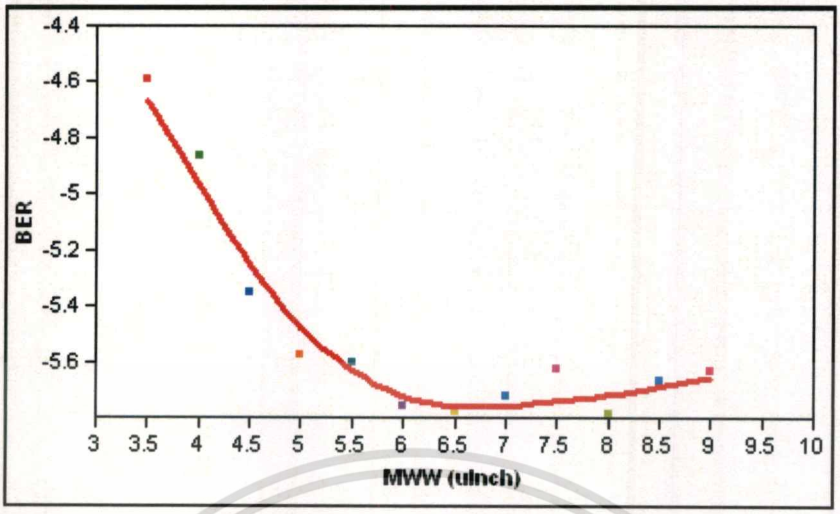


Fig 4.1 BER performance against MWW on Conventional recording.

Fig 4.2 illustrates the performance of the reverse overwrite against the wide range of writer width samples for the conventional perpendicular recording. In this picture, the x-axis denotes the writer width measured in the Guzik tester (in μin). The y-axis denotes the measured reverse overwrite values. The Reverse Overwrite values ranges from 30 dB to 50 dB having an incremental trend from 3.5 μin to 9 μin. The maximum values are obtained with the writer width of 7.5 to 8 μin. After 5 μin the measured ROW values trends flat with the range of 3 to 4 dB. A 30 dB ROW is quite good enough for the recording system and is achieved by 3.5 μin. This value is said to be good writability for the conventional recording. As we can see the trend of the ROW is trending down for the lower writer width samples, the writer width of less than 3.5 μin will have a deficiency for the writability. In conventional recording if the write width is increased it might cause serious ATE issues and also have a concern on the wide area track erasure. Based on the test results obtained, it is understood that one of the key parameters ROW is good enough for the selected samples and these samples are meant to be good for using for further experimental activities. In other words, these samples have good writability for the given range of the writer width values.

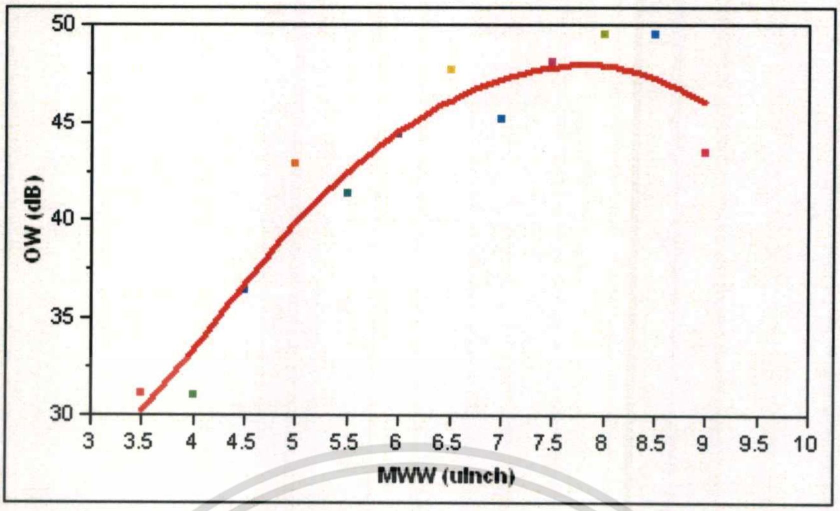


Fig 4.2 Reverse Overwrite performance against MWW on Conventional recording.

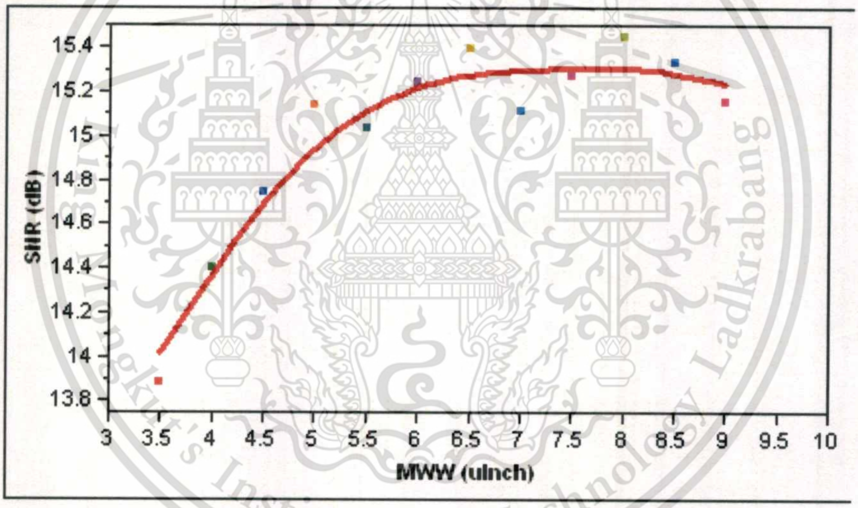


Fig 4.3 SNR performance against MWW on Conventional recording

Fig 4.3 shows the measured SNR performance from the Guzik tester for the pre selected head samples. As for the other two described parameters (ROW and BER), SNR too represents the measured performance for a wide range of write width (3.5 μin to 9 μin) which is shown in the x-axis. The y-axis denotes the measured performance of the signal to noise ratio. The SNR values range from 13.8 dB to 15.4 dB. The lower the writer width is used, the lower SNR seems to be. Similar to the BER performance, the signal to noise ratio has a linear increment against the write width samples. The trend increases from 3.5 μin to 4.56 μin from 13.8 dB to around 15 dB. For the size above 4.5

μin, the performance remains almost flat. Similar to the other key parameters BER, the ROW and the SNR values for the selected parameters have good performance. The values obtained are well ahead of the need of the recording system.

4.2 Experimental Results of Shingled Write Recording

Based on the limitations of the conventional recording due to the so called super paramagnetic effects, there needs to be a new concept to increase the areal density. Several candidate technologies are being explored. One of the promising concepts without a major cost impact or major technological impact is SWR, which is being seriously considered as an alternative. This technology is perceived as an extension of the current perpendicular recording with probable minor changes compared with the conventional recording. In this section, we study and analyze the performance of the same selected samples that were studied for the conventional recording on the new SWR concepts. The same key parameters such as ROW, BER and SNR are measured using the Guzik spin stand testers. For shingled recording, a specifically designed test module solely owned by Western Digital is used to test the samples for shingled recording. The samples were tested with a fixed overlapping track pitch (squeeze track pitch) of 2.5 μin.

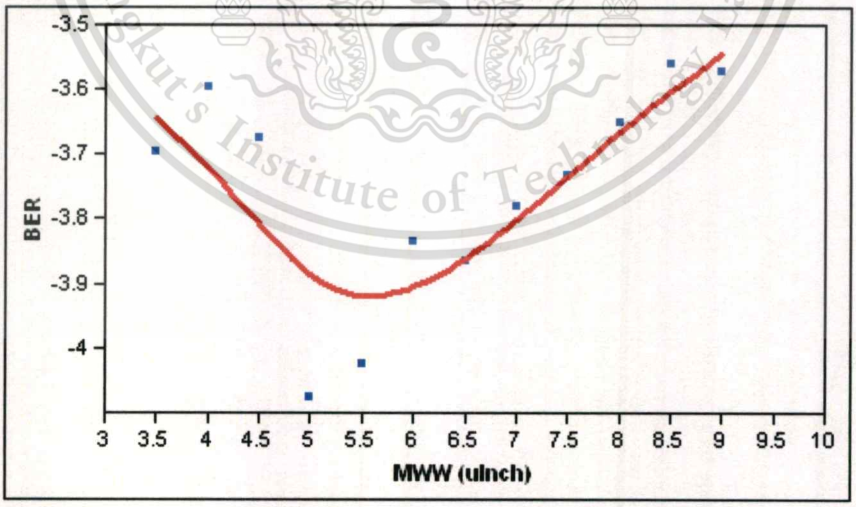


Fig 4.4 BER performance against MWW of shingled write recording.

