Final Progress Report

Award number FA9550-04-1-0446 (FIU grant #: 212400528), June 1, 2004 – December 31, 2004
Title: Three-dimensional Magnetic Recording Device
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I. PROPOSED STATEMENT OF OBJECTIVES

It its statement of objectives, the proposal included the following four objectives:

1) Objective 1

In the course of this proposal, it is proposed to develop and simulate a thermally-stable one-thousand-layer 3-D recording system with an eigth-bit address/word line capable of recording and retrieving eight bits in parallell. Assuming a bit cell with one square micron in cross-section, this is equivalent to an effective areal density of 640 Gbit/in^2. The undegraduate student involved in this proposal (Nissim Amos) and the PI will make a presentation of the results of the numerical simulations indicating the functionality of the device.

2) Objective 2

The simulations proposed will be performed both with PC and a state-of-the-art computer cluster system recently established at FIU. The use of the cluster computing will allow to extend the simulations (in the near future) to systems capable of pentabyte recording. The simulations will incorporate both magnetostatic and micromagnetic (quantum-mechanical) interactions between the grains in the 3-D media. The thermal stability of the recording media will be addressed throughout the simulations.

3) Objective 3

In the course of this proposal, it is planned to raise interest in this technology at least to the level of prototype building. A detailed plan (with drawings and steps) to build a first-principle prototype will be proposed by the end of the project. In the course of this proposal, it is planned to publish at least two articles (one on the modeling technique and the other on the simulation results) in peer-review journals (upon an agreement with the US Air Force).

4) Objective 4

The above-described project on simulation of a 3-D magnetic recording system will be conducted in parallel with the experimental work on the prototype development. For the first time, the first functioning prototype of a 3-D memory chip capable of storing 640 Gigabit of information in a device the size of a coffee cup will be demonstrated. The prototype will be built with the focused-ion-beam (FIB)-based rapid prototyping technology developed at FIU. In this demonstration, no encoding scheme will be used to record and retrieve data. The data rate will be of the order of 200 Mbit/sec and today is limited by the available electronics at FIU.

II. ACCOMPLISHMENTS

Below, the accomplishments associated with each of the proposed objectives will be listed in the respective order (see above for the list of the proposed objectives):

1. Accomplishments Associated with Objectives 1 and 2

The design of a 3-D system included consideration of several following recording configurations:

a) The first configuration is a recording system including a multi-layer-based recording media with each layer addressed separately. Each layer consists of grains coupled not only magnetostatically but also via relatively weak or strong quantum-mechanical exchange coupling, as shown in Figure 1a. The recording media is made of a relatively "hard" magnetic material, such as, CoCr-based, Co/Pd-mutilayers, and others, with no "soft" magnetic underlayer involved. It was found that a "ring" type of magnetic probe should be used to record information and a GMR type of sensor could be used to read to information back.

b) Same as above with the exception of the utilization of a soft magnetic underlayer, as shown in Figure 1b. The soft underlayer is used under the recording layer consisting of many "hard" layers. The soft underlayer is made of Permalloy (Ni79/Fe21), or Fe45/Co55 alloy, or Ni45/Fe55, or FeAlN or similar nitride, or another soft magnetic material. Contrary to the popular so called perpendicular recording mode with a soft underlayer, in the proposed configuration, it is not a problem to use a soft underlayer with strongly reduced noise through a relatively trivial biasing of the soft underlayer. The biasing is used to sweep off the noise-generating and random domain walls in the soft material.

c) The third configuration includes a recording media consisting of many exchange-decoupled "layers" (with layer consisting of exchange-decoupled grains) with no strict definition of the layers as long as the individual grains are exchange-decoupled in all three dimensions. Again, this configuration could be used with or with no soft magnetic underlayer, as shown in Figures 1c and d, respectively.

It was found that these different media configurations vary with respect to the signal-to-noise ratio, with b) being the best in this perspective assuming an "ideal" soft underlayer could be developed.

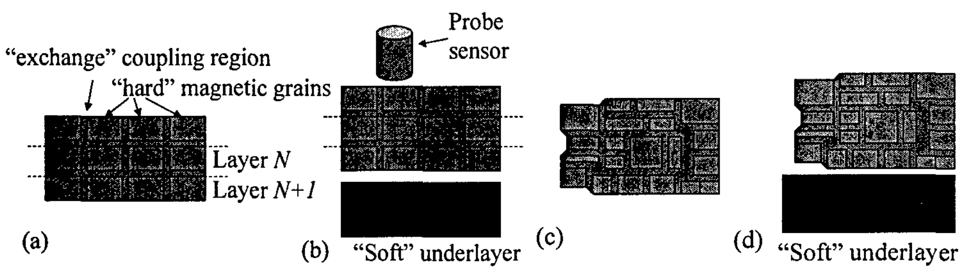


Figure 1. Diagrams of a multi-layer media with well defined layers (a) with no and (b) with a soft underlayer and a "multi-layer" media with poorly defined layers (c) with no and (d) with a soft underlayer.

Throughout the design considerations, two modes of 3-D magnetic recording were defined: a) absolute 3-D magnetic recording and b) multi-level 3-D magnetic recording.

Definition: Multi-level 3-D Recording Versus Absolute 3-D Recording

Throughout this project, two different modes of 3-D magnetic recording (with respect to addressing individual magnetic layers ("hard" magnetic material with perpendicular or another orientation of magnetization)) have been investigated. For simplicity and clarity, although the both modes are three-dimensional, they are referred to as multi-level 3-D recording and absolute 3-D recording modes, respectively. This distinction in definition is merely for description clarity and is explained below.

