Overview of Material Research by Information Integration Initiative (MI2I)

K Terakura
(NIMS)

米国での Materials Genome Initiative (MGI) に刺激されて、世界の多くの国で所謂マテリアルズ・インフォマティクスのプロジェクトが始まっている。我が国でも昨年より、JST のプロジェクトとして、物質・材料研究機構（NIMS) を拠点とした情報統合型物質・材料開発イニシアティブ（MI^2I) が始まった[1)]。主な目的は、データ科学と物質・材料科学の連携により、物質・材料開発を加速することである。本プロジェクトでの重要な出口課題の一つとして、磁石・スピントロニクス材料を設定しており、その枠における一つの具体的な成果として、希土類元素と 3d 遷移金属元素からなる磁性体のキュリー温度の実験データをつかって、機械学習によりキュリー温度の予測をした。機械学習を用いて、望みの性質を持つ物質・材料を探索する仕組みを説明し、いくつかの具体的な例を紹介する。

Reference

1) http://www.nims.go.jp/research/MII-I/index.html (Accessible on 2016/06/01)

データ科学手法による磁性材料探索

小口多美夫
大阪大学産業科学研究所
物質・材料研究機構

Data-Science Approach to Magnetic Materials Exploration

T. Oguchi
Institute of Scientific and Industrial Research, Osaka University, Ibaraki 567-0047, Japan
National Institute for Materials Science, Tsukuba 305-0047, Japan

Data-science approaches with rapidly growing data have recently brought a new trend of research and development to a variety of fields in science and technology. In materials science, it is now widely called "Materials Informatics (MI)", as often seen in several related world-wide projects[1–5]. The key strategy is to integrate data-science techniques with experimental, theoretical, and computational ones. Especially big data generated by computational simulations together with existing experimental databases are the target of data-science methods such as data mining and machine learning interleaved with appropriate physical modeling and descriptors. In MI, first-principles density-functional-theory calculations among the computational approaches play an important role for supplying data and knowledge on materials complemental to the experimental databases. This is one of the characteristic features of MI contrast to the preceding "Bioinformatics". In this talk, I shall introduce some fundamental issues of the data-science approaches to the exploration of magnetic materials in our research project MI^2I.

References

1) Materials Genome Initialtive (MGI): https://www.whitehouse.gov/mgi
2) Materials Design at the Exascale (MAX): http://www.max-center.eu
3) Novel Materials Discovery (NOMAD): http://nomad-coe.eu
4) An e-infrastructure for software, training, and consultancy in simulation and modeling: http://cordis.europa.eu/project/ rcn/198333_en.html
5) Materials Research by Information Integration Initiative (MI^2I): http://www.nims.go.jp/eng/research/MII-I/index.html

Computational exploration of new permanent magnet compounds

Takashi Miyake[1,2]
[1] CD-FMat, National Institute of Advanced Industrial Science and Technology, Tsukuba 305-8568, Japan
[2] CMI[2] and ESICMM, National Institute for Materials Science, Tsukuba 305-0047, Japan

I will discuss current status and challenges for permanent magnet research by information integration. Strong magnet compounds such as $Nd_2Fe_{14}B$, $Sm_2Fe_{17}N_3$ and $NdFe_{12}N$ consist of three elements, namely rare-earth, iron and the third element. A natural question is: What is the best third element, and what about the fourth in a quaternary compound? This is an issue to be tackled by computational screening. As an example, we will present first-principles calculations of $ThMn_{12}$ type iron-based compounds. However, brute-force search based on first-principles calculations is computationally demanding even if using supercomputer facilities, since the number of combinations of chemical composition increases rapidly as the number of elements in a compound is increased. Machine learning is a possible solution to improve the efficiency drastically. It is found that Gaussian process regression using 7 descriptors accurately reproduces the Curie temperatures of bimetal alloys composed of transition-metal and rare-earth elements. This technique can be utilized for virtual screening. Another issue is exploration of crystal structure. Saturation magnetization is expected to be larger as the iron content increases. Hence, the crystal structure of new iron-rich phases is of particular interest. Crystal structure prediction is a hot topic in computational materials science in the past decade, and various efficient algorithms have been developed. Recent progress and applications will be reviewed.

Mining magnetic materials data

DAM Hieu Chi
(Japan Advanced Institute of Science and Technology)

The most important underlying hypothesis of materials researches is that the features of the structure of materials, as well as its derived physical properties has strong multivariate correlations. The task of materials design is to make these correlations clear and to determine a strategy to modify the materials to obtain desired properties. However, such correlations are usually hidden and difficult to uncover or predict by experiments or experience.

