Probe Recording in Magnetic Patterned Media

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Abstract

In this paper we explain why future probe storage systems will use patterned media. As a model system, magnetic patterned media will be discussed, even though their data density is limited to about 7 Tbit/in^2. The first results on magnetic probe storage on patterned media are presented, and the problem of switching field distribution is discussed in detail. Finally we will present the first steps into two-dimensional coding for patterned media.

1 Introduction

Since the invention of the hard disk we have seen a gradual decrease of its size, going down from the 24" IBM 350 to the .85" Toshiba microdrives of today. Further miniaturisation will inevitably lead to using microsystem technology. One architecture investigated today is based on a huge array of read/write probes, derived from the cantilevers used in scanning probe microscopy [1]. Each cantilever has an ultrasharp tip which is used to define bits, and extremely high densities over 600 GBit/in^2 have demonstrated [2].

The use of scanning probe techniques opens up a road which might lead to molecular or even atomic storage. That this is not science fiction is demonstrated beautifully by the work of Bennewitz *et al* [3], who positioned Si atoms on a Si surface by means of STM (Figure 2). Next to moving atoms, one could also modify their charge state [4, 5, 6]. Of course, data rates are ridiculously low, but using massively parallel arrays this can be circumvented. Still the challenges are tremendous. For a workable system, data rates per tip of more than 10 kBit/s are needed, using a square cm array of millions of tips. And at an annual density growth rate of 60%, this has to be achieved within 10 years. The road towards this goal (figure 2) will at least see the transition from continuous media towards patterned media. The first occurence of patterned media is in magnetic recording, but soon after single molecular storage will become an option [7, 8]. Much could be learned about storage in molecular and atomic patterned media, by studying magnetic patterned media. In the following, we will start with a discussion on the rationale behind patterned magnetic media and investigations into the major problem of switching field distribution. Next, we will show initial experiments on magnetic probe recording and finalize with first steps into two-dimensional coding.

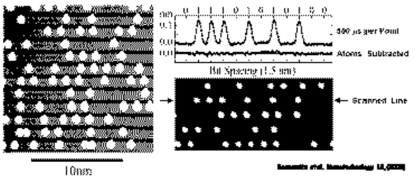

Figure 1: Atomic data storage. Each white dot is a Si atom on a 7×7 reconstructed Si surface [3]

2 Magnetic Patterned Media

The ultimate limit in data density is determined by the thermal stability of the data. Stability is guaranteed by an energy barrier between the (two) stable states of the smallest units. In magnetic recording these states are the magnetisation states of the smallest magnetic entities in the medium. The relaxation time τ of the magnetisation state is described by an Arrhenius process, and can be expressed as:

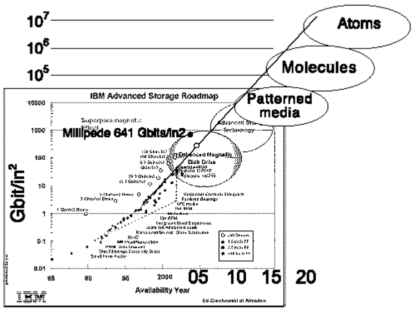

Figure 2: Future recording media will be patterned. Image adopted from Ed Grochowski, IBM Almaden

$$\tau = \frac{1}{f_0} \exp\left(\frac{\Delta E}{kT}\right) \tag{1}$$

Where ΔE is the energy barrier between the two magnetisation states of in the particle, and f_0 is the frequency at which the particle attempts to change its state. The attempt frequency is related to the Larmor frequency of the magnetisation, and usually taken to be 10^9 Hz. It should be noted that this frequency is material, and field dependent, but since the relaxation time exponentially dependent on the energy barrier, that does not really matter at this point. The energy barrier is determined by the volume of the particle V, its magnetic energy density K and the switching mechanism. If we assume a (theoretical) coherent rotation mechanism, the energy barrier $\Delta E = KV$. Hard disk system designers are happy when less than 5% of the grains reverse their magnetisation within the first 6 months, or approximately 10% after 10 years, which means that ΔE should be higher than 40 kT [9]. Magnetic energy densities in the best materials known to us today (FePt in $L1_o$ phase, 6.6 MJ/m^3 [10]) therefore limit the crystal grain size to approximately 3 nm for a stabity of 10 years.

