Microstructure evolution, magnetic properties and switching behavior of sub 5-nm grain size high anisotropy $hcp$ CoPt and $L1_0$ FePt thin films and graded media using ion implantation

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Abstract:

High magnetic crystal anisotropy $L1_0$ FePt has been considered as a potential media material to achieve the ultra high areal density using Heat Assisted Magnetic Recording (HAMR) technology which allows to writing the media near the Curie temperature (480 °C). However, writing the media at such a high temperature causes the problem of lubricant degradation. Hence reduction in Curie temperature without significant loss in magnetic crystal anisotropy is a critical issue. This proposed work will focus to achieve a small grain size (4-5 nm) with narrow grain size distribution and reduce the Curie temperature of FePt film without significant deterioration in magnetic crystal anisotropy. The control of microstructure will be achieved by layer engineering approach using suitable oxide or carbon doping in FePt layer and underlayer, and relation between microstructure and magnetic properties will be studied to understand the underlying physical mechanism. The Curie temperature will be reduced by doping suitable materials such as Co, Cu, Ag, Au, Rh and Pd and relative compositions will be optimized for high areal density application. The crystallographic texture of FePt film deposited on glass substrate will be controlled to achieve the out-of-plane magnetic anisotropy, and switching behavior of such film at different temperature will be studied. In order to fulfill the near future requirement of hard disk industries to achieve the areal density up to 2 Tbits/in² without using HAMR technology, the ECC media using FePt film of magnetic anisotropy $2 \times 10^7$ ergs/cc at ordering temperature below 300 °C will be fabricated and its switching behavior will be studied. In addition, a side by side work will be carried out to increase the magnetic anisotropy of currently used CoCrPt media to meet the immediate requirement of media industries to increase the areal density. Ion implantation technique will be used to make the graded media which is able to control the magnetic anisotropy at atomic scale compared to conventional sputtering technique to fabricate the mulrilayer media.

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Subject of research and relevance to issue(s) to be solved in connection with ASTC stated goals

The demand of increasing areal density depends on the scaling. In order to further increase the areal density beyond current limit, thermally stable grain size below 6-7 nm is required. The CoCrPt based magnetic media being used in the current perpendicular magnetic recording is unable to meet this requirement due to superparamagnetism. L1₀ phase FePt material has been considered as a potential candidate to overcome the problem of superparamagnetism down to 3 nm length scale due to its high magnetic crystal anisotropy (Kᵢᵣ) of 7x10⁷ ergs/cc.¹ ² However, due to its high Kᵢᵣ, FePt requires very high writing field of 125 kOe, which is much higher than the writing field limitation of writing head (2.4 kOe). In order to overcome the problem of writing field HAMR³ has been proposed, in which media is temporarily and locally heated close to its Curie temperature during the writing process which is detrimental to lubricant. Hence despite the advantage of FePt to achieve the thermally stable grain size down to 3 nm, there are many challenges that need to be addressed before its industrial realization. The major challenges are:

- Lowering the Curie temperature without significant decrease in the magnetic crystal anisotropy
- Lowering the ordering temperature of FePt film deposited on amorphous substrate to achieve the high magnetic crystal anisotropy L1₀ phase
- Controlling the easy axis of magnetization direction along the film normal
- Fabrication of small and magnetically isolated grains with small surface roughness
- Understanding the relationship between grain size and magnetic properties such as magnetic crystal anisotropy, coercivity and Curie temperature
- Understanding of switching behavior of small magnetic grains at different temperature for HAMR applications

The proposed research work will focus to address above issues keeping roadmap of media industries into consideration. This proposed work will address the ASTC objective of fabrication of small grains (below 6 nm), requirement of high temperature lubricant, understanding the physical mechanism controlling the switching behavior close to the Curie temperature for HAMR application to achieve the areal density beyond 2 Tb/in² areal density.