For dealing with this issue, data mining methods which can extracting meaningful information and knowledge from large data sets, are attracted a great deal of interest. Motivated by using data mining to solve data-intensive problems in materials science, we develop a method to quantitatively model the multivariate correlations between physical properties of materials and their structures by using sparse modeling. The key idea of our method is to use advanced statistical mining algorithms, in particular multiple linear regression and non-linear regression regularized least-squares [1, 2] to solve the sparse approximation problem on the space of structural and physical properties of materials. We use cross-validation to consistently and quantitatively evaluate the conditional relations of physical properties to all the structural features of the materials in terms of prediction. We apply the method to a data set of more than four thousand transition rare-earth metal alloys. We demonstrate that the obtained sparse model is not only significant for the comprehension of the physics relating to the materials, but also valuable for the guidance of effective material design.

Reference

1) R. Tibshirani, J. R. Statist. Soc. B 58, 267 (1996). B. Efron, T. Hastie, I. Johnstone, and R. Tibshirani, Annals of Statistics 32, 409 (2004).
2) C. E. Rasmussen, C. K. I. Williams, Gaussian Processes for Machine Learning, MIT Press (2006).

Expectation for Materials Informatics in Magnetic Material Research

磁性材料研究におけるマテリアルズ・インフォマティクスへの期待

T. Shoji
Advanced Material Engineering Division, Toyota Motor Corporation, Susono 410-1193, Japan

概要
急激な計算機の計算速度の高速化と記憶媒体の高密度化に伴い、大量のデータの利活用が可能になり、様々な領域へ情報科学（Informatics）を活用した取り組みが波及している。物質・材料の研究開発においても、情報科学の利活用の潮流は確実に押し寄せており、2011 年に開始されたアメリカの Material Genome Initiative[1]を皮切りに世界レベルで物質・材料にかかわるデータを活用した新材料の探索、新たな法則の探求といった取り組みが本格化しつつある。単純に Big Data を活用するといってもデータそのものだけでは何も得ることはできず、そこに情報科学的なアプローチで解析するということが必須となる。得られた結果をデータとして蓄積し、解析を行うことで、データの持つ意味を最大化し、新たな情報への変換や新たな知見を抽出することが材料科学（Materials Science）へ情報科学（Informatics）を適用することへの期待である。
一方、自動車メーカーの先端材料技術に携わる観点から見たとき、現在の電磁気活用を想定した磁性材料を取り巻く状況は、アプリケーション面では拡がりを見せているといえる。例えば、駆動用モーターや電圧変換、直流交流変換など、従来の自動車には搭載されていなかった電磁気部品がハイブリッド車をはじめとする駆動系にモーターを搭載している次世代車では欠くことのできないものとなっている。駆動用モーターを搭載した車両の年間の販売台数も、ハイブリッド車への参入を果たす自動車メーカーが増えてきたことも相まって、加速度的に増加している。現在のところ、NdFeB 系の磁石が駆動用モーターに用いられる磁石としては主流であり、希土類の低減や重希土類フリー化などの課題は依然として解決していない。また、従来車両にも用いられている部品においても、小型補機モーターやスピーカーなど目立たないところにも多量の磁性材料が用いられており、性能とコストをバランスさせた磁石の開発についても、軽量化を目的としてニーズが高い。

講演では、自動車メーカーの材料技術の技術者から見た自動車用途を想定した磁性材料の研究への期待と、研究の深化・加速・拡大に対して情報科学（インフォマティクス）が果たしうる役割についての所感と期待について述べる。

Reference
1) https://www.mgi.gov/

Opportunities and Challenges for Inorganic Material Informatics from a View Point of Big Data Analytics

Yuzuru Tanaka
tanaka@meme.hokudai.ac.jp
(Graduate School of Information Science and Technology, Hokkaido University)

1. Opportunities for Data-driven Sciences

While "big data" in general is characterized by 3V, i.e., the volume, the velocity and the variety of the target data set and/or data stream, by 4V, adding the veracity of data, or by 5V, adding the value of the analysis result, "big data" in applications, especially in cutting-edge science, symbolizes the paradigm shift from mission-driven research to data-driven research, where the volume may not be the major property of the target data set in the current situation. Recent development of big data core technologies including analysis algorithms and high performance data management and analysis platform technologies, together with the development of automatic measurement instruments and/or large-scale high-performance computer simulation technologies, are currently strongly promoting this paradigm shift to data-driven research in varieties of domain sciences, which is gradually allowing us to conduct scientific research studies completely in cyber worlds after having obtained all the required data sets, or through the real-time receiving of data streams. This trend will further allow us to easily share and exchange not only data sets but also analysis and visualization tools and services, analysis scenarios, and meta knowledge about them, and will definitely lead us to what we call open science.