A single bit in a polycrystalline recording medium has to be composed of a sufficient number of grains, because of signal to noise ratio (SNR). By simple counting arguments, the SNR is approximately equal to the number of grains in the bit. For a 20 dB SNR, therefore about 100 grains are needed. Modern data detection and error coding techniques can work with lower SNRs, and it is foreseen that in the future one could work with values less than 10 dB, or 5 grains per bit. This will require very fast processors, and one has to add over 35% extra error correction bits [11].

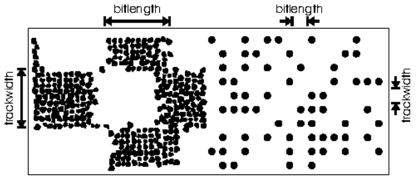

Figure 3: In discrete recording, one bit is written per magnetic element.

Rather than pushing the data channels for lower and lower SNR, one could also consider the medium. If all grains were positioned at predefined locations, one can envision storing one bit per grain (figure 3). This the the concept of a patterned, or discrete, medium [12, 13]. Since the grains in the medium are usually defined lithographically, we prefer to call them dots. An excellent overview of patterned media fabrication techniques can be found in [14, 15], and the over 200 references cited there.

Now it would be naive to assume that gain which can be made when moving from continuous to patterned media is a factor 5-100. Next to technological problems, there is the fact that a ΔE of 40 kT simply is not sufficient anymore. In the case of polycrystalline media, a reversal of 5% of the grains within 6 months is still acceptable. But in a patterned medium, just assume that 5% of the bits will have reversed after 6 months! Channel coding usually can correct "raw" bit error rates of 10^{-4}. Sufficient thermal stability for patterned media therefore means that only one out of 10.000 dots is allow to change its magnetisation. This can only be achieved if the energy barrier ΔE is larger than 49 kT, which means a τ of 50.000 years. The situation is complicated by the fact that the actual energy barrier of the dots is determined by the stray fields of the surrounding dots. Maximum attainable bit density is therefore a function of both the magnetic energy density in the dots, and the magnetisation. In general one would like to have dots with a high energy density and low magnetisation. Carefull analysis of stray fields and thermal stability results in graphs like figure 4 [16]. In this graph the maximum attainable bit density is plotted as a function of magnetisation and energy density. In

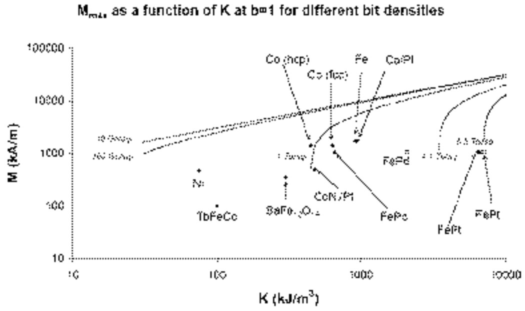

Figure 4: Theoretical upper limits on data density, as function of the saturation magnetisation M_s and anisotropy K.

the calculation, the height of the dots is equal to the diameter, and the diameter is one third of the distance between the centers of the dots. Also shown are various materials found in literature. With the best materials known today, the ultimate density[1] is in the order of 7 TBit/in^2.

3 MFM Studies of Patterned Media

Next to the issue of manufacturability, the second main obstacle in the application of patterned media is the uniformity in the dots. Due to non-uniformities in the magnetic layer, the etching process or dot dimensions, every single dot will have a slightly different switching field.

The switching field distribution can be succesfully studied by MFM. As an example, in the authors lab, patterned media are prepared Laser Interference Lithography (LIL) to pattern the resist layer [17]. The magnetic layer is a CoNi/Pt multilayer, which obtains is perpendicular magnetisation from the interface anisotropy between the CoNi and Pt layers. A cross section on a sample with 500 nm distance between the dots is shown in figure 5. The LIL technique allows us to go down to 150 nm.

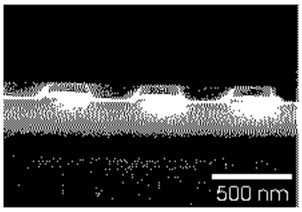

Figure 5: CoNi/Pt multilayered magnetic elements prepared by Laser Interference Lithography with a dot distance of 300 nm. In this image,the resist is still present on the dots, the thin white line is the CoNi/Pt multilayer.