In order to fulfill the immediate requirement of hard disk drive (HDD) industries to achieve the areal density up to 2 Tbits/in², the alternative is either to increase the magnetic anisotropy of current CoCrPt media being used by industries or to use a high Kᵢᵣ L1₀ FePt with magnetic anisotropy 2 x 10⁷ ergs/cc and use the exchange coupled graded media to switch the magnetization direction. The media material of this anisotropy is able to keep the thermally stable grain down to 5 nm and can be switched using the currently used writing head without using HAMR technology. But major challenges are:

- How to increase magnetic anisotropy of CoCrPt media?
- How to make the graded media in which magnetic anisotropy would be controlled at atomic length scale?
In this proposed work, parallel work will be performed to increase the magnetic anisotropy of currently CoCrPt media being used by industries. Ion implantation technique will be used to make the graded media which is able to control the magnetic anisotropy at atomic scale compared to the conventional sputtering technique to fabricate the multilayer media.

[2] Proposed research approach(es)

[2.1] Experimental

[2.1.1] How to reduce the Curie temperature and the order-disorder temperature of FePt

Since, it is well established that Curie temperature (Tc) and order-disorder temperature depend on the local atomic environment of constituent elements and inter-atomic distance. Hence any change in the local atomic environment may causes to change the Curie temperature and ordering temperature of FePt. In this work we will investigate the effects of doping on Tc and order-disorder temperature for varying composition of different elements such as Co, Cu, Ag, Au, Rh and Pd in FePt. In addition, the effect on doping on magnetic crystal anisotropy will be also studied. The underlying physical mechanism will be studied based on the first principle calculation.

[2.1.2] How to control the easy axis and grain size

Recently many efforts have been done to reduce the grain size of FePt films by adding excess amount of SiO$_2$, TiO$_2$, Ta$_2$O$_5$, MgO and C in FePt film, which also reduces the intergranular exchange interaction. Despite the achievement of these outcomes, an undesirable side effect of excess doping is the deterioration in the magnetic properties. Hence, using an alternative approach is necessary in order to reduce the grain size and intergranular exchange interaction without affecting the magnetic properties. It has been well established in the CoCrPt based perpendicular magnetic recording media that grain size and texture of magnetic layer can be controlled by the microstructure of underlayer. As a result, in this study we propose to reduce the grain size and texture using layer engineering approach of underlayer microstructure. In order to achieve such a small grain size a composite target of FePt-C or FePt-oxide will be sputtered deposited on MgO/ Cr$_{90}$Ru$_{10}$ underlayer where CrRu will be deposited in the two steps. In the first step, CrRu will be deposited at optimized process parameters to induce (002) texture. In the second step, CrRu-oxide will be deposited on the top of CrRu layer. The deposition of CrRu-oxide will help to grow small grain size CrRu with (002) texture surrounded by amorphous grain boundaries. Since the surface energies of oxide materials are generally less than that of CrRu, hence during the deposition oxide materials diffuses towards the grain boundaries and the surface. The diffusion of oxide towards grain boundaries is useful to reduce the grain size and intergranular exchange interaction, but detrimental to develop hetero-epitaxial growth of the subsequent layer once diffuses towards the surface. A thin layer of oxide from top of CrRu surface will be etched away before deposition of FePt, and thereafter FePt will be deposited on the template of small grain size CrRu underlayer. The surface roughness will be control by optimizing the process parameters during sputtering. In addition to CrRu, other underlayer materials with suitable lattice mismatch with FePt will be explored.
[2.1.3] How to increase the magnetic anisotropy of CrCrPt media

The alloy of CoCrPt is the base media material for hard disk drive, which is in the use since long back. During the deposition process, Cr segregates on the grain boundaries and helps to magnetically isolate the grains. However, experimentally it has been established that complete Cr is not segregating on the grain boundaries, and a part of it remains in the grain which deteriorates the magnetic anisotropy. With the evolution of time and need of high magnetic anisotropy material, the Pt composition starts to increase and Cr composition decreases. This indicates that by controlling the relative composition of constituent elements, the magnetic anisotropy of CoCrPt can be enhanced. In addition to the relative compositions, the underlayer and seedlayer materials, their interfaces and quality of crystallographic texture and process parameters also play very important role in determining the magnetic anisotropy. In this proposed work we will focus to optimize the compositions of CoCrPt, and different process parameters such as deposition pressure, deposition rate and layer structure to achieve the high magnetic anisotropy.