2. Challenges for Data-driven Sciences

Bioinformatics has made the first big success among data-driven sciences to encourage other sciences to follow. Personalized medicine and material informatics are example followers. However, their researchers are gradually recognizing the difficulties to fill in the gap between varieties of available data analysis methods and the goals to find out new meaningful personalized treatments or new functional materials. This gap has two major causes.

In these data-driven sciences, most of the target systems are complex systems of systems in which more than one subsystem with different mechanisms interact with each other, and each of them is also a heterogeneous system, i.e., a mixture of more than one subsystem following either different mathematical models or the same model with different parameter values. In the machine learning of such a system, the learning data set inherently consists of more than one subset that follow different mathematical models or the same model with different parameter values. It is necessary to appropriately segment the learning data set into homogeneous subsets before applying the machine learning separately to each subset. Such segmentation is generally not an easy task. Furthermore, the size of each homogeneous data subset may often become too small for statistically meaningful analysis. Personalized medicine aims to find out a personalized treatment that works best for a specific patient, but not necessarily well for the others. The learning data set of patients is inherently a mixture of different types of patients with different chemo-responses. Each existing large-scale database of inorganic natural materials is also a mixture of different types of materials consisting of different atoms arranged in different structures. The total number of the learning data for a certain type of inorganic natural materials for which we can assume the same physical model for simulation and/or the same regression model for analysis may be in the order of 10^3, or 10^4 at most, which is definitely small for machine learning, and definitely not sufficient for the deep learning.

Besides the first cause of the gap, i.e., the heterogeneity of the learning data set and the comparatively small size of each homogeneous data subset, it is often difficult to define sufficient number of appropriate explanatory variables in providing the learning data set through measurement and/or simulation. In bioinformatics, "genome" constitutes substantial portion of explanatory variables. In material informatics, we also need its counterpart, i.e., "materials genome". For proteins and peptides, a web server called PROFEAT computes structural and physicochemical features from amino acid sequence to systematically define a sufficient number of explanatory variables. It is a challenge, especially in inorganic material informatics, to systematically define a sufficient number of appropriate explanatory variables, i.e., inorganic materials genome.

3. Proposed Action Plan for Inorganic Material Informatics from a Computer Scientist's View Point

In order to increase the size of each homogeneous subset of the learning data set, we may focus more attention on artificial inorganic materials than on natural ones. Examples may include those with amorphous structures and those with higher-order crystal structures of atom clusters. Such higher-order nanostructures and/or mesoscopic structures may increase not only the design parameters but also the value space spanned by these design parameter variables. An amorphous material, for example, may introduce two more design parameters, i.e., the average and the variance of its crystalline diameters. A super crystal of atom clusters may introduce the design parameters of both each atom cluster and the super crystal structure. These design parameters may work as explanatory variables of the learning data set, which may be provided by the simulation based on the first-principle-calculation modeling of the artificial materials and by databases of related physical properties of the involving atoms and crystal structures. We can compute only a sufficiently large finite number of simulations to calculate some functional properties of our concern. These functional properties of the materials may include conductivity, magnetic property, optical property, interfacial activity, catalytic activity, and bulk modulus. The machine learning for the regression using the simulation result as the learning data set will estimate the values of such physicochemical properties for arbitrary value combinations of explanatory variables for which the simulation is still missing.

It is not always possible to mathematically model the total system with all the physicochemical and structural parameters taken into account as explanatory variables for estimating some functional properties of our concern. The original idea of machine learning was to give a solution to this problem. Instead of assuming the knowledge about the underlying mechanism of the total system, it uses the observation records of the relation between a sufficiently large set of aspects and each functional property of the system as its learning data set to estimate this functional property value for an arbitrary new value combination of aspects. The success of machine learning heavily depends on the quality and the quantity of such aspects of the target system. Each aspect defines explanatory variables as parameters of its mathematical modeling. In the simplest case, an aspect defines a single explanatory variable.

Aspect modeling is different from the total-system modeling. It may use a simple model that may explain the specified aspect of the system. In naive application of machine learning to materials data, some material properties become difficult to estimate accurately. Material properties such as lattice constant and magnetic moment can be accurately estimated from simple descriptors, i.e., explanatory variable, using basic machine learning methods [1]. However, in the experiments, machine learning did not work well to estimate the material bulk modulus (the resistance to compression of the material). After adding new explanatory variables such as bond type, energy difference in compression and expansion, and density for the aspect modeling of the material bulk modulus, and calculating, for each record in the learning data set, the values of these added explanatory variables through the simulation of this aspect modelling, the bulk modulus could be well estimated.