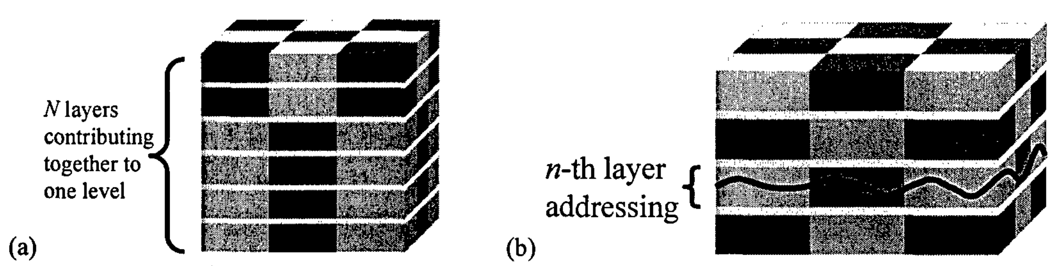


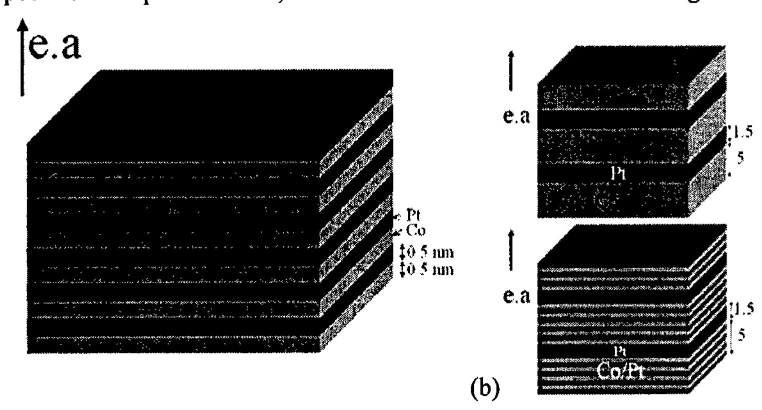
Figure 2. Schematic diagrams illustrating how information is addressed in cases of (a) 3-D multi-level and (b) 3-D absolute recording modes, respectively.

In the multi-level 3-D recording mode, although a 3-D space is utilized for recording, it is not used effectively. The degree of use is determined by the mechanism of data access during writing and reading. In one of the most straightforward cases, when the signal recorded and/or read back from a cell stack is defined by a recording transducer located above the stack, the information recorded in all N layers within the stack contribute simultaneously (as a stack) to each signal level, as shown in Figure 2a. The number of signal levels, L, may be substantially smaller than the total number of layers, N, and is determined by the ability of the recording transducer to generate a signal with a sufficiently large signal-to-noise ratio (SNR) for the L levels to be distinguished from each other during writing and reading. In this case, the effective areal density increases only by a factor of Log_2L with respect to the areal density of the equivalent binary single-layer media.

In contrast, in the absolute 3-D recording mode, each (n-th) layer in the N-layer recording media is addressed separately (see Figure 2b). In this case, the effective areal density increases by a factor of N with respect to the areal density of the equivalent single-layer media. For example, if one thousand layers are used, assuming a bit cell cross-section of 160 x 160 nm^2, 25 terabits of data could be stored in a square-sheet-shape media with a 1 inch side and a 10 micron thickness.

Modeling Approach

As mentioned in the proposal, the idea of 3-D magnetic recording was nourished during the exploration of Co/Pt (Pd) multilayers as recording media with high surface-induced perpendicular anisotropy – a key property used in perpendicular magnetic recording. Similarly, the "3-D magnetic media" is proposed as a stack of magnetic layers separated from each other by thin non-magnetic interlayers, as shown in Figure 2. In each set, the layer and the interlayer are approximately 5~10 and 1~2 nm thick. Some of the potential material choices could be CoCr-based or high-anisotropy Co/Pt (Pd) perpendicular multilayers or others. These multilayers could not be confused with conventional Co/Pt (Pd) multilayers [1] as used in perpendicular recording. In the current context, the purpose of the interlayers is to break the quantum "exchange" coupling between adjacent magnetic layers and thus to be able to independently record information on magnetic layers. Assuming that the recording layers have a preferred orientation perpendicular to the plane, the magnetization in adjacent layers could be directed in opposite directions because there is no strong exchange coupling between the layers. The lack of the exchange coupling is due the sufficiently thick "exchange" breaking interlayer (>~1-2 nm). Otherwise, due to the "exchange" coupling all the layers in a bit cell would have had magnetization directed in the same direction. The latter occurs in the conventional multilayers used as high-coercivity recording media in perpendicular recording. In the traditional case, the interlayer separation is chosen to be < 1 nm to maximize the exchange coupling between the adjacent layers and increase the perpendicular anisotropy due the surface effects. This difference between Co/Pt (Pd) multilayers, as used in the conventional perpendicular mode and in the proposed 3-D implementation, is described below and illustrated in Figure 3.



(a) (b)

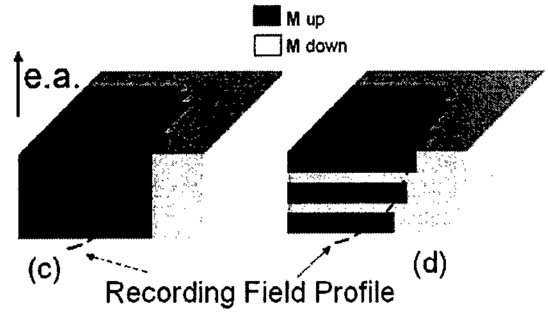


Figure 3. (a) A schematics showing a Co/Pt stack in the conventional sense as used in perpendicular recording: Pt interlayers are ~0.5 nm thick. (b) The 3-D implementation of multilayers: with Co (top) and Co/Pt in the conventional sense (bottom) as "single" layers in a stack. Micromagnetic simulations illustrating the effect of the interlayer spacing on the ability of the magnetization to follow the recording field profile: (c) the interlayer spacing is ~< 1nm (strong exchange coupling); (d) the interlayer spacing is ~> ~1nm (weak exchange coupling).