[2.1.3.1] Previous work carried out by the group member

Since the presence of small quantity of Cr inside the grain reduces the magnetic anisotropy. Therefore, in our previous work we focused to increase the magnetic anisotropy by optimizing the relative composition of Co and Pt. It was observed that with increasing the Pt content, the magnetic anisotropy and out-of-plane coercivity increases and reaching maximum for Co_{72}Pt_{28} (Figure 1)\textsuperscript{13}. With further increasing the Pt content above 28 at.\%, out-of-plane coercivity and magnetic anisotropy decreases due to increasing stacking fault. The magnetic anisotropy was further increased by improving the interface roughness of Ta seed layer (Figure 2)\textsuperscript{14}.

![Figure 1: Variation of magnetic anisotropy ($K_u$), in-plane coercivity ($H_c(//)$), out-of-plane coercivity ($H_c(\bot)$) with Pt.](image1)

![Figure 2: Magnetic anisotropy for different surface roughness of Ta seed layer.](image2)
[2.1.4] How to control the magnetic anisotropy of L10 FePt

Since magnetic anisotropy of FePt is the function of ordering which depends on the deposition temperature and doping of third element. Better the chemical ordering, higher the magnetic anisotropy. Therefore, deposition temperature and doping of different elements such as Co, Cu, Ag, Rh, Pd and Au will be optimized to achieve the magnetic anisotropy close to 2 x 10^7 ergs/cc.

[2.1.4.1] Previous work carried out by the group member

In our preliminary work we study the effect of doping Co on out-of-plane coercivity and ordering parameter. It was observed that ordering parameter defined by \( S = \left[ \frac{I(001)}{I(002)} \right]^{1/2} \) (where \( I(001) \) and \( I(002) \) are the integrated intensity of (001) and (002) peaks respectively in the XRD \( \theta-2\theta \) scan) and coercivity decreases with increasing the Co concentration and follow the same trend (Figure 3-4).\(^{15}\) It indicates that proposed method can tailor the magnetic properties of FePt as per the requirement.

![Figure 3: Out-of-plane hysteresis loops of [Co\(_x\)Fe\(_{100-x}\)]\(_{50}\) Pt\(_{50}\) for varying x.](image1)

![Figure 4: Variation of out-of-plane coercivity (Hc) and ordering parameter of [Co\(_x\)Fe\(_{100-x}\)]\(_{50}\) Pt\(_{50}\) for different x.](image2)

[2.1.5] How to fabricate graded media by controlling magnetic anisotropy at atomic scale:

As discussed in section 2.1.4, that magnetic anisotropy can be controlled by doping third element in the binary alloy. Therefore, ion-implantation of suitable materials can control the magnetic anisotropy at atomic scale due to its very controlled nature of implanted species, dose and depth. This technique has been suggested to fabricate the graded media by controlling the doping level. This can be done by implanting ions into the recording layer in such a manner that the doping profile has its peak at the top surface of recording layer, as shown in Figure 5, and a gradual tail goes deep into the recording layer hence creating a gradient in anisotropy across the recording layer. In the present study, Co and Fe will be implanted due to their relatively larger saturation magnetization.
Figure 5: Schematic of doping profile (Red) of ion species in recording media.

[2.1.3.1] Previous work carried out by the group member

In order to see the effects of ion implantation on magnetic properties, different species such as nitrogen, oxygen and cobalt has been implanted in CoCrPt media deposited on Ru underlayer. Results show that coercivity decreases with increasing the dose of implanted species. Further characterization indicated that magnetic anisotropy also decreased with increasing the dose of implanted species. The effects of higher atomic weight implanted species are more prominent (Figure 6) [16]. Based on the observed result, it is clear that ion implantation is able to fabricate the graded media.

Fig. 2. (a) Coercivity verses dose for different ions implanted.