Some aspect of our concern may be defined as a function of already defined explanatory variables. Depending on the types of machine learning, such an aspect may require the explicit introduction of a new explanatory variable as a derived variable, i.e., a function of other variables. In linear-regression machine learning, derived variables defined as linear combinations of other explanatory variables need not be explicitly introduced as new explanatory variables. They are implicitly considered by the algorithm if necessary. However, such a derived variable as x/y should be explicitly introduced as a new explanatory variable. Some indices obtained as analysis results such as cluster ids or pattern ids may sometime work as new explanatory variables for further segmentation and analysis. We call such explanatory variables marker variables or, simply, markers.

It should be noticed that the design of appropriate explanatory variables and the process of segmentation and analysis are both by their nature exploratory processes. This implies the importance of the development of an integrated exploratory visual analytics platform for data-driven sciences. A further shift toward open science requires not only the sharing of platform systems, but also a shared repository of data sets, analysis and visualization tools and services, analysis scenarios, and meta knowledge about them in reusable forms. Meme media and meme pool architectures [2] as well as their web-based implementation Webble World will answer these requirements.

Reference

1) K. Takahashi and Y. Tanaka, "Material synthesis and design from first principle calculations and machine learning," Computational Materials Science, vol. 112, pp. 364–367, 2016.

2) Y. Tanaka, Meme Media and Meme Market Architecture. Piscataway; NJ; USA: IEEE Press, 2003.

Comments on Materials Informatics from a Researcher in Industry

Takeshi Nishiuchi
Magnetic Materials Research Laboratory, Hitachi Metals, Ltd., Osaka 618-0013, Japan

Over 30 years passed since invention of an Nd-Fe-B magnet, there are strong demands of “new materials” exhibiting characteristics more excellent than this magnet. To realize this matter, for example, there are many efforts to find out a new compound with better magnetic properties than $Nd_2Fe_{14}B$.

“Materials Informatics” is an approach which combines material sciences and data sciences, and has great possibility to change a way of development of new materials in industry in the future. Several national projects are promoted in Japan, and magnetic materials, especially permanent magnets, are one of the important targets of them.

In this talk, I will give personal comments on application of “Materials Informatics” for research and development of permanent magnets based on my own experiences in industry.

Perspective／展望

Satoshi ITOH／伊藤　聡
(Japan Science and Technology Promotion/JST)

A new national project concerning the materials informatics (MI) research has been started from July 1st 2015 in the NIMS; which called MI^{2}I (Materials research by Information Integration Initiative).　In this project, a new data will be added to the materials database operated by NIMS, the tools required in the MI research will be developed, and a data-platform for materials research will be constructed.　By using this platform, the effectiveness of the MI approach will be demonstrated in the development of magnetic materials including spintronics materials.　Considering that many practical magnetic materials are multi-component compounds, we have to develop a more advanced searching system.　A recent development in AI technology will play an important role in that way.

The MI approach will significantly reduce the time to discover, develop and manufacture new magnetic materials; in which a key issue is open and easy accessible database of the materials.　The materials database contains crystal structure, composition rate, etc., but it is not enough.　That is, in addition to materials data of the ideal state such as a perfect crystal, information of manufacturing processes in the actual material should be gathered in the materials database.　However, production or manufacturing process usually is concealed as know-how.　In order to promote the MI study, a policy regarding the handling of materials data including the know-how has become extremely important.

Surface Plasmon Polaritons for Magnetic Applications

K. Nakagawa, and Y. Ashizawa
College of Sci. & Tech., Nihon University, Chiba, 274-8501, Japan

Surface Plasmon Polaritons (SPPs) are very useful for magnetic applications, especially for Heat Assisted Magnetic Recording (HAMR), magneto-optical sensing, and triggering magnons, because SPPs can be confined into a small spot beyond its optical interference limit. HAMR head is a good example for the application of SPPs[1]. Optical light is efficiently transferred into a SPP waveguide, and is effectively propagated to a Near-Field Transducer (NFT) at the end of the waveguide in HAMR head. A calculated result at a recording layer and a NFT tip at the end of SPP waveguide as an example is shown in Fig. 1. Magnetic sensing technique applying SPPs is also beneficial to sensitively detect magnetic condition[2]. Kretschman-Raether configuration at a critical incident angle as shown in Fig. 2 is very sensitive to reflective index. It can detect magnetization direction by its reflectivity of an incident light. For example, the reflectivity changes about 4 point at the incident angle $\theta \sim 41$ degree as shown in Fig. 3. It could detect magnons distribution if we would apply NFT as a detecting sensor. As T. Satoh reported[3], an optical light can trigger magnons, so SPPs must set off magnons if we control SPPs. We also found that the wavelength of SPPs can be controlled by a SPP waveguide structure as shown in Fig. 4[4].