Figure 4.4 shows the BER performance at various write width samples ranging from 3.5 μin to 9 μin, with the constant shingling track pitch of 2.5 μin. The BER varies from -3.6 to -4 orders across multiple write width samples. However, the graph shows as a U curve with a function BER = a*MWW^2 + b*MWW + c (or others…). Based on the results, the optimal result is obtained with a write width of 5 to 6 μin, having the best case of BER around -4.1 orders with the 2.5 μin squeeze test. Also this graph suggests that for the write width samples smaller than 5 μin, the BER does not have a fixed pattern or a trend. This is due to the deficiency of the writability for the lower write width samples. For the write width samples greater or equal to 5 μin, we see the performance drops in a linear way, i.e., the higher the write width results to the lower performance, and the impact of drop between two different writer width levels does not have a significant difference and this difference can be attributed to the repeatability of the head, media and the system as theoretically the values are to be flat. The BER values that are obtained across multiple write width samples are acceptable for the recording system.

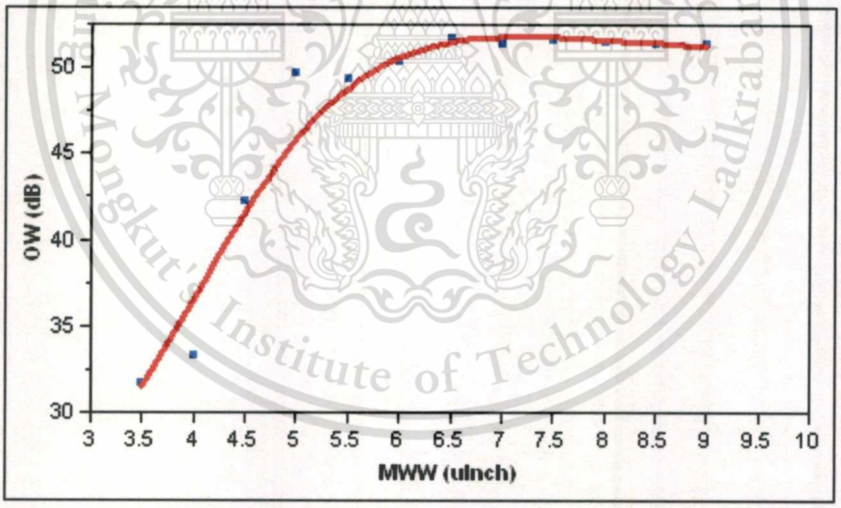


Fig 4.5 Reverse Overwrite performance against MWW on shingled write recording

The shingle write performance in terms of the ROW from the Guzik spinstand is shown in Fig 4.5. The track pitch of 2.5 μin was used to overlap the previous written track for shingling. The graph can be divided into two parts based on the write width values. The write width values of less than 5 μin as one part and above 5 μin as the other part. The lower part has the ROW values ranging around 30 to 40 dB which is due to the insufficient writability for the write width samples below 5 μin, and the other part has the flat ROW performance at around 50 dB. It means that for the write width values above 5 μin, the ROW remains constant and is similar to the theoretical predictions, in other words, it is saturated to a value. This proves beneficial for the writability since we have seen that with a 2.5 TPI, we cannot achieve a good overwrite performance in the conventional recording, unlike the shingled recording. This is a good sign to overcome the writability deficiency when we need to increase the areal density because for the conventional recording, the only way to increase the areal density is to reduce the writer widths. Shingling can prove it right for increasing the areal density.

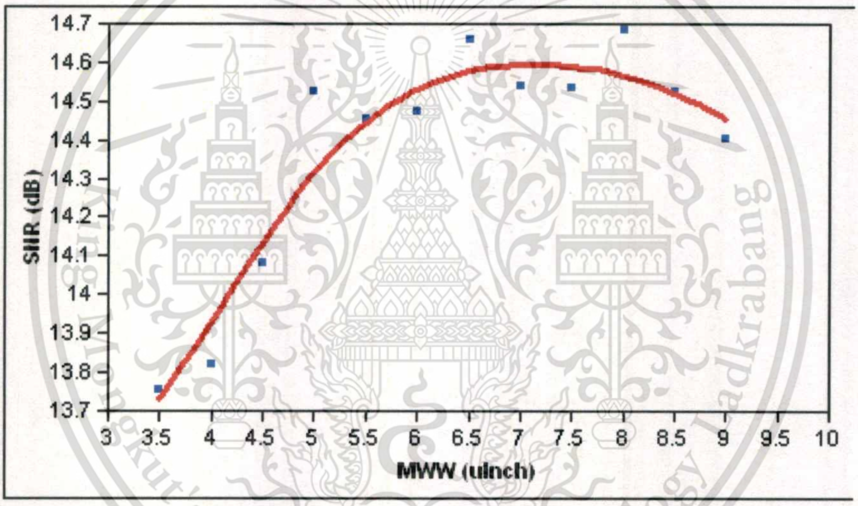


Fig 4.6 SNR performance against MWW on shingled write recording

Fig 4.6 describes the Signal to Noise Ratio performance with a constant overlapping track pitch of 2.5 μin across various write width samples (3.5 μin to 9 μin). Similar to the ROW results shown previously, the SNR results are different for the two ranges of the MWWs. We can see that for the samples with the write width higher than 5 μin, the performance of the SNR seems to be almost flat averaging in the range of 14.5 dB (+/- 0.1 dB) which matches to the theoretical values which are supposed to be flat. These SNR values are higher than those found in the current recording systems and are well within the nominal distribution values. For the write widths below 5 μin, the SNR values drop significantly. For every decrement step of 0.5 μin, the SNR drops sharply by about 0.2 dB to 0.3

dB. This drop is due to the writability deficiency on the lower write width samples. On the lower write width samples, the signal that is recorded by the writer is over dominated by the noise level or the reader head could not read the signal to the full extent suppressing the noise level. Thus we have the writability deficiency.

4.3 Comparisons between Conventional recording and Shingled Write Recording

In the previous sections the conventional recording results and the shingled recording results are discussed separately. In this section we combine both the conventional recording and the new shingled recording techniques to find out the performances difference between the two recording techniques. The same sample size is being compared between the two recordings to understand the performance of the two techniques. As mentioned earlier, the SWR uses the 2.5 μin constant overlapping track pitch for the shingled recording. Just to clarify that the results discussed here are similar to the above sections. The plots are just overlaid to understand the differences. The same key parameters such as ROW, SNR and BER are discussed here.