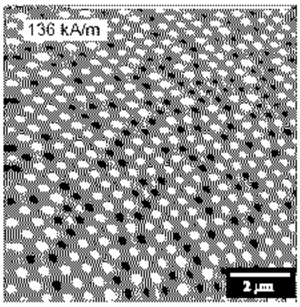

Figure 6: MFM image of patterned medium prepared by Laser Interference Lithography.

Using in-field Magnetic Force Microscopy, the array is imaged as a function of the applied field. A measurement at 136 kA/m is shown in figure 6. By taking images at various field values, the switching field of the individual dots can be determined. A faster method is to stop the slow scan direction, and image the magnetisation state of a row of dots under increasing field values. This measurement is shown in figure 7. As can be seen, the variation in switching field of neighboring dots is quite substantial compared to the average switching field. In hard disk recording, this will cause a problem since the trailing fields extend over a certain range, and vary in angle. The field strength of the head has to be adjusted to the dot with the highest switching field. The situation might than occur than an previously written dot with a very low switching field is overwritten. In magnetic probe recording using MFM tips the situtation is even worse. Since the field of the MFM tip is low, a background field has to be applied. If the distribution in switching fields between the dots is larger than the field of the MFM tip, the background field will have to be so high that it erases the dots with the lowest switching field.

The reason for the large switching field distribution is unknown and can be manifold. Several

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[1] Which we would like to nickname the "Murillo limit on magnetic data storage", after its proposer.

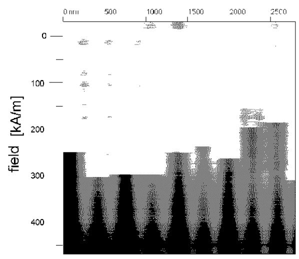

Figure 7: MFM measurement of the reversal of 9 dots as a function of the applied field.

causes can be ruled out. Stray field interaction from neighbouring dots by itself is not sufficient to explain such a large distribution. Calculations indicate that for the dot spacing used, the stray field is at most 7 kA/m. Thermal fluctuations are small for the dot volumes used, and moreover the switching fields are reproducable: the weakest dots always switch first. Etch damage could be a cause of reduction in switching field, but than it is difficult to explain why this damage differs so much for neighbouring dots. So remaining causes will have to do with irregularities in the dots themselves. This could be cause by irregularities in the resist profile, which are transferred into the magnetic material by etching, or in the material of the dots. The latter seems to be the most likely candidate. It is naive to assume that dots will be identical when patterning a polycrystalline material with grians in the order of 10 nm into 70 nm dots. The image which emerges is displayed in the cartoon of figure 8. Each dot will contain irregularities like a different number of grains, grains cut in half, differences in grain boundaries etc. So one prerequisite for low switching field distribution will be to start from an as homogeneous material as possible. Experiments with patterned epitaxial layers are indicating however that the switching field distribution improves, but does not vanish [18]. The authors believe this is caused by remaining inhomogeneities in the material, rather than variation in the grain boundaries.

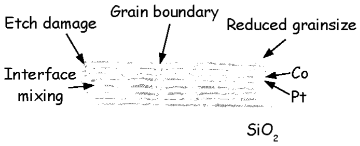

Figure 8: Schematic illustration of non-uniformities in patterned magnetic elements.

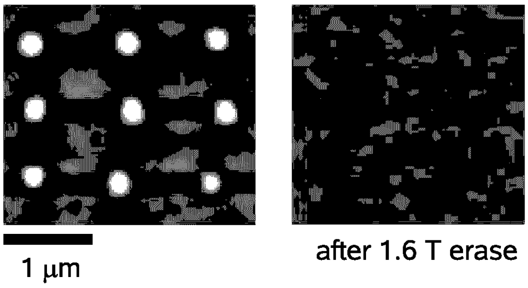

Figure 9: Bits written in a CoNi/Pt mulitlayer using an STM tip[22]

4 Magnetic Probe Storage

One of the first experiments on magnetic probe recording were on continuous media by using MFM tips [19]. Other researchers used STM [20], locally heating the medium and reducing the switching field. The stray field of the surrounding material helps in reversing the magnetisation. Imaging of written bits has to be done by transporting the medium to an MFM, and erasure is not possible (figure 9). Erasure becomes possible with a write assist field (figure 10), and pulsed currents can also be applied from an MFM tip which allows for direct imaging [21]. The minimum domain size which can be obtained in continuous media is close the critical bubble domain collaps diameter, and bits as small as 80 nm could be written.