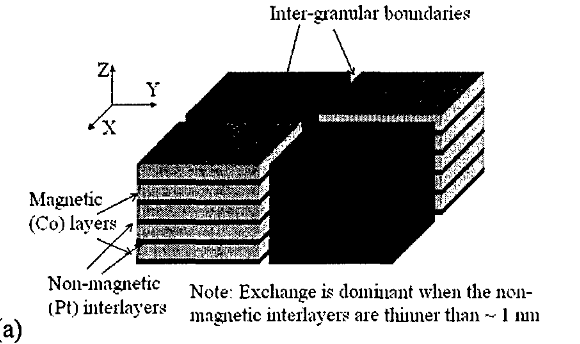
Ideally, throughout this project, even multilayers in the conventional sense could be effectively used as "single" magnetic layers (equivalent to single Co layers) in a stack of 3-D multilayers. In a stack of 3-D multilayers, adjacent "single" magnetic layers (just Co or Co/Pt multilayers in the conventional sense) are separated by a relatively thick (1~2 nm) Pt interlayer to break the exchange coupling between the "single" layers, as shown in Figure 3b. In other words, each "single" layer could be made either of pure Co or an entire stack of Co/Pt multilayers in the conventional sense. However, for the below described reason, it might appear difficult to implement the case of pure Co as a magnetic layer. If the exchange-breaking layers are sufficiently thick, the surface effects are minimized and thus the magnetic anisotropy is determined by the interplay of intrinsic crystalline and shape anisotropy. In other words, the magnetization would be randomly directed in the place. In contrast, as illustrated in Figure 3a, Co/Pt multilayers in the conventional sense have Pt interlayers relatively small (<~0.5 nm) to provide sufficient exchange coupling between the adjacent Co layers and thus create strongly surface-dominated perpendicular anisotropy.

Assuming there are one thousand "independent" layers and the cross-section of each cell is approximately 80 x 80 nm^2, this type of 3-D media could store the amount of information in the 100 terabit-per-square-inch effective density range and even more in the patterned form of a 3-D media, as described below. However, as described below, the effective areal density is going to be limited not by the maximum capacity of the recording media but rather by the available data recording and retrieval mechanisms. These mechanisms will be investigated later.

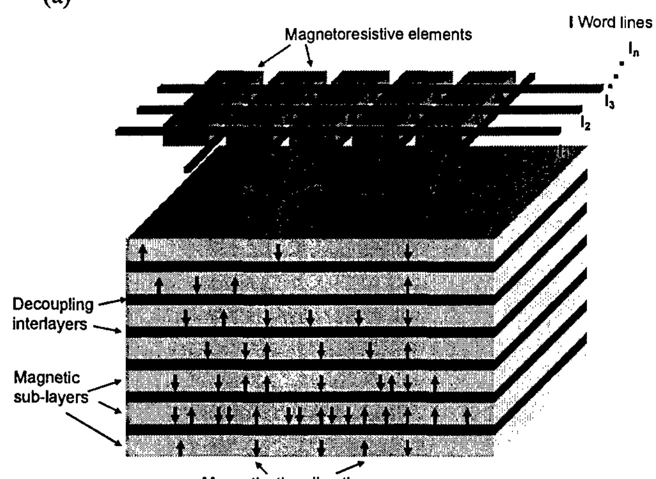
It could be noted that due to the 3-D approach, the bit cell cross-section does not have to be ultra-small to achieve relatively high densities. In fact, no ultra-sophisticated nanofabrication tools may be necessary to achieve areal density values exceeding what is projected to be achieved within the next decade with 2-D recording systems (e.g., heat-assisted magnetic recording (HAMR [[2]])) using E-beam or focused ion beam (FIB). In the case of 3-D, the effective density will be achieved just via the deposition of a stack of layers. Considering a relatively large cell size, a periodic pattern satisfying hundreds of gigabits-per-square-inch areal densities could be achieved with conventional UV-optical lithography. For example, an arrangement with a bit cell with a 160 x 160 nm^2 cross-section and a stack of 20 "independent" layers would be equivalent to an effective areal density of approximately 500 Gigabit/in^2. More advanced fabrication methods, such as E-beam and FIB-based, would increase the areal densities much beyond 1 Terabit/in^2 mark.

Preliminary Numerical Simulations of 3-D Media

To simulate the grain interactions in the complex 3-D media, an in-house developed micromagnetic code was used [[3],[4]]. In this simulation, a 3-D media is represented as a stack of alternating magnetic and non-magnetic layers with each layer consisting of interacting grains (in the form of a simplified square mesh, as shown in Figure 4a). The short-range exchange coupling between adjacent grains and the long-range magnetostatic coupling between grains are described through the Landau-Lifshits-Gilbert (LLG) formalism [5]. In other words, the simulation took into account the magnetostatic interactions which contribute to the demagnetization field. Therefore, the simulations could help to avoid the magnetization patterns with exceedingly large (compared to the media coercivity) demagnetization fields. Each square grain in had a 3-nm side and a thickness equal to the respective layer's thickness. In one specific example, the default magnetic "single" layers, conventional Co/Pt-multilayers or others, were modeled as materials with anisotropy constants (*K*) of 5 x 10^5 and 1 x 10^7 erg/cc, saturation magnetization of 250 emu for both, coercivity field of 3 and 8 kOe, respectively. The relative exchange coupling constant, h_e, was modeled to be anisotropic: with the in-plane and perpendicular-to-the-plane exchange constants equal to 0.05 and 0.5 for Co-based "single" layer, respectively, and 0.1 and 0.5 for Co/Pt-based "single layer, respectively.



(a)



(b)

Figure 4. (a) A simplified mesh cell (not to scale) in the in-house micromagnetic code. (b) A schematic diagram showing a structure of a proposed 3-D magnetic media and a grid of write/read elements above the media.

Figure 3c illustrates a micromagnetically simulated magnetization pattern [6] after applying the recording field from a single pole head to a stack of multilayers with an interlayer separation (Pt layer thickness) of less than one nanometer. The field from the single pole head was also modeled micromagnetically. It was assumed that it was made of a high moment FeAlN amorphous alloy with an anisotropy field, H_k, of 15 Oe, saturation magnetization, $4\pi M_s$, of 20 kG, and an exchange constant, A, of 10^{-6} erg/cm. Before the recording field was applied, the media was saturated in the opposite direction. It could be observed that the magnetization pattern in the media did not follow the curved recording field profile. This could be explained by the relatively strong exchange coupling between the adjacent magnetic (Co) layers. As a result, the magnetization was relatively uniform across the thickness. In fact, this is exactly the case in the conventional implementation of Co/Pt multilayers in perpendicular magnetic recording. (Please note that in the two plane directions, the exchange inter-granular interaction was substantially weaker so that individual bit cells could be defined in the plane.) In contrast, in the proposed 3-D implementation, the interlayer thickness was chosen sufficiently thick to break the exchange coupling so that the magnetization pattern could follow the profile of the recording field and thus each individual grain in the volume (not only on the surface) could be accessed independently, as illustrated in Figure 3d. The preliminary simulation indicated that the interlayer (Pt) thickness should be ~> 1-2 nm for the exchange coupling to be sufficiently weak.