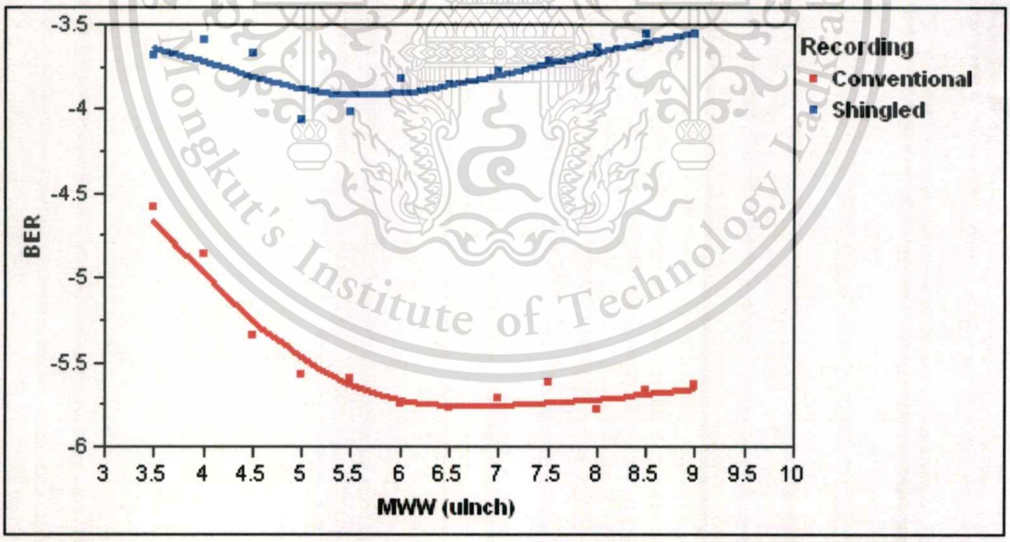


Fig 4.7 BER comparisons between the Conventional Vs Shingled Write Recording

Fig 4.7 shows the comparison between the conventional recording and the SWR. The x-axis is the magnetic write width ranging from 3.5 μin to 9 μin. The y-axis is the test performance of the BER results. From the figure, the red colored lines correspond to the conventional recording and the blue colored ones represent the shingled recording. As said earlier, due to the deficiency of the writability for the lower write width samples, both the conventional and the shingled recording has relatively poor performance for the samples ranging from 3.5 to 4.5 μin. The results show that in the conventional recording, the BER is better and, in the case of the shingled recording, the BER results appear to be lower in performance with similar trend to the conventional recording with a gap of around 3 orders. The results suggest that in the shingled recording techniques, the wider writer width samples could be used. This is one of the critical parameters to control during the manufacturing process. Wide writers also give an additional option for increasing the AD since the higher flux generated from the wide writer (recording field) allows the higher anisotropy material on the media. Also from Fig. 4.7, for the narrow write width samples, the BER levels of the SWR is close to those of the conventional PMR. Using conventional recording, the BER of -2.5 orders is sufficient for use in a recording system. So the results from the shingled recording suggest the BER level of -3.5 to -4 orders. This level of BER could be enough for the currently available read channel to detect and retrieve the necessary information from the medium using the SWR.

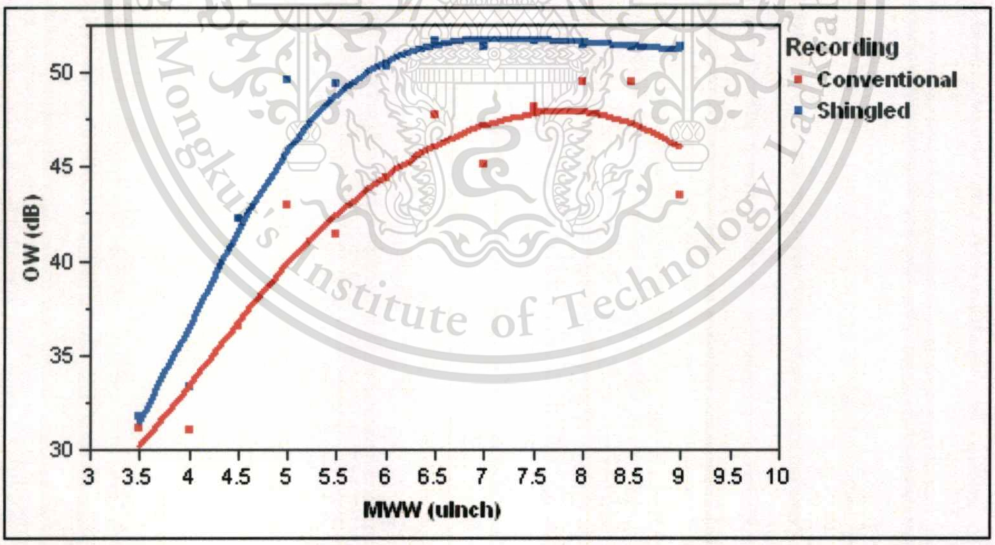


Fig 4.8 ROW comparisons between Conventional and Shingled Write Recording

Fig 4.8 shows the difference in ROW between the conventional recording and shingled track recoding. For the narrow write widths both types of recording show similar ROW levels. As the write width increases, the shingled recording reads better ROW at any given point of the write width values. The delta between the two recording techniques is around 5 dB whereby the shingled write recording reads higher values. The trends of these two techniques are quite similar. The better Reverse Overwrite values are observed for the writer width values above 5 µin. For the conventional recording, the ROW values are observed to be around 46 dB, and for the shingled recording the values are shown to be around 50 dB. Both of these ranges are considered to be a good representation of the better writability.

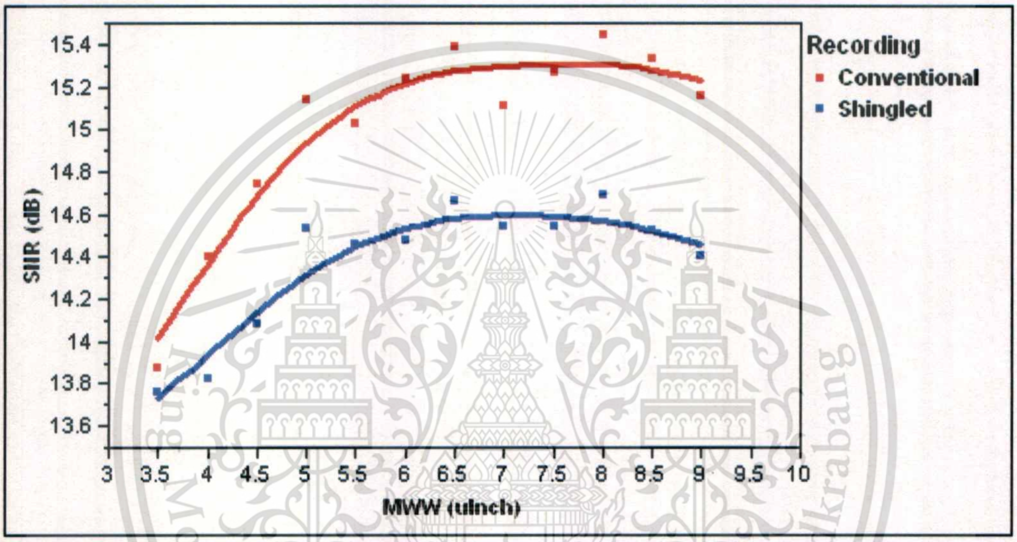


Fig 4.9 SNR comparisons between Conventional and Shingled Write Recording

Fig 4.9 shows the comparison difference between the conventional recording and the shingled recording for the SNR against various writer width values. As seen in the ROW difference, SNR too have the similar trend as the narrow writer width values senses the lower SNR performances. As the write width values increases, the results from SWR and the conventional recordings appears to be flat. For the conventional recording the maximum SNR is in the range of 15.2 dB and for the shingled recording, the values are noted to be 14.8 dB. The delta between the two recording techniques remains to have the same ratio after 5 µin until 9 µin write width values.

4.4 Conclusions on the Shingled Write Recording Feasibility

The spinstand tests on the writability of the conventional and shingled recording using the available heads in the manufacturing process have been investigated. Various magnetic write width samples are tested and compared between the conventional PMR and the recently proposed SWR using the commercially available Guzik spinstand with the constant overlapping track pitch of 2.5 µin. The result obtained from the commercially available Guzik spinstand testers demonstrates the feasibility of the SWR with sufficient BER and SNR values. The ROW data of the SWR are comparable to that of conventional recording, indicating the suitable writability. The SNR study shows only a 0.8-dB gap between both types of recording. With the BER level of -3.5 and the SNR of around 14 dB, the current commercially available read channel can retrieve the signal from the medium after the recording. The ROW study with different write width samples explains that the SWR has better values when compared to the conventional recording. This is an another advantage and a benefit of the shingled approach since the current conventional perpendicular recording needs to reduce the write width in advancing towards the AD, which in turn will affect the writability. Based on the test results, we observed the samples that range from 3.5 to 4.5 µin; the deficiency is clearly observed on all the key parameters. Comparing to the earlier studies, we observed that the ROW observed similar increasing trend than the conventional recording. SNR and BER also observed similar trend with a constant delta between the conventional and the shingled recording, whereas the shingled recording exhibits lower performance. Based on the experimental results, we see that the SWR is feasible and it also illustrates that the conventional perpendicular magnetic recording could be well extended.

Chapter 5

Spin stand Experiment on Multiple Shingling

In the previous chapter 4, the performances of the shingled writing and the feasibility of the shingled for a fixed track pitch were studied and discussed. In this chapter, we will evaluate the performances of the same key parameters (ROW, SNR and BER) that were studied before using the same samples against multiple shingling (overlapping track pitch). We observed that the samples smaller than 5 μin has the writability deficiency. Though, we use those samples in the multiple shingling to understand and study their ability across multiple shingling. At the end of the chapter, we will be able to identify the optimum value for the shingling track pitch. Also we will be able to identify the optimum writer widths which would give us the better performance on the shingle.

In this chapter, we will discuss the experimental results of all the key parameters. In section 5.1 the Bit Error Rate test result analysis is discussed. In section 5.2, SNR test result analysis is discussed. The ROW test result analysis is discussed in the section 5.3. We will focus on the areal density and the interpretation of the areal density against different shingling in section 5.4.