References

1) K. Tamura, Y. Ashizawa, S. Ohnuki, and K. Nakagawa, *J. Magn. Soc. Jpn.*, **38**, 131-134 (2014).
2) Y. Ashizawa, S. Shinohara, T. Nawata, and K. Nakagawa, Abstr. MORIS, 2011, p. 103.
3) T. Satoh, Y. Terui, R. Moriya, B. A. Ivanov, K. Ando, E. Saitoh, T. Shimura, and K.Kuroda, *Nature Photon.*, **6**, 662-666 (2012).
4) T. Matsumoto, Y. Ashizawa, and K. Nakagawa, *Tech. Meeting Magnetics, IEE Japan*, MAG-16-018, 23-28 (2015).

Acknowledgements Computational simulation for HAMR head and multi-layer SPPs has been calculated by the university students: K. Tamura, Y. Hayashi, and T. Matsumoto. This work is partially supported by a Grant of MEXT-Supported Program for the Strategic Research Foundation at Private Universities, 2013-2017.

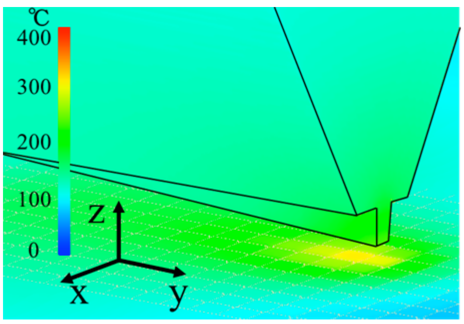

Fig. 1 One of the calculated results of temperature for HAMR.

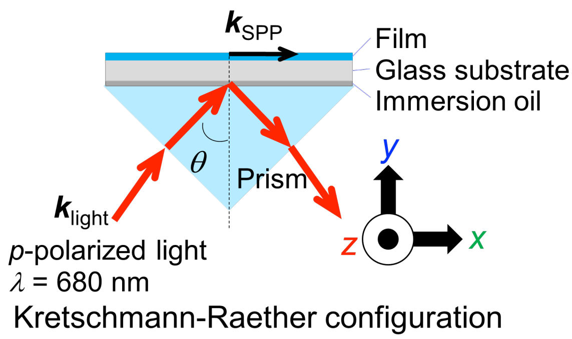

Fig. 2 Kretschmann-Raether configuration.

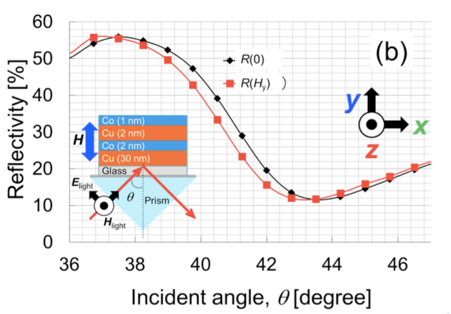

Fig. 3 Reflectivity change depending on magnetic field.

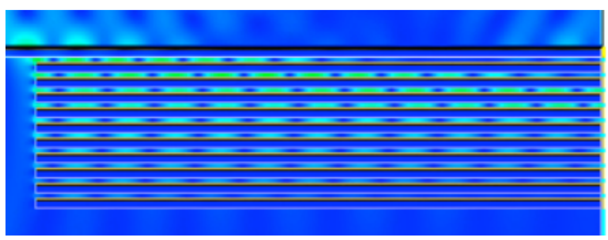
Fig. 4 SPPs in metallic multilayers.

Recent progress in fundamental studies on spin-photonics with magnets, semiconductors and insulators

H. Munekata, N. Nishizawa, and K. Nishibayashi
(Institute of Innovative Research, Tokyo Institute of Technology)

Digital information technology has great impact on our lives, which has strongly motivated scientists to look for faster and more energy-efficient ways to process streams of digital signals. This presentation reviews some works carried out recently in our group; namely, (i) devices for circular polarized light (CPL) technology and (ii) all-optical new functional devices.

Spin-LED as a monolithic CPL emitter (Fig. 1)

Compared with optics and photonics based on linearly polarized light, not so much research has been carried out for the development of technology based on CPL. We report bright electroluminescence of nearly pure circular polarization at room temperature with relatively high current density using lateral-type spin LEDs consisting of Fe stripe electrodes, 1-nm crystalline AlO_x tunnel barriers, and laser-quality AlGaAs/GaAs double hetero-structures (DH) [1,2]. Electrical helicity switching up to 100 kHz has been demonstrated using dual spin injection electrodes formed on the DH [3,4].