2. Accomplishments Associated with Objectives 3and 4

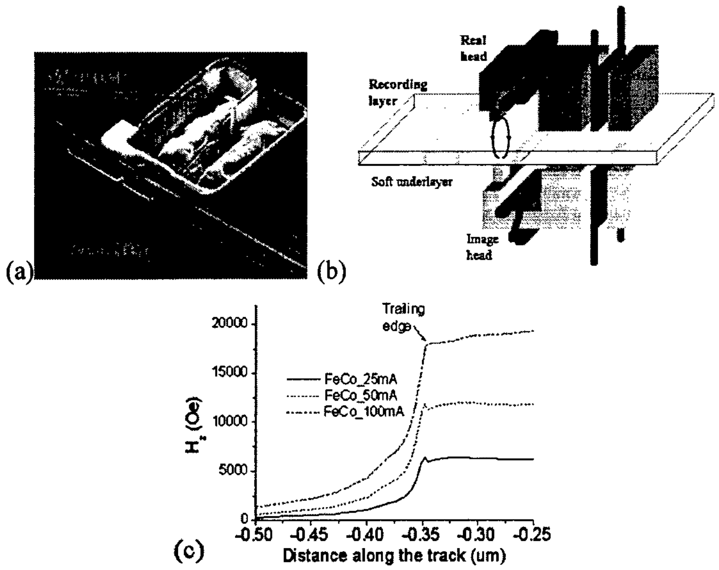


Figure 5. (a) An ion image of a FIB-fabricated nanoscale transducer. (b) A diagram illustrating the magnetic "image" model for the single pole head with a medium with a soft underlayer. (c) Vertical recording field versus the distance along the track at three values of the drive current, 25, 50, and 100 mA, respectively.

First Experiment

In the Spinstand experiment below, the 3-D multi-level recording mode is tested with a simplified version of the 3-D medium. The tested media were fabricated via sputter deposition. The transducer was fabricated using FIB trimming of a commercially available Seagate transducer. FIB was used to define an adequate geometry and further reduce the transducer dimensions. For simplicity to demonstrate the feasibility of the concept, a medium consisting only of three magnetic layers was investigated. Each pair set (one magnetic layer plus one non-magnetic layer) consisted of a 8-nm thick Co/Pd (0.3/0.7nm) stack and a 2-nm thick Pt interlayer. X-ray verified the perpendicular orientation of the magnetic anisotropy in this stack of layers. An ion image of a focused-ion-beam (FIB)-fabricated recording head with a trackwidth of less than 100 nm is shown in Figure 5a [7]. The recording head is a single pole type head as used in perpendicular magnetic recording. In this mode, the SUL is necessary to increase the recording field throughout the entire thickness of the recording medium [8]. Previously, it was shown that the increase by at least a factor of two is feasible [9]. Typically, the magnetic "image" model [10, 11] is used to illustrate the increase of the recording field due to the SUL. According to this model, to calculate the recording field at a point within the recording medium, the SUL could be replaced with an image head located at a certain distance from the other side of the medium, as shown in Figure 5b. The net recording field consists of the recording fields generated by the real head and the image head. The vertical recording field versus the distance along the track in the vicinity of the trailing edge of the head at three values of the drive current, 25, 50, and 100 mA, respectively, is shown in Figure 5c. In this experiment, the SUL was made of a high moment composition of Fe/Co with a $4\pi M_s$ of 22 kG [.]. A Guzik Spinstand was used to characterize the recording process.

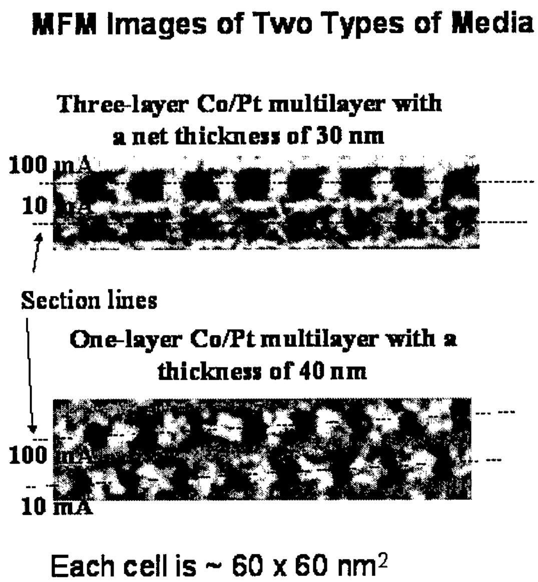


Figure 6. MFM images for the two studied cases.

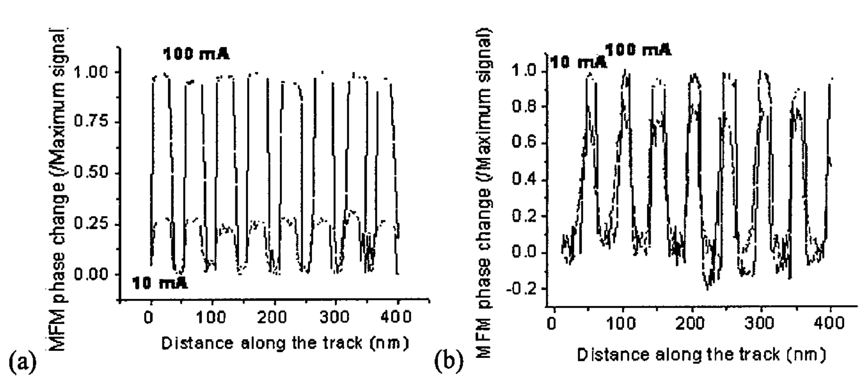


Figure 7. Along-the-track cross-sections of MFM images of sets of two adjacent tracks, recorded with a drive current of 10 and 100 mA, respectively, onto (a) a three-layer (Co/Pt)/Pt multilayer with a net thickness of 30 nm and (b) a single layer multilayer with a thickness of 40 nm (bottom left).