In contrast to the results by Ohkubo *et al* [19], writing without locally heating proved to be impossible on continuous media. Due to inhomogeneities

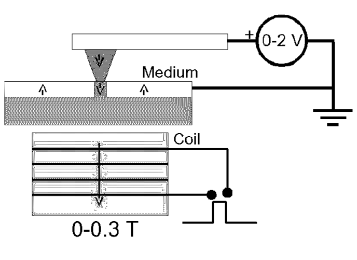

Figure 10: Configuration for magnetic probe recording.

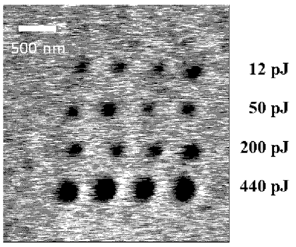

Figure 11: Bits written in a CoNi/Pt multilayer using an MFM tip and induced current

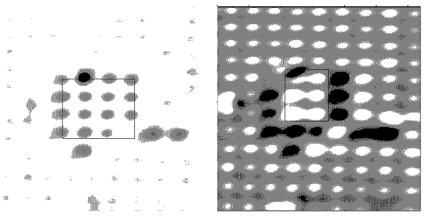

Figure 12: Write experiment on CoNi/Pt patterned medium [24]

in the medium, reversal starts at an unpredicted location resulting in random nucleation of stripe domains. Since very soft media were used, the nucleated domains could propagate very easily throughout the medium.

We noticed however that during experiments it is extremely important to ground the sample. The coil which generates the magnetics field forms a large capacitance with the sample (see figure 10. Applying a current pulse to the coil inadvertedly also causes charging of this capacitance. If the sample is not grounded, the charging current passes through the tip, which locally heats the sample. Allthough it is possible to write in this way, resulting in severe sample damage [23].

The effect of domain propagation does not appear in pattern media, and field only write experiments were attempted in media prepared by Laser Interference Lithography[16] . In this experiment we used an MFM mounted in between the pole shoes of a large electromagnet. Using the electromagnet, the sample is saturated completely into one direction first. Subsequently the field is applied in the opposite direction, at a value just below the switching field of the individual dots. This field is sufficient however to reverse the magnetisation of the tip. Than the tip is brought in contact with the medium, and by selecting a very limited scanrange, 16 bits are reversed by the combination of the background field and the field of the tip (figure 12, left). As can be seen in the figure, some bits outside the scanarea were reversed so the background field was too large. On the other hand not all addressed bits were reversed either. Apparently the switching field distribution of the medium is still too large and improvements need to be made. Still we could demonstrate erase, by applying the opposite experiment using a smaller scan area which only addressed 6 bits (figure 12, right). These experiments demonstrate that field-only writing on patterned media is possible if the switching field distribution is improved.

5 Two-dimensional coding

As noted in the introduction, it is unavoidable that future mass storage media will be patterned. This has serious implications for the system architecture. We will need to deal with issues like write synchronisation for instance. Another important aspect of patterned media is that the data between tracks has a phase-relation. Unlike continuous media, like hard disks or phase change, we know exactly where the adjecent bits are positioned. This opens the possibility to extend our data detection and coding strategies from one dimension (along the track), to two dimensions.

Essentially, a patterned medium consists of a two-dimensional (2D) arrangement of rows and columns of magnetized dots (islands) where each dot represents one single data bit. The phenomenon of crosstalk during reading will show itself in both directions, and can be taken as a combination of the conventional intersymbol interference (ISI) along the rows, and the so-called intertrack interference (ITI) along the columns. The difference with continuous media is the occurrence of a predetermined phase relation between the tracks, which can be exploited. In order to combat ITI, extensions of traditional one-dimensional channel coding and detection methods have been proposed [25, 26], including run-length limited (RLL) codes for two-track systems, 2D partial-response maximum likelihood, and the application of turbo coding.