From photo-excited precession of magnetization to all-optical new functional devices (Fig. 2)

We found through the study of photo-excited precession of magnetization using ultrashort (10^{-13} sec) weak laser pulses of 1 μJ/cm^2 or less, that spins in ultra-thin Co/Pd multi-layer films are very susceptible to light; namely, a material that could be a candidate for photo-sensitive magnets [5]. This finding has been followed by the demonstration of polarization modulation of light signals in an optical waveguide with the same class of magnets, GdFe thin films [6]. In this work, we have emphasized the feasibility of the multiplexed transmission of polarization-modulated signals, controlled ultimately by photo-excitation of a class of light-sensitive magnetic layers.

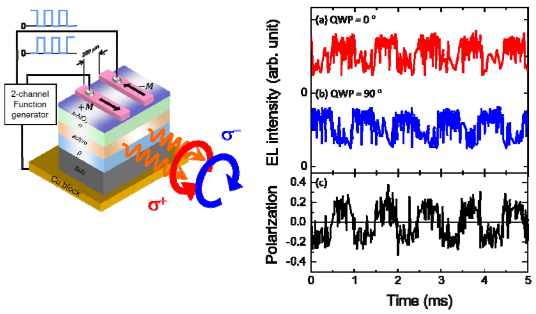

Fig. 1: (left) schematic device structure of dual-injection spin-LED, and (right) the data representing 1 kHz helicity switching at RT.

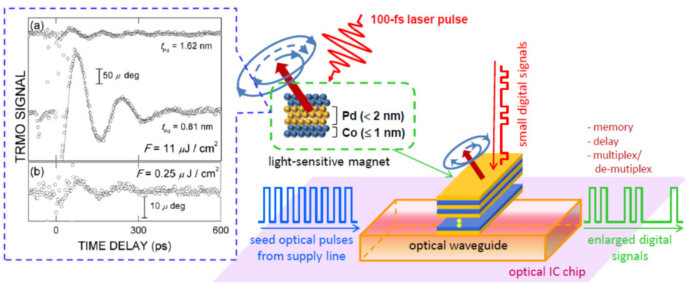

Fig. 2: Experimental data of photo-excited precession of magnetization (left), schematic illustration of Co/Pd ultra-thin multi-layers (upper center), and the concept of three-terminal photonic device utilizing photo-magnetic property (lower right).

Reference

1) N. Nishizawa and H. Munekata, JAP **114**, 033507 (2013).
2) N. Nishizawa, *et al.*, presneted at SSDM 2015 (Sept. 28, 2015, Sapporo) A-2-5 (Late News).
3) N. Nishizawa, *et al.*, APL **104**, 111102 (2014).
4) M. Aoyama, *et al.*, presented at JSAP Spring Meeting (March 19, 2016, Tokyo) 19p-P1-55 (Poster).
5) K. Yamamoto, *et al.*, IEEE Trans. Mag. **49**, 3155 (2013).
6) K. Nishibayashi, *et al.*, APL **106,** 151110 (2015).

Challenge to magnetization dynamics observation by Kerr microscope with real-time processing of differential-polarization images

Sakae Meguro [1, 2], Shin Saito [2]
[1] Neoark Corporation, 2062-21 Nakano-machi Hachioji, Tokyo, 192-0015 Japan
[2] Department of Electronic Engineering, Graduate School of Engineering, Tohoku University, 6-6-05, Aoba, Aramaki, Aoba-ku, Sendai, 980-8579 Japan

1. Introduction

In recent years, the functional spin-related devices that apply spin wave and the spin current have been developed. In most cases, these devices has been operated by detecting an electrical signal. However, the electrical signal might reflect not only the magnetic but also other properties, that it is important to verify other detection methods. The detection method by using magneto-optical effect is a useful detection method which has the advantages of non-contact and non-invasive. Additionally, Kerr effect microscope based on the photographic method is useful because it can visualize the two-dimensional spin propagation in a short time. We have been developed the Kerr effect microscope by photographic method[1-4]. In general, conventional Kerr effect microscope which applies extinction method uses a saturation-image subtraction method[5] in order to emphasize the magnetic domain image. However, this method has the following problems; a sample with high saturation magnetic field cannot be observed; image deterioration caused by the position deviation of the sample which is affected by magnetic field and thermal expansion and efficiency of light is as low as a few percent. Accordingly, we report the development of Kerr effect microscope for observation of magnetization dynamics by differential-polarization imaging method, which can observe magnetization images in real time.