For the comparative purpose, a conventional one-layer perpendicular medium made of a 40-nm thick Co/Pt co-sputtered multilayer (0.3-nm Co and 0.6-nm Pt) [12] was also tested. MFM images and along-the-track cross-sections of MFM images of sets of two adjacent tracks, recorded with a drive current of 10 and 100 mA, respectively, onto a three-layer (Co/Pt)/Pt multilayer with a net thickness of 30 nm and a single layer multilayer with a thickness of 40 nm are shown in Figures 6 and 7, respectively. It could be observed that for the first medium, the signal from the track recorded at a 10-mA current is substantially smaller than the signal from the track recorded at a 100-mA current. In contrast, for the "single-layer" Co/Pt medium, these two signals are substantially closer to each other. This experiment indicates that, indeed, some adequate separation between the magnetic layers (more than ~ 1 nm to break the exchange coupling) will be necessary to separately record on different layers. In this case, one could distinguish at least two distinct signal levels with the same polarity. On the contrary, as explained above, for the Co/Pt medium in the conventional sense, Co layers are too close to each other and thus the strong exchange interaction couples them into an effectively one magnetic layer.

In the future, Spinstand and MFM characterization of FIB-defined transducers will be used to study the nanoscale sensors and optimize the composition and structure of the 3-D recording medium from the angle of the signal-to-noise ratio (SNR) at high densities.

Explored Data Writing and Reading Mechanisms

Figure 8a illustrates the skeleton of the proposed technology. It is proposed to use a two-dimensional grid of lines to access information for writing and reading in a 3-D medium, respectively. The access (address) grid will be positioned on top of the recording medium similar to one of the emerging 2-D MRAM implementations [13]. Different implementations to be investigated are discussed in the order of complexity. To demonstrate the feasibility of 3-D recording, the grid will be fabricated using optical lithography with further FIB trimming down to sub-100 nm dimensions. The test structure will be quite similar to the previously developed (by the PI) structure to demonstrate high-data-rate perpendicular recording [ ]. This structure allows arranging a large number of transducers in a grid form to test 3-D patterned media. Each optically fabricated transducer will be further trimmed with FIB down to sub-100-nm dimensions. After the write and read mechanisms are studied at the described test-structure level, Seagate will help to utilize E-beam lithography to define a grid with a sub-100-nm bit period [14].

Data Writing

There are a number of potential implementations that will be comparatively studied throughout this project. It is believed that understanding of the physics of 3-D magnetic recording as a result of this research might result in other viable implementations.

<u>Implementation One: Magnetically-induced Data Access</u>
There will be no moving components in the future system. On top of the recording stack, a control layer will be defined with a grid of crossing word lines, as shown in Figure 8b. As mentioned above, the parallel data recording and retrieval (readout) will be explored. In the version described, the information from a horizontal layer will be recorded and retrieved with one shot. The grid's algorithm is similar to the grid's algorithm as used in one of the MRAM implementation, with exceptions related to the 3-D nature.

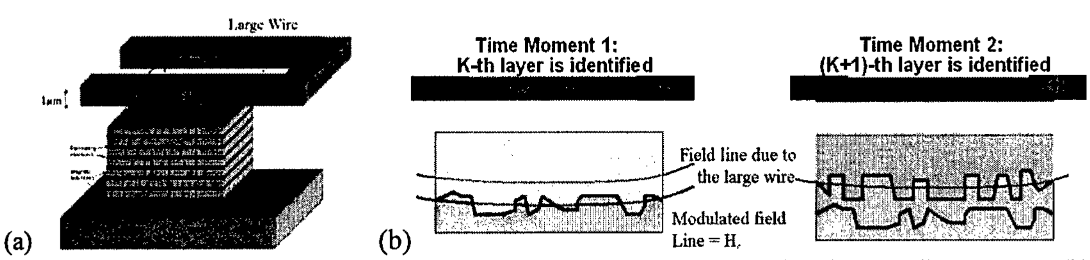


Figure 8. (a) A diagram showing a mechanism to identify each layer during the recording process. (b) Cross-section diagrams showing two consecutive time moments illustrating how the field due to the electric current in the "large wire" can be used to identify each layer in a 3-D medium (starting from the bottom and going up).

To identify each layer during the writing process, a certain electric current is driven through a biasing "large wire" on top of the system, as shown in Figure 5a. The word "wire" is not meant literally here. In fact, in practice, this "wire" will be made of connected in series coils, with each coil wrapped around a "soft" pole in each grid element. The current through the "large wire" generates a relatively large bias field perpendicular to the 3D medium. To increase the biasing field almost by a factor of two, a "soft" underlayer (SUL) is used under the recording medium. The SUL will be similar to the SUL as used in perpendicular magnetic recording [15]. The two main purpose of the SUL are 1) to increase the recording field during the writing process and 2) to identify each recording layer during the reading process, as described below. By varying the electric current through the "large wire", one can vary the biasing field. The current range is chosen so that the biasing field is within ~5 percent of the coercivity of the magnetic layers. For example, if coercivity of the layers is 8000 Oe, the biasing field would be ~ 7700 Oe. Recording will be produced sequentially, "layer" by "layer". In a final system, these "layers" won't necessary have to coincide with the physical layers as long as the reading process uniquely matches the writing process. First, the electric current is driven to a value sufficient to generate a large field (close to the coercivity, H_c) in the vicinity of the bottom layer (farthest from the grid), as shown in Figure 5b (left). (The closer a layer is located to the grid, the larger the field in the plane is.) Then, electric currents through the word/address lines are driven to modulate the field surface in the layer. The word/address grid can generate a field of the order of 500 Oe depending on the set of signals in each line. Each set of signals defines a bit pattern according to a selected data encoding mechanism. Thus modulated information is recorded in the bottom layer. Then, the current in the "large wire" is reversed and reduced to identify the "next" layer (closer to the grid). Another set of signals is driven through the word/address lines to modulate the signal in this layer, as shown in Figure 9b (right), and so on. In short, in this implementation, information will be recorded sequentially, starting with the bottom layer and ending with the top layer.