[2.2] Computational

Effects doping on the Curie temperature and magnetic crystal anisotropy will be investigated using first principle calculation in correlation with observed experimental result, which will help to understand the underlying physical mechanism. The effects of size and temperature on switching mechanism will be studied using freely available micromagnetic OOMMF software.
[3] Likely outcome of research

This proposed research work is able to address the many issues such as reducing the Curie temperature, order-disorder temperature and grain size of FePt thin film, which are the major challenges in the industrial realization of FePt as a media material to achieve the ultra high density in the hard disk drive using HAMR technology. In addition to address the many issues related with HAMR technology to increase the areal density in near future, the proposed work can extend the ion implanted exchange coupled graded media using the high anisotropy hcp CoPt and L10 FePt thin film to achieve the areal density up to 2 Tbits/in² and able to meet the immediate need of hard disk industries.

[4] Resources required performing project

[4.1] Personnel, students, etc.

Proposed work will be carried out by proponent with the help of university research fund assisted graduate students and postdoctoral fellow. (Please note resources needed are more than requested from ASTC and will be supplemented by my other research projects)

[4.2] Equipment, lab, etc.

All research work will be performed using the experimental facilities available in the university and university affiliated research institute. We are able to access following experimental facilities which are required to carry out this research work.

- AJA sputtering system with 19 gun for sample fabrication
- Bruker thin film and high resolution X-ray diffractometer
- Transmission Electron Microscopy
- Scanning Electron Microscopy
- Scanning Probe Microscopy
- Vibrating Sample Magnetometer
- SQUID
- Electron Beam Lithography
- TR MOKE
- TEM
- ToF-SIMS

[4.3] Computational

- All the required computational facilities are available in the university and university related research institutes

[5] Resources other than ASTC funding dedicated to perform project

a. Grants Prof C Singh Bhatia has a funded project for 10 terabits/in² and has now got new cleanroom lab built equipped with sputtering, e-beam tool, TR-MOKE, VSM, AFM/MFM, Ion etcher, access to Filter Cathodic Arc, XRD, AES, SIMS,
XPS, MOKE, SQUID, tools. He also has a joint study agreement with IBM Yorktown Heights where we have access to ion implantation tool.

b. Contracts N/A

c. Other N/A

[6] Resources requested from ASTC and how they will be utilized

d. Funding

i. Overhead 30%

ii. Direct project cost 95K/Yr

iii. Facility use fees: 10K

iv. Materials 10K

v. Postdoc(1.2x) 60K

vi. Travel 15K (3 trips/yr to attend ASTC meeting)

NOTE: If ASTC awards project funding to NUS as an “unrestricted gift” then no overhead is required.

[7] Time line (Gantt chart)

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<th>Task</th>
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<td>Fabrication of graded media using ion implantation</td>
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<td>Texture and easy axis dispersion control in FePt film deposited on glass substrate</td>
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<td>Grain size and grain size distribution control down to 4-5 nm using layer engineering</td>
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Lowering the order-disorder temperature | X | X | X | X
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Magnetic anisotropy control by doping | X | X | X |
Understanding the effect of doping on magnetic anisotropy | | X | X |
Fabrication of ECC/graded media | X | X | X |
Study of doping on Tc | | X | X |
Summary | | | X | X

[8] Not more than one-half page per contributor: contact information and biographical sketch of researcher.

C. Singh Bhatia worked on magnetic hard disk drives at IBM/HitachiGST for ~30 years and many ideas developed in the lab were commercialized under his management. INSIC presented the 2008 Distinguished Contribution Award to Prof. C. Singh Bhatia in recognition of his dedicated, longterm leadership and outstanding level of contribution to the INSIC EHDR Research Program in advanced hard disk storage technology. Dr. Bhatia is the only individual to have twice been awarded the INSIC Leadership Achievement Award (in 1998 and 2003). He was honored for his recent efforts in leading a working group to define approaches to the head-disk interface for 10 terabit per square inch recording, and for his pioneering efforts to include Singapore in INSIC's research programs. Prof Bhatia joined NUS as Professor in Electrical and Computer Engineering Department, NUS in Aug 2007.

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References