Design, Fabrication, Optimization and Verification of 
FePt based Bit Patterned Media 

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Abstract

Wang’s group has been supported by INSIC and recording industry for years and may be the 
only university group in US with the demonstrated and integrated capabilities to fabricate and 
investigate FePt based bit patterned media. We developed seedlayer/underlayer(s) and a 
low-substrate-temperature (350°C) process to grow smooth continuous L1₀ FePt film on glass 
substrate with relatively large Hₖ (~ 80kOe). Recently we designed and demonstrated FePt/Fe 
exchange coupled composite (ECC) bit patterned media (BPM) with 30 nm dot size and 35 nm 
pitch using diblock copolymer lithography on 2.5 inch disk substrate [1]. We also proposed and 
experimentally demonstrated a new ECC media design concept, which increased the Gain Factor 
(Figure of Merit of ECC stack) up to 3.2 for the first time with total magnetic layer thickness less 
than 10 nm [2]. Furthermore, we have developed a Nano-Imprinting process and demonstrated 
the feasibility for fabricating FePt bit patterned media with dot size less than 20 nm on 1 cm x 1 cm 
Si substrate [3]. Switching field distribution of the FePt ECC BPM has been characterized 
by several methods through collaboration [1,2]. Several fabrication processing and stack design 
factors were identified, which may cause the switching field distribution.

In this proposal, we will address key challenges listed by ASTC on the magnetic materials and 
properties for future bit patterned media by using the above-mentioned established research 
capabilities on the growth of continuous and smooth FePt ECC stack, fabrication processes of 
FePt ECC BPM and characterization methods for the switching field distribution.

1. To develop the continuous L1₀ FePt to reach large perpendicular Hₖ with minimum 
in-plane hysteresis and reduced roughness. This will be realized by selecting and 
exploring different seed and underlayer(s) by engineering its surface energy and interface 
energy;
2. To design, fabricate and demonstrate FePt ECC BPM media (both enclosed structure and 
graded structure) to reach the maximum Gain Factor (~ 4) of ECC media with ultra thin 
magnetic recording layer (< 10 nm); The targeted dot size and pitch size are 15 nm and 20 
nm respectively for the first year.
3. To characterize and understand quantitatively the origins of the switching field distribution 
for FePt ECC BPM;
4. To pattern and demonstrate FePt ECC BPM with low switching field distribution (~ 5 - 10%) 
with targeted 15nm dot size and 20 nm pitch size;
Research description

This proposal is focused on the BPMR topic No. 10: *BPM Magnetic materials and properties for BPM*. Also is related with the BPMR topic No. 4: *BPM island fabrication strategies (etch, ion implant, alternative) and effects on magnetic properties*.

We will try to address several key challenges for future FePt type BPM media: 1) how to reduce the in-plane component while keeping its high perpendicular \( H_k \); 2) how to design, grow and pattern ECC type FePt BPM media (both graded and enclosed structures); 3) what are the real key factors for the switching field distribution; 4) how to reduce the switching field distribution for FePt BPM media; 5) how the patterning processes (both diblock copolymer mask and nanoimprinting processes) contribute to the in-plane component and the switching field distribution;

In this research, several ideas will be tried to grow high quality continuous L1\(_0\) FePt film with large perpendicular (~100 kOe), minimum in-plane hysteresis and a small roughness. Our very recent interesting data (figure 1c) showed a very promising effort along this line. ECC bit pattern media with both graded structure and enclosed structure will be fabricated and tested based on the optimized L1\(_0\) FePt film. Several schemes for soft region will be explored including the temperature and composition control. Further optimization and design will be combined with micromagnetic simulation to achieve the maximum gain factor (~4) and meanwhile keep the thickness of the magnetic recording layer within 10 nm. To theoretically verify our design, we will carry out the simulation (LLG & OOMMF) and also collaborate with Prof. Randall Victora and Prof. Haowen Liu for a more complicated recording system level.

We have successfully established and demonstrated two FePt BPM patterning processes (30 nm dot size and 35 nm pitch size). We will continue to optimize these processes to pattern FePt ECC dots (graded structure) with size around 15 nm and pitch size around 20 nm by end of the first year. We have experimentally demonstrated that an enclosed or so-called core-shell type FePt ECC media has several advantages over other designs including the large gain factor (~ 3.2) with ultra thin recording layer (<10 nm) and low dipole interaction between dots [2]. We admit that it is a great challenge to fabricate enclosed type FePt ECC media (thickness control of side wall). However, its great potential to reduce the dipole interaction between neighboring dots and lower the total magnetic layer thickness makes it very attractive to address the concern of the broadening switching field distribution caused by the dipole interaction and to increase the writing field gradient. We plan to demonstrate the feasibility of the enclosed ECC FePt BPM structure with 30 nm dot size and 35 nm pitch size.