The multiple shingling track pitch is varied from 1.5 μin to 3.5 μin and the key parameters ROW, BER and SNR is measured for a wide range of write width samples. The shingling track pitch to the original write width of the sample is normalized by percentage and this shingling percentage is also discussed for the key parameters. The areal density calculation will also be analyzed based on the shingling percentage. The optimization is the key for this study as we go beyond the current PMR. For all the key parameters, the optimizations need to be done with respect to the areal density requirement. The limitation in this study is that we use the fixed linear density for all the calculations. Though it is not a serious concern and the appropriate optimization limits could be very well used for all future testing as the best case scenario is explained in this study.

5.1 Bit Error Rate test result analysis

The spinstand test result of the BER is discussed in detail below. This parameter is one of the key parameters to predict the functionality of the head media combination, particularly the recording head. The results discussed here are the on track raw error rate performance after the iterative code with a single loop. The BER in this study is defined as log (total erroneous bits/total bits). In general a -2.5 order of the BER is quite good enough for the recording channel to function and retrieve the information from the storage with the current available channels. Also with multiple iterations, a further better performance of the BER may be achieved.

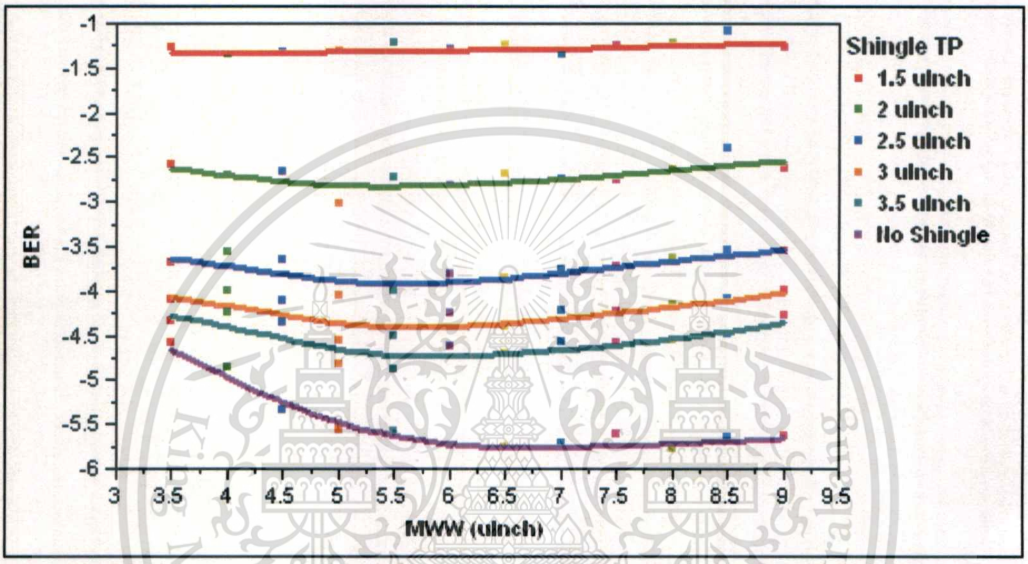


Fig 5.1: BER performances for various write width using different Shingle TP

Fig. 5.1 shows the performance of the BER against a large variation of the write width samples (ranges from 3.5 μin to 9 μin) against various shingling track pitches (overlapping track pitch of 1.5 μin to 3.5 μin including the data from No shingle). From the plot, each colored line denotes by the shingling track pitch and each dotted point is colored based on the writer width of the samples used.

For the shingling track pitch of 1.5 μin, the BER are observed to be almost flat for various writer width samples, with the BER reading around -1.25 to -1.35 orders. For 2 μin shingling, the graph is observed to be a marginally U shaped with the values ranging from -2.5 orders to -2.8 orders. The best performance is observed with the magnetic write width of 5.5 μin to 6 μin range. With shingling track pitch of 2.5 μin, the BER varies from -3.6 to -4 orders across multiple write width samples. At 3.0 μin shingling track pitch, the BER reads from -4 to -4.5 orders. And at 3.5 μin shingling track pitch, the BER reads in the range of -4.3 orders to -4.8 orders. The graph shows as a U-curve for various shingling track pitches, on the contrary to the flat line as expected from the theory. This is due to the poor performances of the samples that are between 3 to 4.5 μin as described in the previous chapters. The values above these write width samples are almost observed to be flat for all the shingling track pitch values. From the previous literature review studies from Fig 2.14, we observed that the BER value at 2 μin (500 KTPI) was in the range of -2 orders. In our current experimental study, we observed the BER value to be in the range of -2.4 orders which validates this experimental study and also the samples that are selected.

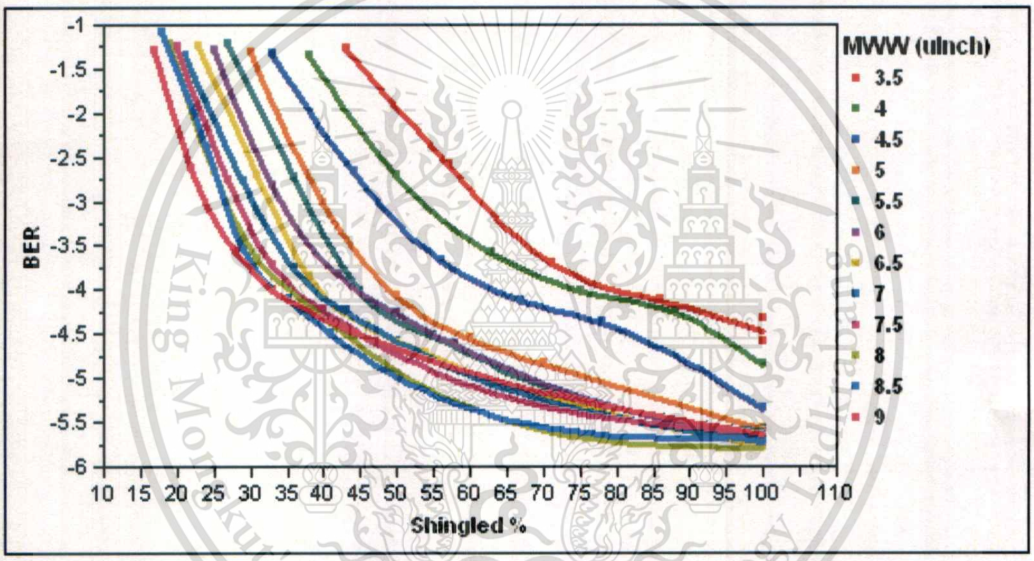


Fig 5.2: BER performance against the normalized Shingling percentage

Fig 5.2 shows the plots of the BER performances against the shingling percentage for various write width samples. The x-axis denotes the shingling percentage and the y-axis denotes the BER performance. Every writer width is separated out by individual colors as shown in the figure. The shingling percentage is calculated as follow:

$$\textbf{Shingling \% = } \mathbf{TP_s/MWW * 100}$$

Where TP_S is the shingling track pitch.

Shingling TP is the overlapping track pitches that we used in the study 1.5 to 3.5 µin and MWW ranges from 3.5 to 9 µin. From the graph, the value 100% means no shingling that are tested using the same write width values as the track pitch. Also, the MWW value of 3.5 µin against the shingling TP of 3.5 is considered to be no shingling which is 100%. The BER values ranges from -1 order to -5.5 orders for various samples. We observe that the lower the percentage of shingling, the BER tends to drop. There is a good linearity towards the shingling percentage. There seems to be a kind of two groups from the plot. The writer width values of 3.5 to 4.5 µin seem to be separating from the rest of the other group of writer width samples. This is due to the poor performance of the lower write width samples or as explained earlier these samples have writability deficiency. This graph gives us a clear idea to determine the value of the BER against multiple write width samples. Shingling percentage which is lesser than 50% has huge variations (around 3 orders range) on the BER compared to the shingling above 50% which has lesser range (around 1.5 orders).