2. Principle of the differential-polarization imaging method

The schematic diagram of the differential polarization imaging method is shown in the Fig. 1. Light from the lamp illuminates the sample through a relay lens and an objective lens. The reflected light from the sample is imaged by the objective lens and the imaging lens. Images of two orthogonal polarizations are imaged separately by inserting the Glan-Thompson polarizing beam splitter between the imaging lens and the CCD camera. The analog video signals of the CCD camera 1 (CCD1) and the CCD camera 2 (CCD2) are amplified by the differential amplifier. Common background noises which are included in the both CCD camera images like the reflectivity change and so on are canceled by the differential amplifier. Kerr signal is increased by a differential amplifier because each signal is in the reverse phase. For this reason the output signal from the differential amplifier emphasizes the Kerr signal. These signals are captured into PC through the frame grabber with 8 bit brightness resolution. This method has the following advantages; magnetization image can be observed in real time, without application of saturation magnetic field; with no image deterioration according to positional deviation of the sample; the light utilization efficiency is high because of using all of the illumination light forms an image on the two CCD cameras.

3. Experiment

The optical system was arranged to measure the polar Kerr effect. The ample was a GdFeCo thin film with perpendicular magnetization. It was needed to perfectly match the images from each CCD camera to get a correct result. To accomplish this, the position, angle and focus of CCD1 were adjusted by using the pulse motor stage of the XYZθ axis. Electronic shutters of the CCD1 and CCD2 were set to 1/2000 seconds. An observation result of the maze magnetic domain of the GdFeCo thin film which is patterned to 40 × 100 μm is shown in Fig. 2. The images of CCD1 and CCD2 are shown in Fig. 2(a) and Fig. 2(b), respectively. The image of the difference between CCD1 and CCD2 is shown in Fig. 2(c). And the image which is obtained by the conventional extinction method is shown in Fig. 2(d). Domain structure is not observed in the image of Fig. 2(a) and (b) because the brightness change of the magnetic domain is less than the brightness resolution of the frame grabber. Maze magnetic domain structure has been observed in Fig. 2(c). In the differential polarization method, the obtained images contain hardware specific noise such as caused by a CCD camera and signal processing circuitry. To cancel the background noise which is caused by the hardware, the image which is recorded in the metal mirror is subtracted from the measured image. The image observed by the conventional extinction method is shown in Fig. 2(d) as comparison to the measurement result. Both Magnetic domain structure images of (c) and (d) are consistent. In conclusion, the present study has demonstrated that the magnetic domain image can be observed by the differential-polarization imaging method. Image of Fig.2 (d) has been acquired by setting the electronic shutter of the CCD camera to 1/30 seconds. The magnetic domain image was captured by the differential-polarization imaging method with light exposure of 1/67 less than the conventional extinction method. From these results, the Kerr microscope by differential-polarization imaging method is suitable for observation of magnetization dynamics using stroboscopic method. In the conference, the observation on longitudinal Kerr arrangement will be reported.

Acknowledgment
This work was supported by JSPS KAKENHI Grant Number 15H02255.

Reference

1) S. Meguro et al., Proc. Ann. Conf. Magn. Soc. Jpn. 2004, 24aF−9.
2) S. Saito et al., Bulletin of the 155th Topical Symp. of the Magn. Soc. Jpn., 2007 , p. 1.
3) S. Meguro et al., Proc. Ann. Conf. Magn. Soc. Jpn. 2008, 14p1PS－90(E).
4) S. Meguro et al., Bulletin of the 204th Topical Symp. of the Magn. Soc. Jpn. , 2015, p. 9.
5) A. Hubert and R. Schafer, Magnetic Domains: The Analysis of Magnetic Microstructures, (Springer, Berlin, 1998) Chap. 2.3.