The fabricated FePt ECC BPM will be characterized to quantitatively understand the origins of the switching field distribution and its correlation with the design stack(s), thin film deposition parameters and patterning parameters. The target of this research is to demonstrate writable and thermally stable FePt type bit patterned media with low switching field distribution of less than 10% and high density with 15 nm dot size and 20 nm pitch size.
Current status and proposed research approaches

Fabrication and optimization of FePt based composite continuous film.

The quality of the continuous thin film is the key to prepare bit patterned media with low or no in-plane component. To keep the switching field distribution (SFD) of the patterned media as small as possible, the continuous film must be super flat and uniform. Also to fabricate the exchange coupled composite films, the hard magnetic film has to be very thin as well. In our previous work, 5 nm FePt continuous film was fabricated on Si wafer with structure of CrRu(30 nm)/Pt(3 nm)/FePt(5 nm) using an 8-target magnetron sputtering system with the base pressure as low as 4x10^{-8} torr. Good ordering and FePt (001) texture were achieved at 350 °C substrate temperature. Fe layer was coated on top of the FePt after the sample was cooled down to room temperature. Fig. 1 (a)- (c) shows the TEM cross-sectional images and XRD spectra of the composite continuous film with structure of CrRu(30 nm)/Pt(3 nm)/FePt(5 nm)/Fe(7.5 nm). Fig.1 (a) and (b) verify the continuity and flatness of FePt and Fe layer in both low and high magnification. The XRD spectra in (c) indicates the good ordering and (001) texture. Fig.1(d) shows the out-of-plane and in-plane MH loops of a recently optimized MgO substrate/CrRu(30 nm)/Pt(3 nm)/FePt(5 nm) continuous film with ultra low in-plane coercivity (almost zero); This film also shows huge perpendicular Hk (estimated around 80 kOe).

We will explore several new seedlayer and underlayer by engineering the surface and interface energy to increase the ordering and completely eliminate the in-plane remanence of the FePt continuous film. The in-situ temperature during FePt film deposition will be increased a little bit to get higher ordering but keep the flatness. On the other hand, since Fe has high Ms value and high etching resistance, it may not be the best choice for practical patterned media. We will replace the simple FePt/Fe bilayer structure by FePt film with graded anisotropy. There are two ways to fabricate graded FePt film. One is to decrease the heating temperature while depositing the FePt layer to achieve graded ordering parameter of FePt along the perpendicular direction. The other one is to gradually change the composition. For example, gradually decrease the sputtering power of Fe while co-sputtering the Fe and Pt element targets. Our sputtering system has the capability to do both.

Patterned structure fabrication

We have successfully established two approaches to fabricate FePt patterned dots: diblock copolymer mask and nanoimprinting. Both approaches will allow us to pattern sub 10 nm FePt dot size in future.
First, our grown continuous films were patterned using a mature diblock copolymer patterning technique that was developed by Toshiba. Hard mask arrays were formed by diblock copolymer self assembling and the films were etched by ion milling. There are two efforts in parallel along this line. Dr. A Kikitsu and his team members from Toshiba agreed to continue to help us on the formation of the diblock copolymer mask. Also we have been working with Prof. Marc Hillymer of Chemistry Department at UMN (leader of diblock copolymer project at UMN) on this topic as a long term collaboration through a NSF MRSEC grant.

Figure 2 (a) SEM plan-view image and (c) TEM cross-sectional image of patterned media with structure of CrRu(30 nm)/Pt(3 nm)/FePt(5 nm)/Ru(3 nm). (b) SEM plan-view image and (d) TEM cross-sectional image of ECC patterned media with structure of CrRu(30 nm)/Pt(3 nm)/FePt(5 nm)/Fe(5 nm)/Ru(3 nm). All the TEM samples and images were prepared by Hao Wang (PhD student of this project).

Figure 3 (left) Coercivity of the continuous FePt (5 nm)/Fe films and patterned FePt/Fe media (31 nm dot size and 35 nm pitch size); (right) AFM and MFM images at different magnetic field along the MH loop for the patterned FePt media;

Fig. 2 shows the SEM plan-view image and TEM cross-sectional image of patterned media with structure of CrRu(30 nm)/Pt(3 nm)/FePt(5 nm)/Ru(3 nm) and CrRu(30 nm)/Pt(3 nm)/FePt(5 nm)/Fe(5 nm)/Ru(3 nm). The diameters of the pillars are about 31 nm with a size distribution of 8%. Their technique allows to further decrease the pillar size down to 10 nm and less.
Fig. 3 shows the coercivity of the continuous films and patterned films with different Fe layer thicknesses. The FePt thickness was kept as 5 nm. Fig. 3 (right) shows one way to characterize the switching field distribution by collaborating with Dr. Y. Chen at DSI. We also tested SFD by using the minor loop method. The SFD for the samples with Fe thickness of 0 nm, 5 nm and 10 nm is still larger than 20% because these are not optimized continuous films. With recently optimized continuous FePt films, we believe SFD will be further reduced. Also we will study and optimize the etching process both ion milling and reactive ion etching (RIE) to further reduce the SFD.