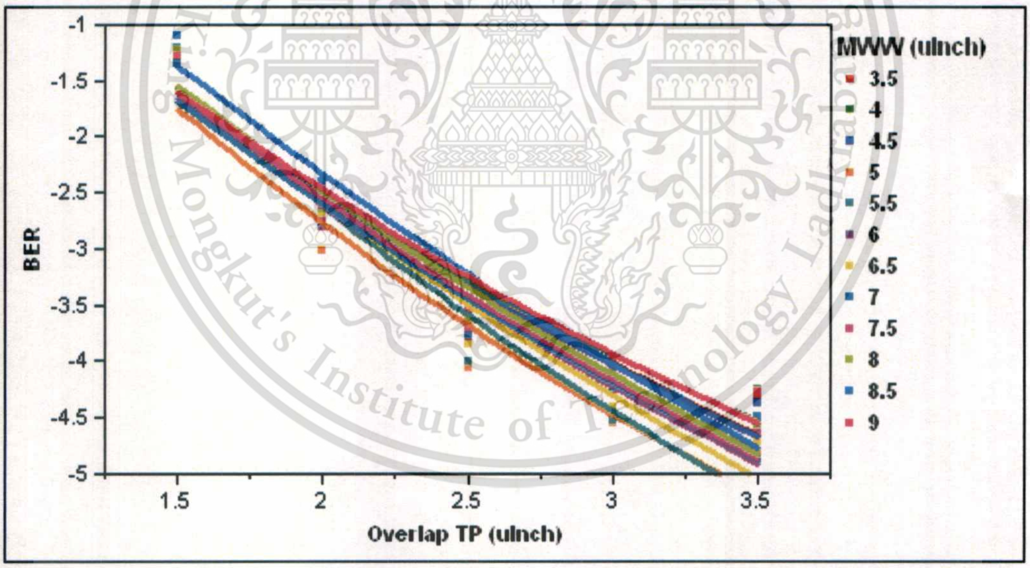


Fig 5.3: BER performance against Shingling TP

Fig 5.3 again shows the performance of the BER against multiple shingling track pitch (overlapping track pitch). The data is similar to those in the earlier graphs, but here it is shown to find out the ranges within the shingling track pitch. The range is observed to be narrow for the entire write width samples within each and every shingling track pitches. The mean value of the BER is shown in the Table 1.1.

Table 1.1: BER performance data against Shingling TP for various MWWs

Shingling TP	Mean
1.5 μin	-1.3
2 μin	-2.7
2.5 μin	-3.8
3 μin	-4.2
3.5 μin	-4.6

For multiple writer width samples, the mean ranges from -1.3 orders to -4.6 orders. The range of the BER values fro each shingling track pitch for various writer width samples seem to be lower which is around 0.5 orders. We observe that the wider shingling track pitches lead to better BER.

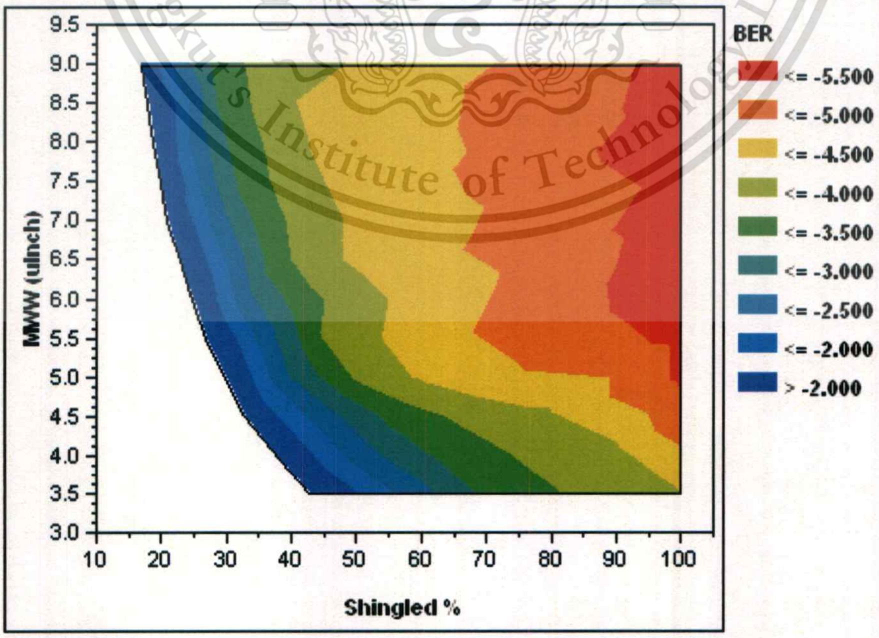


Fig 5.4: BER Contour Plot for various shingling percentages.

Fig 5.4 represents the contour plot of BER against the shingling percentage. The data is equivalent to the Fig.5.2, but here in this graph, we can clearly identify the shingling percentage against multiple writer width samples. The range of the shingling percentage gets higher for the samples that are lesser than 5 μin. This one suggests that for a better BER performance on shingle, it is suitable to use the samples that are greater than 5 μin. Also, the higher the shingling percentages yield the higher BER results.

5.2 SNR test result analysis

The spinstand test result of the SNR is discussed in detail below. This parameter is another key parameter, in addition to the BER, to predict the functionality of the head media combination, particularly, the recording head. The results discussed here are the combined ratio from the head, media and the system noise. The SNR in this study is derived from multiple spectrum ranges that ranging from the pattern 1T to 6T bit cell periods. In general, a 12 dB of the combined SNR is sufficient for the recording system. Fig 5.5 shows the Signal to Noise Ratio against various write width samples for Shingling track pitch ranging from 1.5 μin to 3.5 μin. From the figure, we observe that the SNR values are good without shingling. For the 1.5 μ-in writer widths, we observe the lowest SNR from the other groups. The SNR increases from 13 dB to 13.7 dB for the writer width samples ranges from 3.5 μin to 6 μin and it almost remains flat thereafter. All other shingling track pitch values observe the same trend which has a linear increment from 3.5 μin writer widths to 6 μin writer widths and the SNR observed to flat after 6 μin writer widths. The optimal performance of the SNR is achieved at 6 μin for all the shingling track pitch where 2 μin of shingling observed 14.1 dB, 2.5 μin observed 14.4 dB, 3 μin observed 14.6 dB and 3.5 μin observed 14.7 dB, respectively. So we see a 1 dB of SNR increase from 1.5 μin to 3.5 μin shingling track pitch (optimal value). From the previous study in Fig 2.13, we observed the SNR value of 12 dB for the 2 μin TP (500 KTPI). The current experimental study observed the SNR value of around 14 dB for the similar 2 μin shingling track pitch which satisfies the trend and also the credibility of this study.

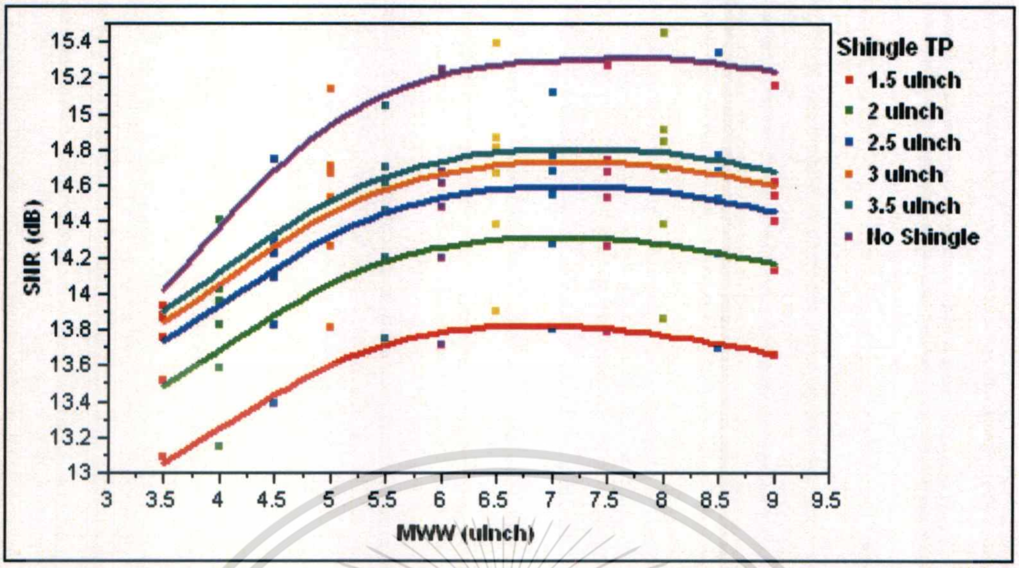


Fig 5.5: SNR performances for various write width using different Shingle TP.

The SNR values for all the shingling track pitches are well sufficient for the recording system point of view. Based on this, SNR is not a concern for the discussed shingled track pitches, but when compared to the BER, an optimal point is needed to consider in order getting the better SNR and BER for the recording channel point of view.