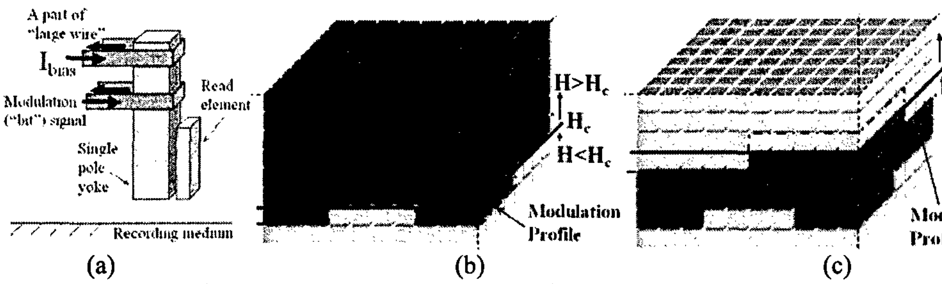


Figure 9. (a) Schematics of a single grid element including a read element and a "soft" rod with the "large wire" and the modulation coil wrapped around it. Magnetization contours (b) near and (c) away from the bottom layer (as the biasing current is decreased and reversed).

To quantify the described mechanism, numerical simulations will be performed. To model the biasing and modulating magnetic field and the magnetization in the medium, the above-described in-house developed (Chomko) micromagnetic code will be used. A schematics of a single grid element above the medium is shown in Figure 9a. It includes a piece of the "large wire" and the modulation coil wrapped around a "soft" rod of Permalloy, plus a read element. The rode acts as a single pole head used for writing in perpendicular recording. As an example, two simulated instances of the magnetization distribution during the writing process in a small piece of the medium away and close to the grid are shown in Figures 9b and c, respectively. The simulation will help to choose optimal properties and the requirements for the recording medium and the recording field [16]. The above-described writing mechanism is a part of the provisional patent on a 3-D memory device filed at FIU on August 8^{th} 2004.

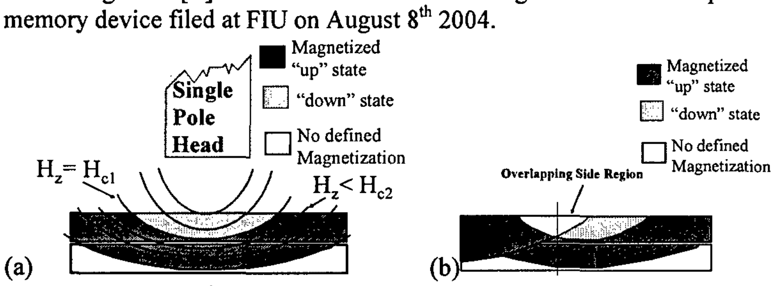


Figure 10. Diagrams with magnetization patterns recorded on (a) a dc-erased medium and (b) a medium with information recorded in a adjacent bit cell. The overlapping side region is highlighted.

A potential issue with such a trivial data accessing is the relatively strong overlapping of the field profiles used for recording into adjacent bit cells. To illustrate this issue, Figures 10a and b show the magnetization pattern (a) right after some information is recorded into both layers of a two-layer dc-saturated medium and

(b) when one of the adjacent cells has been preliminarily recorded, respectively. The highlighted overlapped region indicates the region in the medium where the information is "wasted".

3-D Patterned Medium: To overcome the issue of the data "erasure" in the overlapped region, a medium will be patterned. Today, it is not an issue to controllably fabricate a 2-D patterned medium with a periodic cell in the Nanoscale region. Fabrication tools, such as atomic lithography, electron-beam [17] and FIB lithography [18], nanoimprint [19], X-Ray patterning [20], self-assembly [21], and many others are routinely used to define patterned media with cell sizes of less than 100 nm. It can be noted that in the proposed implementation, a medium is automatically patterned in the third (-z) dimension during the above described preliminary multi-layer deposition step.

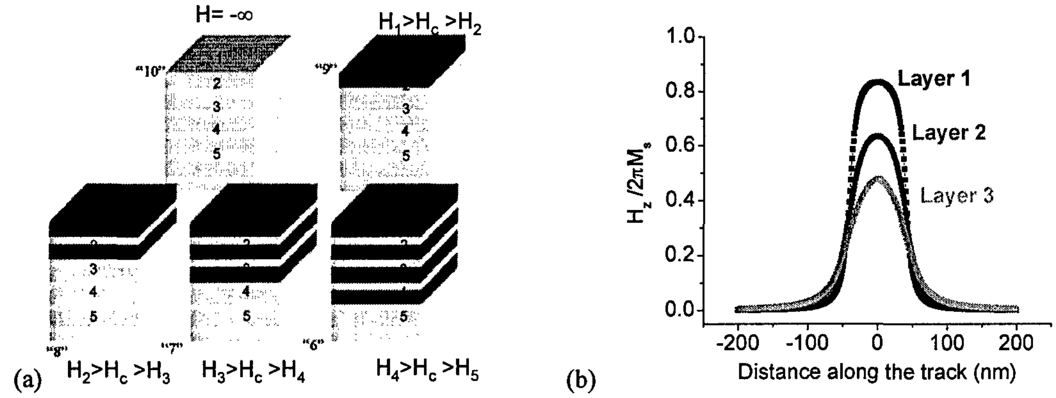


Figure 11. (a) A diagram illustrating sequential recording of different levels in a 3-D patterned medium. (b) The recording field profiles in the first, second, and third layers at a given value of the drive current in the recording transducer above the cell.

Figure 11a illustrates an example of how each layer in a bit cell stack could be recorded in a patterned medium in the 3-D multi-level recording mode. Initially, a bit cell is assumed to be saturated. This means that the entire bit cell stack is magnetized in one direction (blue color). In one encoding form, this state may, for example, reflect a digital state "10". Then, the recording field is increased in the opposite direction to reverse the magnetization (red color) in the top layer. This state could reflect a digital "9". When the field is further increased to the value overcoming the coercivity of the second (counting from the top) layer, the magnetization in the second layer is reversed. This state would reflect a digital "8". And so on. The simulated recording field profiles in the first, second, and third layers, at an arbitrary current value in the recording transducer above the cell are shown in Figure 11b.