Second, the grown continuous films were patterned by an established Nanoimprinting process in our lab [3]. Nanonex NX-B200 nanoimprinter was used. We prepared the Nanoimprinting mold using an AAO process, which limited the pitch size. A newly installed Vistec EBPG5000+ E-beam lithography system in our lab will allow writing isolated lines with 6 nm width. We plan to prepare the nanoimprinting mold using this system (4 – 6 hours writing time for 1cmx1cm sample with dot size and pitch size both around 20nm). Fig. 4 shows the images of the patterning facilities and patterned 25 nm FePt dot using a nanoimprinting process and AAO mold.

Figure 4 (a) Photo and (b) demonstrated lines with 6 nm width of Vistec EBPG5000+ E-beam lithography system (100 keV) (c) Photo and (d) demonstrated 25 nm size dots of NX-B200 nanoimprinter

**Measurement and verification.**
The ordering and texture of the films will be measured by XRD. The microstructure, composition distribution and etching damage will be evaluated under SEM and HRTEM. Magnetic properties including thermal stability and SFD will be tested under VSM, AGFM, MOKE, MFM and MPMS [4-7]. SFD measurement will be carried out by collaborating with Dr. Chen at DSI.

**Resources required to perform project**

**Personnel, students**
Principle investigator: Prof. Jian-Ping Wang; two weeks summer salary;
Student: Hao Wang (senior PhD student) with 12 months support;

Hao has been working on FePt ECC BPM for three years based on INSIC support. He has developed
FePt ECC BMP using two approaches 1) diblock copolymer hard mask process (collaborating with Toshiba group and UMN polymer group) and 2) nanoimprinting; He has the experience to prepare high quality TEM cross-section samples and carry out the high-resolution TEM analysis too.

**Target materials and substrates:** FePt, CrRu and MgO targets (2 inch); Si and glass substrate;

**Usage of Electron Beam Writer:** *(available at Nano Fabrication Center, same building of my lab)*

To prepare the Nanoimprinting mold (1 cm x 1 cm or larger) to imprint FePt ECC BMP media;

**Usage of etching facility to fabricate BPM:** *(available at Nano Fabrication Center, same building of my lab)*

To pattern the FePt ECC BPM;

**Self-assembly of diblock copolymer mask:** *(available, two resources: Prof. Marc Hillymer, UMN; Dr. Akira Kikitsu, Toshiba)*: To prepare the self-assembled diblock copolymer mask on FePt ECC continuous layer;

**Resources other than ASTC funding dedicated to perform project**

**Grants**

1. **National Science Foundation, Materials Research Science and Engineering Center (MRSEC):**
   My research on magnetic materials has been intensively supported by NSF, MRSEC program. I have been collaborating with Prof. Mac Hillymer (MRSEC IRG1 (polymer) team leader) on the formation of diblock copolymer mask using his latest developed diblock copolymers.

2. **National Science Foundation, Nano Fabrication Center (NFC), NNIN Program:**
   My research on the fabrication of magnetic nanostructure has been supported by NSF, NFC. We acquired and installed a Nanoimprinting System through a NSF support in year 2008. My student has successfully developed a process to fabricate the FePt BPM with 20 nm dot size using this machine in clean room.

3. **National Science Foundation, Acquiring an Advanced Electron Beam Lithography Writer:**
   We installed an advanced Vistec Electron Beam writer (100 keV, 6nm resist resolution) in our clean room in Nov 2010. The system is running well now. My student has been using it to prepare new Nanoimprinting Mold.

**Available Diblock Copolymer Self-assembly Processes for Etching Mask**

1. **Dr. Akira Kikitsu, Toshiba Central Lab:**
   We have collaborated with Dr. Kikitsu’s group for years. They provided us the diblock copolymer self-assembled mask, which enabled us to prepare the FePt/Fe ECC BMP with 30 nm dot size and 35 nm pitch size. The paper was presented at MMM 2010 and published in JAP, 2011. This collaboration is under way and the new samples we are preparing target at large H_k and smaller dot size and pitch size.