Fig 5.6 shows the plots of the SNR performances against the shingling percentage for various write width samples. From the graph, a 100% level refers to no shingling case. The SNR values ranges from 13 dB to 15.4 dB for various write width samples across the entire shingling percentage. We observe that the SNR drops with the lower shingling percentage. There is a good linearity towards the shingling percentage against the SNR. Based on the graph, we observe two groups. The writer width values of 3.5 to 4.5 μin seem to be separating from the rest of the other group of writer width samples. This graph gives us a clear idea to determine the value of the SNR against multiple write width samples for every shingling percentage.

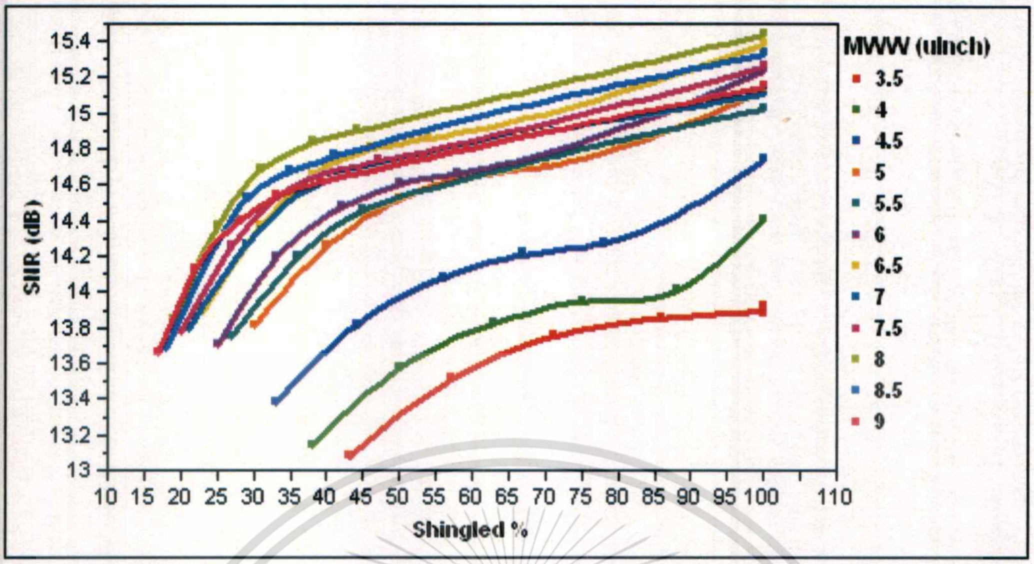


Fig 5.6: SNR performance against normalized Shingling percentages.

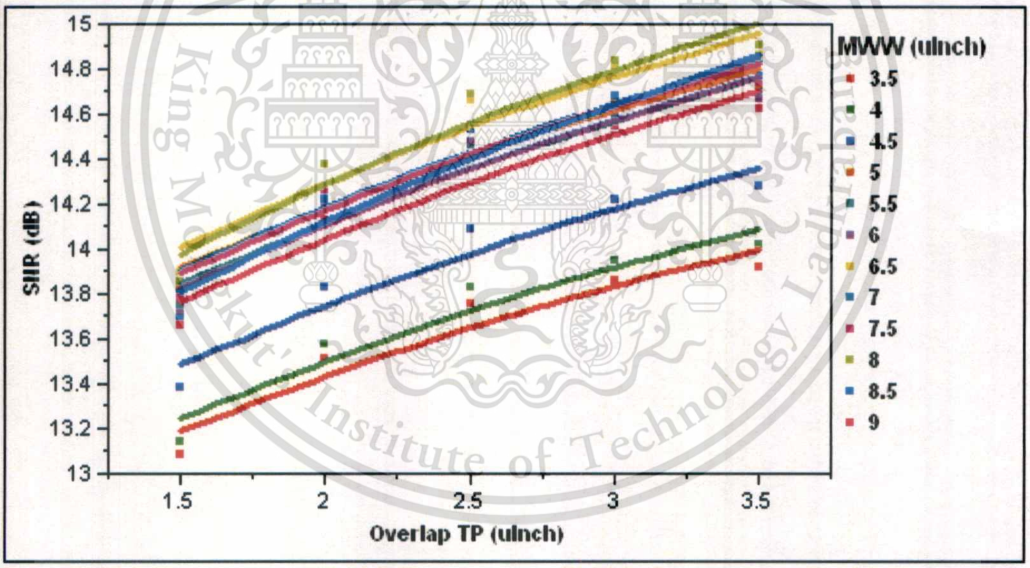


Fig 5.7: SNR performance against Shingling TP for various MWWs.

Fig 5.7 here shows the performance of the SNR against the shingling track pitch (overlapping track pitch). From this graph we observe a clear separation of two groups as we have seen before and also have explained the performance due to the poor writability. Also we see a very good linearity of the SNR against the shingling track pitch where we observe the SNR increases as the shingling track pitch increases. Based on the data, we observe that for the shingling track pitch, the mean value of the

SNR does not vary much. The data is shown in the table below. For every step the mean is inclusive of all the writer width samples. This is described to see the variations within the individual group of shingling track pitch. Due to a clear separation with two different group as specified earlier, the below data from table 1.2 seems to be having closer SNR values. This graph also denotes a good understanding on samples that are to be used and finding a potentiality for the shingled write recording.

Table 1.2: SNR performance data against Shingling TP for various MWWs

Shingling TP	Mean
1.5 µin	13.6
2 µin	14.1
2.5 µin	14.4
3 µin	14.5
3.5 µin	14.6

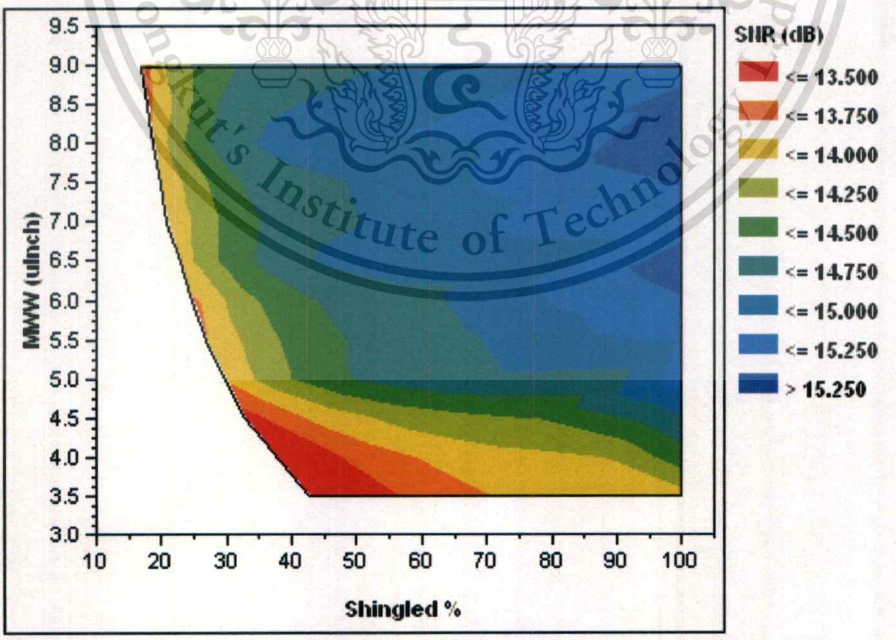


Fig 5.8: SNR Contour Plot against various shingling percentages.

Fig 5.8 shows the contour plot of the SNR for multiple write width samples against the shingling percentage. The data is equivalent to the figure shown in 5.6. Here in this graph, we can clearly identify the shingling percentages against multiple writer width samples for SNR behavior. The SNR could not be predicted for the samples that are less than 5 μin. For the samples above 5.5 μin the shingling percentage and the SNR relation could be very well predicted for usage. Also, the higher the shingling percentage yields the higher SNR results. Even the lower shingling yields the SNR values which are sufficient for the recording system. Also the trend between the BER and the SNR appears to be similar illustrating a good correlation between these two parameters.

5.3 Reverse Overwrite test result analysis

The spinstand test result of the ROW is discussed in this section below. Overwrite determines the writability for any particular writers. Conventionally, the writer width is always reduced to increase the areal density. As the writer width is reduced, there are always writability issues. Also due to the manufacturing process tolerances, the writer width could not be manufactured precisely to meet the target values. ROW is the ratio between the 13 T to 2T pattern. Normally for a good writer, a 30 dB of ROW is reasonable for the recording system.