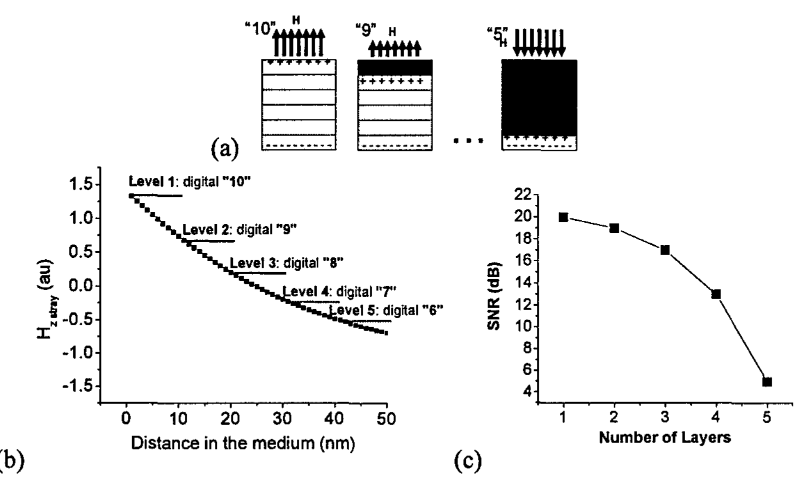


Figure 12. (a) The "charge" representation of different digital values in the bit cell consisting of many magnetic layers. (b) The stray field versus the digital level in the 3-d multi-level mode. (c) SNR versus the number of layers.

Data Reading

Implementation One: Direct Reading of Magnetic Field above Recording Medium

It is believed that the most straightforward implementation would be when the net signal is read directly from a location above the medium. Similar to conventional magnetic recording, a giant magnetoresistive (GMR) sensor could be used to read the magnetic signal emanatin`g from the medium in the vicinity of each bit cell [22,23]. In other words, this reading scheme reflects the 3-D multi-level recording mode, as described above (see Figure 11). For example, the net magnetic signals corresponding to the multi-level magnetization patterns, as shown in Figure 11, can be illustrated by the magnetic "charge" configurations, as shown in Figure 12a. For example, for the totally saturated state (digital "10"), the net signal consists of the magnetic fields emanating from the "charge" on the top and bottom surface of the effective magnetic layer, respectively. For each intermediate state ("9", "8", etc), there is also contribution from the "charge" in the respective boundary plane, as shown in Figure 11a. According to this magnetic "charge" model, it is a fairly trivial task to calculate the net field for different magnetization patterns []. Thus calculated signal levels are shown in Figure 12b. It could be observed that the signal exponentially drops with the increase of the number of recording layers. The net signal-to-noise-ratio (SNR) strongly depends not only on the read sensor (GMR, and others) but also on the medium transition- and dc- noise and the electronic noise in pre-amplifiers [24]. The calculated SNR versus the number of layers for a simplified case is shown in Figure 12c. The medium is assumed to be ideally patterned in all three directions and thus the medium noise can be neglected. It is assumed that there are two sources of the electronics noise: 10 Ohm GMR sensor and 0.2 nV/sqrt(Hz) preamp noise over a 500 MHz CTF bandwidth at 1 Gigabit/sec data rate. It is believed that the most advanced encoding software channels (e.g., turbo) could reduce the bit error rate (BER) to 10^{-9} even for a 10 dB SNR recording system [25]. Even with such advanced encoding, only four to five layers could be distinguished in such a trivial implementation of 3-D recording. If the project to be continued, advanced data recognition methods will be exploited to further improve the reading process. In addition, a novel (co-developed by PI) differential arrangement of GMR sensors will be exploited to increase the effective sensitivity of the sensors [26].

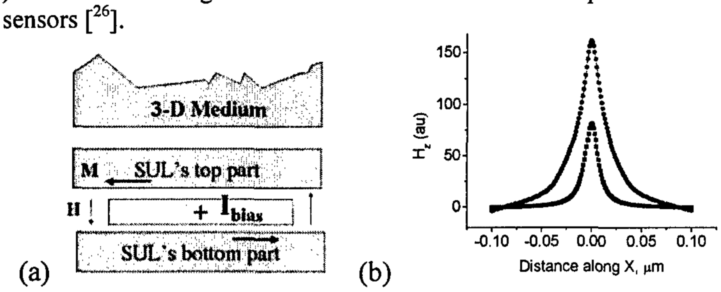


Figure 13. (a) A cross-sectional diagram showing the control of the "softness" of the soft underlayer. (b) Sensitivity field for each read cell element with a "free" (red line) and saturated soft underlayer.

Implementation Two: Data Access with Soft Underlayer

In this case, it is more illustrative to use the Principle of Reciprocity to describe the information retrieval (reading) [.]. Each cell includes a GMR element in a linear region. To identify each layer during the reading process, the sensitivity field of each cell is varied via the controlled variation of the "softness" of the SUL on the bottom of the medium. The "softness" can be controlled via variation of biasing of the SUL. The variation of biasing is produced by a relatively small electric current (~100 mA turn) through a wire underneath the SUL. This method was developed by PI during the development of perpendicular magnetic recording at Seagate Research [27]. A schematic diagram showing the mechanism of biasing the SUL is shown in Figure 13a. The SUL system consists of top and bottom layers connected with each other magnetostatically and isolated electrically. Due to the magnetostatic coupling, the top and bottom layers of the SUL system have magnetization in opposite directions. Due to the well-defined magnetic loop around the biasing wire it takes a fairly small electric current (and thus relatively small power loss) to saturate the entire system. As a result, just via relatively small variation of the electric current through the biasing system, one can drastically change the effective permeability of the SUL and consequently drastically change the sensitivity function of each cell. The biasing mechanism is a part of the provisional patent on a 3-D memory device filed at FIU on August 8th 2004.

According to the reciprocity principle, the signal in each cell is given by the following expression,

$$S \sim \int H_z(\vec{r} - \vec{r}')\cdot M_z(\vec{r}')\partial\vec{r}'$$

where H_z and M_z are the perpendicular components of the sensitivity field of the cell and the magnetization in the medium. It should be noted that this integration is taken over the entire volume of the recording medium. Therefore, if the signal can be calculated in a 3-D space around the medium, one can obtain all the information about the magnetization (i.e. all the information stored in the 3-D medium) as a result of the deconvolution of the sensitivity field with the signal obtained as a result of the variation in the z-direction. The sensitivity field is a property of each read element and the SUL. Therefore, the field can be calculated for given properties of the read element and the SUL. As for the signal, S, each read cell represents a point in a 2D plane of the grid. Consequently, the one parameter missing is the dependence of the signal on the perpendicular direction, z. This is exactly the purpose of the earlier described control of the "softness" of the SUL. Earlier, it was found that as a result of the variation of the "softness" of the SUL, one could effectively create sufficient variation of the sensitivity field in the vertical (-Z) direction []. The simulated sensitivity field for each read element with and with no SUL present is shown in Figure 12b. The simulations indicate that a change by a factor of two should be expected between the extreme cases, with a "free" SUL and a saturated SUL, respectively. The FEM-based simulations were performed by Chomko, as described above. The micromagnetics was taken into account to calculate the micromagnetics of Nanoscale read elements and of the region of interest in the recording medium [,].