2. **Prof. Mac Hillymer, Chemistry Department, University of Minnesota:**
   We have collaborated with Prof. Marc Hillymer at Chemistry Department, University of Minnesota since 2010. They provided us several new diblock copolymer powders. We are working together to prepare etching mask with smaller dot size (10 nm or less) directly on FePt/Fe ECC stack.

**Available Equipment and Processes:**

1. **Multilayer thin film growth facilities (Wang’s lab)**
   Eight-target ultra-high vacuum magnetron sputtering system with high substrate temperature (up to 3 inch wafer);
   Six-target ultra-high vacuum magnetron sputtering system with low substrate temperature (up to
6 inch wafer);
2. Microstructure and crystalline characterization: (UMN Central Facility)
   X-ray diffractometer (XRD); Scanning electron microscope (SEM); High resolution transmission
   electron microscope (TEM); TEM Nanoprobe EDX for composition analysis of individual magnetic
dot;
3. Magnetic characterization: (Wang’s lab, UMN Central Facility)
   Three high-magnetic-field magnetic property measurement system (MPMS) (up to 9 T), vibrating
   sample magnetometer (VSM), alternating gradient force magnetometer (AGFM), Magnetic force
   microscope (MFM), magneto-optical Kerr effect (MOKE);
4. Bit patterned media fabrication (UMN Nano Fabrication Center)
   Diblock copolymer self-assembly and mask formation;
   Vistec E-beam Writer (100 keV, 6 nm photo resist line definition);
   Nanoimprinter (capable for 3 inch wafer);
   Ion miller; three different reactive ion etching (RIE) processes;

**Resources requested from ASTC and how they will be utilized**

*a. Funding*
Total: $80,870 (could be cut to $70,000 if the targets can be provided by sponsors)
i. Overhead (51.5%): $22,118
ii. Direct project cost: 58,752
iii. Facility use fees: $8000
iv. Materials: $6800 (could be cut down to $1000 if FePt targets can be provided by sponsors)
v. Student stipends (12 months): $38,952
vi. Travel: $5000 (could be leveraged with other travel, if need)

*b. Expected technical cooperation with sponsor(s): materials to be provided by sponsor(s) (e.g., targets,
devices, engineering support, etc.)*
FePt alloy targets (2 inch)

*c. Sponsors’ facility utilization*
SFD measurement and high-field vector SQUID

*d. Expected students’ internships:* yes

**Time line**
1. Optimize the FePt continuous thin film to improve the ordering, texture and flatness. (2 months)
2. Pattern the optimized FePt film with relatively large feature size (25nm) and characterization. (2 months)
3. Design and optimize the composite continuous film with bilayer structure and graded structure and understand the origins of the in-plane component. (2 months)
4. Pattern the optimized composite continuous film and SFD characterization. (2 months)
5. Explore a method to fabricate the proposed enclose (core-shell) type FePt bit patterned media and SFD characterization. (2 months)
6. Based on the results, further optimize and design new structure of the composite film as well as the patterning process. (4 months in total, 2 months in parallel with item 4)
7. Further reduce the feature size down to 20 nm or less, and understand the origins of SFD. (2 months in parallel with item 6)
Home institutions & resources

1. The Center for Micromagnetics and Information Technologies (MINT), Dept. of Electrical and Computer Engineering, University of Minnesota.
   Equipments: Magnetron sputtering system, VSM, AGFM, MPMS, MOKE

2. Characterization Facility (Charfac), University of Minnesota.
   Equipments: XRD, SEM, TEM, MFM

3. Nanofabrication Center (NFC), University of Minnesota.
   Equipments: E-beam lithography; Nanoimprinter; Ion mill; RIE.

Contact information and biographical sketch of researcher

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Biographical sketch:
Jian-Ping Wang is a full professor at Electrical and Computer Engineering Department, and a leader on experimental applied magnetic research being the Associate Director of the Center for Micromagnetics and Information Technologies (MINT) at University of Minnesota. He is also a graduate faculty member of Physics Dept and Chemical Engineering and Materials Science Dept at University of Minnesota. His current research programs focus on searching, fabricating and fundamentally understanding new nanomagnetic and spintronic materials and devices. He has built and run the Magnetic Media and Materials program in Data Storage Institute, Singapore, as the founding program manager, from 1998 to 2002. He received the INSIC technical award in 2006 for his pioneer work in exchange coupled composite magnetic media. He has authored and co-authored more than 200 publications in peer-reviewed top journals and conferences.

Hao Wang (senior PhD student) in Wang’s group. Hao Wang has been working on FePt ECC BPM for two years based on INSIC EHDR support. He has developed FePt ECC BMP fabrication process using two approaches 1) diblock copolymer hard mask process (collaborating with Toshiba group and UMN polymer group) and 2) nanoimprinting; He has fabricated the nanoimprinting mold with sub 20 nm feature size.