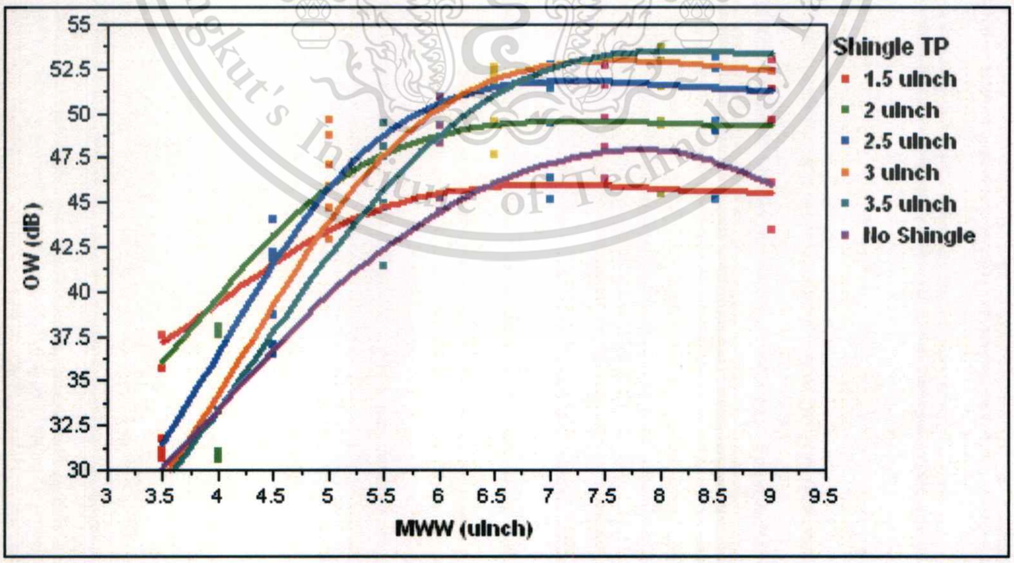


Fig 5.9: ROW performances for various write widths using different Shingle TP.

Fig. 5.9 shows the ROW performance for various writer width samples against a multiple range of shingling track pitches. From the graph we see that the ROW increases as the magnetic writer width increases up to 6.5 µin. Beyond this writer width value, the ROW is observed to be remains almost flat. This graph clearly indicates that the shingled overwrite is significantly higher than the non shingle case. Except for the 1.5-µin shingling, all the other shingling from 2 µin to 3.5 µin shows significantly higher ROW values. The 1.5 µin shingling also shows the higher ROW until 6 µin of writer width samples. Beyond this, it seems to be flat saturated curve. From the earlier literature reviews, the ROW value from Fig 2.12 is observed to be in the range of 30 to 45 dB for multiple heads using 2 µin shingling track pitch (500 KTPI). In our experimental study, we obtain the ROW in the range of 30 to 50 dB. This comparison looks encouraging and also validates the credibility of the current experiment. This will also facilitate to use these key parameters for calculations sake in further studies.

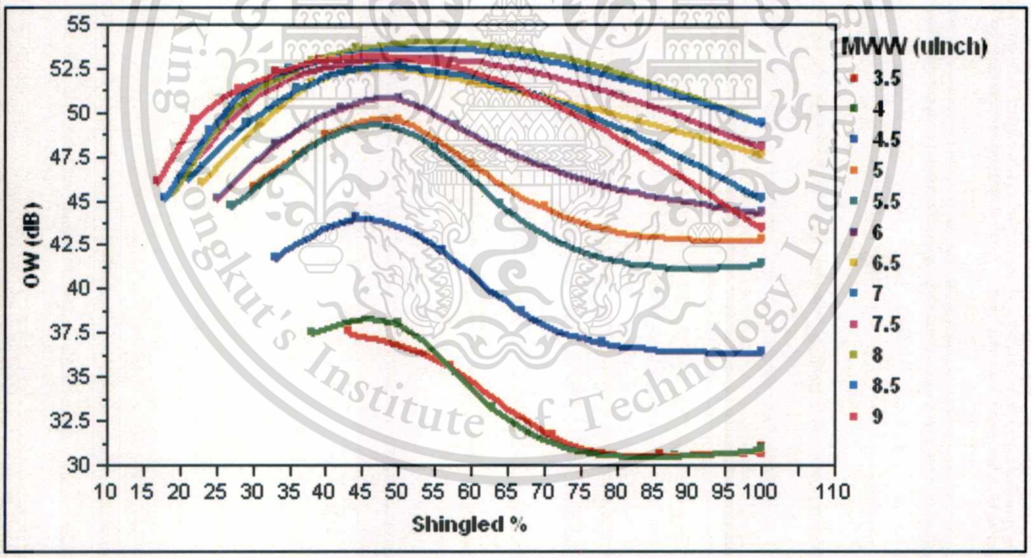


Fig 5.10: ROW performance against normalized Shingling percentages.

Fig. 5.10 shows the plots of the ROW performances against the shingling percentage for various write width samples. From the graph, 100% is defined as No shingling. The ROW values ranges from 30 dB to 53 dB for various write width samples across the entire shingling percentage. We observe that the ROW drops with the lower and higher shingling percentage. The ROW seems to have a roll off around 45% to 50% and the best optimal values are achieved in this shingling percentage. Based on the graph, we observe two groups. The writer width values of 3.5 to 6 µin seem to be separating from the rest of the other group of writer width samples. The ROW value above the 6 µin has a narrow ROW distribution compared to the lower group. This graph gives us a clear idea to determine the optimum value for the ROW against multiple write width samples for every shingling percentage.

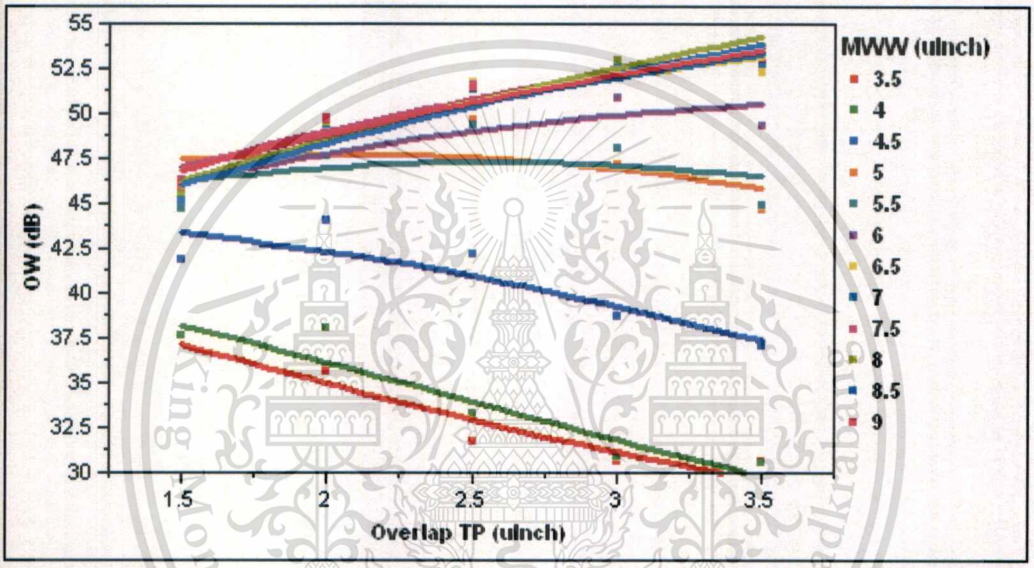


Fig 5.11: ROW performance against Shingling TP

Fig 5.11 here shows the performance of the ROW against the shingling track pitch (overlapping track pitch). From this graph, we observe a clear separation of two groups as we have seen before for other parameters but here the two groups separation is either lesser than 5 µin or over 5 µin of the writer width samples. The higher group has a raising ROW as the shingling track pitches increases. And it is vice versa for the lower group which is lesser than 5 µin which is due to the writability deficiency on the lower write width samples. Based on the data from table 1.3, we observe that for the shingling track pitch, the mean value of the ROW is as below. For every step the mean is inclusive for all the writer width samples. This is described to see the variations within the individual group of shingling track pitch. Due to a clear separation with two different group as specified earlier, the below data seems to be having closer ROW values. This graph also denotes a good understanding on samples that are to be used for the SWR.