In preliminary simulations, a 3-D medium with some pre-recorded information was tested for reading back the information using the described above method. For example, two chunks of information pre-recorded into the second and fourth layers of a 20-layer recording medium, respectively, are shown in Figure 14a. The respective signal profiles which were read back at SUL's biasing current values of 5.85 and 1.56 A turn, respectively, are shown in Figure 14b. The similarity between the recorded and read back patterns indicates that the information certainly could be retrieved back. Novel encoding mechanisms based on the advanced deconvolution techniques have been developed to maximize the SNR [28].

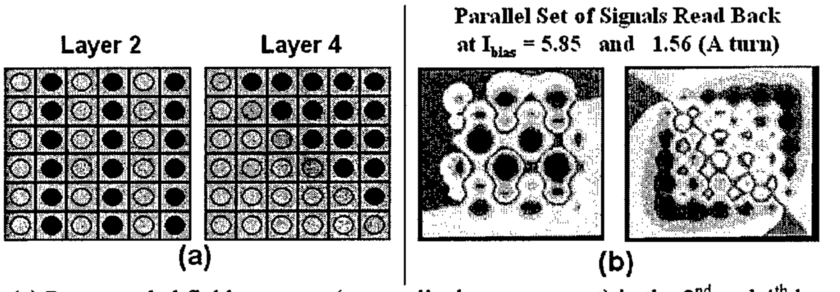


Figure 14. (a) Pre-recorded field contours (perpendicular component) in the 2nd and 4th layers of a 20-layer recording medium. (b) Sets of signals read back at a SUL's biasing current of 5.85 and 1.56 A turn.

III. PUBLICATIONS, PATENTS, AND PRESENTATIONS RESULTED FROM THE CURRENT PROJECT

Peer-review Papers

1. S. Khizroev, Y. Hijazi, N. Amos, R. Chomko, and D. Litvinov, "Considerations of three-dimensional/multi-level magnetic memory," in press, *Appl. Phys. Reviews – Focused Review, JAP* **98** (2005), in press.
2. S. Khizroev, R. Chomko, Y. Hijazi, S. Mukherjee, R. Chantrell, X. Wu, R. Carley, D. Litvinov, "FIB-fabricated nanoscale magnetoresistive sensor," *Appl. Phys. Lett.* **86**, 42502 (2005).

3. F. Candocia, E. Svedberg, D. Litvinov, S. Khizroev, “Deconvolution processing for increasing the resolution of magnetic force microscopy measurements,” *Nanotechnology* **15**, S575-84 (2004).

Patents Filed

- One provisional patent filed with US PTO on August 28, 2004

Presentations

1. N. Amos, R. Ikkawi, R. Chomko, V. Renugopalakrishnan, D. Litvinov, S. Khizroev, “Magnetic and Protein Memory Systems for Areal Densities Beyond 1 Terabit/in^2,” 2nd IEEE Conference on Nanoscale Devices and System Integration (NDSI-2005), Houston, Texas, April 4-6, 2005.
2. S. Khizroev, “Nanoscale Memory Devices,” Solid State Technology and Devices Seminar at the University of California at Berkeley, October 22nd 2004.

IV. STUDENT INVOLVEMENT

Undergraduate Student’s Involvement

The funding of this projected proved to a critical milestone in attracting top undergraduate and graduate students to conduct research at Florida International University (FIU). For example, this grant had supported the involvement in this project of undergraduate student Nissim Amos. Amos was the only student who a BS degree with BS in Electrical Engineering with a perfect GPA 4.0 in December 1994. There is no doubt that this talented student could have gone to continue his graduate school to any school of his choice. Nevertheless, he chose to continue his graduate study at FIU. Currently, he is successfully working on his MS and PhD degree under the supervision of the PI. As a result, this also increased the quality of the graduate school at FIU.

Graduate Student’s Involvement

The successful start of this proposal helped to attract two of the best graduate students at FIU to continue their PhD studies under the supervision of the PI. One of the students is the above mentioned Nissim Amos. The other student is Yazan Hijazi who is scheduled to get his PhD in December 2005. These two students became models for other bright students to chose continue their graduate studies at FIU. Currently, 6 MS and 3 PhD students are involved in the research center under the leadership of the PI.

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13. ABSTRACT *(Maximum 200 words)*

The design of a 3-0 system included consideration of several following recording configurations:
a)The first configuration is a recording system including a multi-layer-based recording media with each layer addressed separately. Each layer consists of grains coupled not only magnetostatically but also via relatively weak or strong quantum-mechanical exchange coupling, as shown in Figure 1a. The recording media is made of a relatively "hard" magnetic material, such as, CoCr-based, Co/Pd-mutilayers, and others, with no "soft" magnetic underlayer involved. It was found that a "ring" type of magnetic probe should be used to record information and a GMR type of sensor could be used to read to information back.
b) Same as above with the exception of the utilization of a soft magnetic underlayer, as shown in Figure lb. The soft underlayer is used under the recording laycr consisting of many "hard" layers. The soft underlayer is made of Permalloy (Ni79/Fe21), or Fe45/Co55 alloy, or Ni45/Fe55, or FeAIN or similar nitride, or another soft magnetic material. Contrary to the popular so called perpendicular recording mode with a soft underlayer, in the proposed configuration, it is not a problem to use a soft underlayer with strongly reduced noise through a relatively trivial biasing of the soft underlayer. The biasing is used to sweep off the noise-generating and random domain walls in the soft material.
c) The third configuration includes a recording media consisting of many exchange-decoupled "layers" (with layer consisting of exchange-decoupled grains) with no strict definition of the layers as long as the individual grains are exchange-decoupled in

14. SUBJECT TERMS
all three dimensions. Again, this configuration could be used with or with no soft magnetic underlayer.

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