Figure 13 displays the simulated read signals

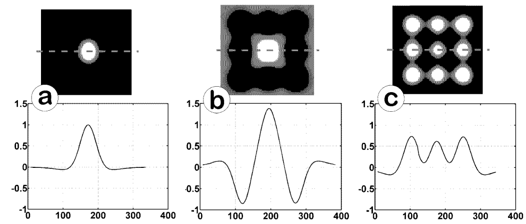

Figure 13: Three configurations of computed magnetic dots scanned by MFM probe (upper); Simulated MFM-probe read signals scanned along the dotted lines (lower). The x axes are in nanometers. (a) single bit (b) 'one' bit surrounded by 8 'zero' bits (c) 9 'one' bits.

of perpendicularly magnetized dots in a patterned medium. The waveforms are typical for both giant magnetoresistive (GMR) and magnetic-force microscope (MFM) read-head technologies, in combination with a recording medium with soft-magnetic underlayer (SUL). As a result of 2D ISI, the amplitude of a bit (dot) surrounded by 8 identical bits (figure 13c) is seen to be relatively low, and in view of bit-detection reliability such a bit combination can be considered to be a "worst case" pattern.

A simple method to avoid such worst-case patterns to occur in a patterned medium is the application of a geometric 2D channel code [27]. An example of such a code is shown in figure 14 where particular bit positions are occupied by fixed bit values (1 of 0), leaving the remaining positions for recording of user bits. This scheme stops the square nine-bit combination of figure 13c (9 'ones', or 9 'zeros') to occur. Obviously, this coding scheme results in a code rate 7/9 (or redundancy 22%).

The benefit of the introduction of such a fixed bit pattern on bit detection was analysed using a computer simulation program. This program incorporates 2D ISI and offers, among other things, facilities for simulation of bit-position jitter. After computation of the read signal for a serpentine scanning trajectory (indicated in figure 14), the data bit sequence was reconstructed. Figure 15 shows the number of detection errors in a sequence of 15876 bits as a function of the magnitude of uniformly distributed bit-position jitter. Here the elementary read pulse was taken with a relatively large 16% overshoot in order to investigate the effect of the introduction of the 2D channel code of figure 14.

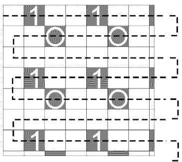

Figure 14: 2D channel code with geometric constraint (fixed '1' and '0' bits) imposed to 2D bit patterns. The empty positions are available for recording of user-data bits.

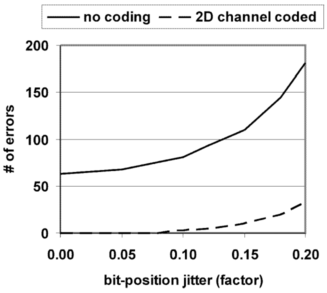

Figure 15: Impact of 2D channel code on bit-detection performance.

For non-coded data and low jitter levels we found the bit errors generally to occur on medium locations corresponding with the bit pattern of figure 13c, i.e. a block of nine (or more) identical bit values. Introduction of the 2D code eliminated this class of errors (figure 15). Increasing the jitter magnitude above factor 0.1 resulted in new errors at locations of bits which are surrounded by both "one" and "zero" bits. However, the plotted curves in figure 15 suggest that the 2D channel code only modestly combats this second error category.

The code method as depicted in figure 14 does not require complicated signal processing. It can be considered as a 'brute force' approach, because it claims redundant bit positions on the medium, which are located on fixed positions not correlated to local data content. More research is required for the development of more efficient coding methods in view of the required immunity to 2D ISI and (other) noise effects.

6 Conclusion

It is inevitable that future mass storage systems will use some kind of patterned medium (magnetic, molecular, atomic). The maximum areal density for magnetic patterned media is around 7 TBit/in^2, which might be too low for using in probe based data storage. Still a lot can be learned about patterned data storage by studying magnetic probe storage.

One of the biggest obstacles in magnetic probe storage in patterned media is the high switching field distribution, which in our case was as high as 100 kA/m. This high value phohibits field assisted writing, since the stray field of the tip is insufficient to discriminate between the weakest and strongest dots . Using in-field magnetic force microscopy, the nature of the switching field distribution was studied, and it appears the distribution is caused by intrinsic material properties. Still by optimising the write conditions, writing and erasing of single magnetic elements could be demonstrated.

A beneficial property of patterned media is that there is an exact phase relation between written data in adjecent tracks. This can be exploited for advanced two-dimensional data-detection and coding techniques. A first attempt in this direction revealed that by simply preallocating bits, a considerable robustness against bit jitter could be achieved.

The first steps presented in this paper show that many issues which will arise in future molecular or atomic probe storage systems, can already be studied in a much earlier stage on magnetic patterned media.

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