Table 1.3: ROW performance data against Shingling TP for various MWWs

Shingling TP	**Mean**
1.5 μin	43.9
2 μin	46.5
2.5 μin	47.0
3 μin	46.7
3.5 μin	46.1

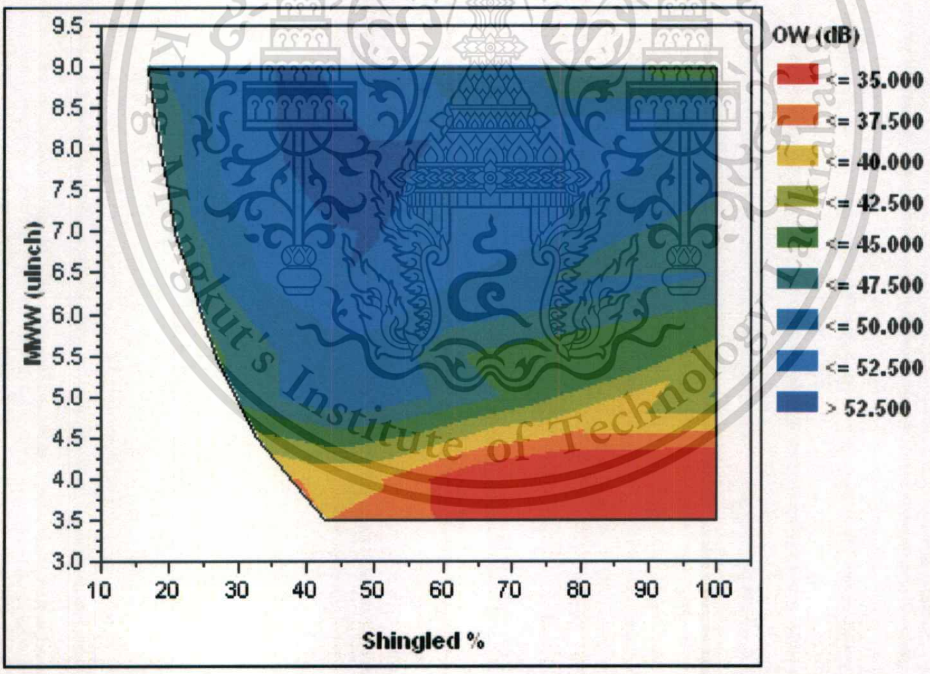


Fig 5.12: ROW Contour Plot against shingling percentages.

Fig 5.12 shows the contour plot of the ROW for multiple write width samples against the shingling percentage. The data is equivalent to the figure shown in 5.10. The trend is similar to the earlier graph too. Here in this graph we can clearly identify the shingling percentage against multiple writer width samples for ROW behavior. The ROW could not be predicted for the samples that are less or equal to those samples with 6 μin. For the samples above 6 μin the shingling percentage and the ROW has a u curve in this graph. The lower shingling percentage and the higher shingling percentage observe lower ROW. The lower ROW on the lower write width samples are due to the writability deficiency and on the higher write width samples are mostly affected by the erase bands. These erase bands play a major role while increasing the write width parameters (need further study on this topic). However, the values that we obtain from this experimental study for the ROW is convincing enough for the current recording systems. The major writability deficiency on the conventional recording when the write width is reduced was explained previously. The current practical and experimental analysis shows that the SWR is not a threat for ROW.

5.4 Focus on Areal Density

For the past decade the AD growth is tremendous. HDD serves the majority data storage for the entire world. We know that the conventional perpendicular recording will serve the industry until 1 Tb/in^2 based on the theoretical analysis. Currently, the entire HDD industry is operating at 600 GB/in^2. Shingled Magnetic Recording is proposed quite long ago for the extension of the areal density. Now the entire industry is eyeing this concept and studying the feasibility as this concept is an extension of the conventional recording without as excessive investments as other new technologies that have been proposed so far. Based on the spinstand test results, the AD is calculated. In this section, we will analyze the possibility of the AD with multiple overlapping track pitches. The calculations are based on the fixed KFCI and the shingling track pitch. Figures 5.13 show the trend of the areal density. It is seen that the areal density increases upon the squeeze value increment.

Fig 5.13 shows the areal density (calculated based on the fixed KFCI used and the track pitch) for different shingling track pitches. As the shingling track pitch reduces, the areal density could be increased. Fig 2.11 (from previous authors) shows the AD could be increased by reducing the track pitch which is similar to the current trend.

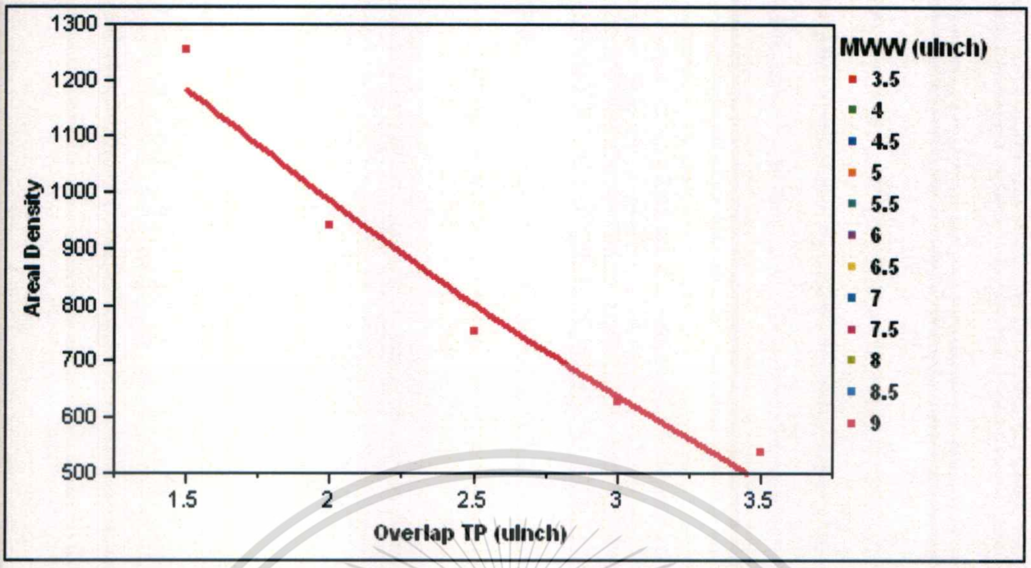


Fig 5.13: AD against different Shingle TP

The areal density of 1Tb/in^2 or higher is feasible but advanced read channel side is required to make the shingled write recording a really feasible candidate at that level of areal densities. From [4], we could see that the AD of 3 to 4 Tb/in^2 is possible. The key geometries are calculated based on the micro-magnetic simulations. Here the samples that we select are practically 50% lower than that of the modeling and here we proved that more than 1 Tb/in^2 is feasible.

Chapter 6

Conclusions

In this thesis, the optimized writer width, fixed shingling track pitch and the variable shingling track pitch for the shingle write recording is proposed and investigated. We started with the session "Introduction" and the detailed descriptions of shingled write recording were explained. Some important researches in the area of Shingled write recording have been discussed in the next section. The advantages and the disadvantages of the Shingled write recording were all discussed. In Chapter 2, the details of the Shingled recording techniques and the advantages were discussed based on the earlier works done on this topic.

In the research methodology, we discussed the conventional magnetic recording, the need for shingled recording and its basic concepts, the sample selection to perform the experimental evaluations, the tools required for this thesis and we also discussed the plan and method of the experiments based on the selected head samples. Using the available pre-selected head samples, the experiment was carried on by first testing the samples with the current conventional recording and then with the shingled recording using a constant overlapping track pitches. The performance of both the conventional and the shingled write recording were extensively analyzed to find out the feasibility of the shingled write recording. It is clearly understood that the shingled write recording could be an easy option to extend the areal density beyond the limitations of the current conventional recording.

Based on the research method, the samples were tested using multiple shingling track pitches and the results of the key parameters such as ROW, BER, SNR and AD were all discussed. The trends from the results obtained exactly match the earlier studies done either theoretically or experimentally. Also we touched on the areal density to verify and determine the need for the future areal density and how the shingling could solve the need of the future demands. Based on all the experimental results, the optimized performance of the key parameters could be estimated. Based on this data, the criteria for manufacturing the write width samples could be estimated. The fixed shingling track pitch and the variable shingling track pitch to suit the areal density demands of the future using the Shingled write recording and its feasibility is extensively discussed.

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