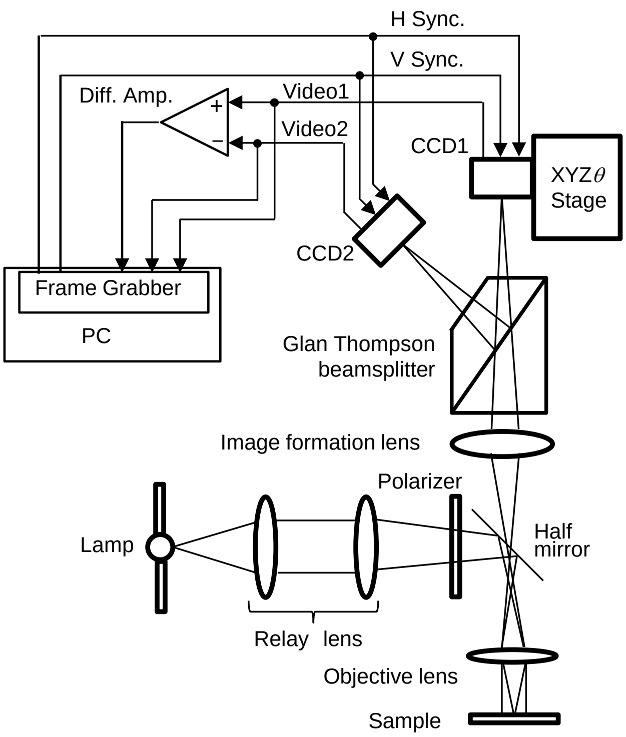

Fig. 1 Schematic diagrams of the differential-polarization imaging method.

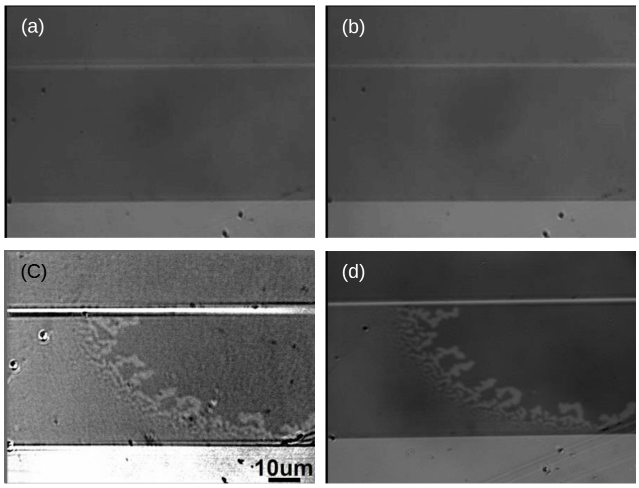

Fig. 2 Observation images and domain images for the GdFeCo thin film pattern (40 ×100 μm). Observation images of (a) CCD1 and (b) CCD2. Domain images of (c) differential-polarization imaging method and (d) conventional extinction method.

Artificial Magnetic Lattices and Their Optical and High Frequency Applications

○M. Inoue[1], Y. Nakamura[1], H. Takagi[1], T. Goto[1,2], P. B. Lim[1] and H. Uchida[1]
[1]Toyohashi University of Technology, Toyohashi 441-8580, Japan
[2]JST, PRESTO, Kawaguchi 332-0012, Japan

Artificial magnetic lattices (AMLs) introducing the artificial structure of the scale from a few 10 nm to several 100 nm show a novel magnetic functions attributed to their structures, so the studies utilizing these AMLs become an important engineering field. A magneto photonic microcavity (MPM) is a typical AML, in which transparent ferromagnetic garnet is sandwiched with two Bragg mirrors, and shows giant magneto-optical (MO) effect[1)]. This presents a feasibility of new optical media controlling its optical properties by spin. On the other hand, the magnoic crystals, in which the light of MPC is replaced with the spin waves in ferromagnetic material, can control the precession of spin of the magnetic material and show the magnonic band gap[2)]. In this symposium, these optical and high frequency applications using the artificial magnetic lattices are presented.

Holography is a key technology for three-dimensional (3D) displays, shape measurements, and high-capacity data storage. A holographic display is a realistic 3D display because it produces an exact copy of the wave front of scattered light from 3D objects[3)]. Recently, we developed a 3D magneto-optic spatial light modulator (3D-MOSLM) that had a two-dimensional magnetic pixel array with sub-micrometer-scale pixels for a wide viewing holographic display. A thermomagnetic recording with an optical addressing method is used to form sub-micrometer-scale magnetic pixel arrays without a driving line, and 3D image is reconstructed using the MO effect. The first 3D-MOSLM used an amorphous TbFe (*a*-TbFe) film as magnetic film[4)], but the brightness of reconstructed images was very low. To achieve bright 3D images, the magnetic film should have high transmittance and a large Faraday rotation angle, so we developed a 3D-MOSLM with MPM structure using the Bi substituted rare earth iron garnet (Bi:RIG) as a recording magnetic layer. As a result, as shown in Fig. 1 (b)-(d), we could achieve the reconstruction 3D image as bright as 100 cd/m^2 by using the designed 3D-MOSLM having a MPM structure with high diffraction efficiency[5)]. Another application of holography is the hologram memory that is a promising candidate for next data-storage technology with high recording densities of greater than 1 TB/disk. We have employed a collinear holographic system that can write and read data using a single optical axis with a spatial light modulator[6)]. Similar to 3D-MOSLM, we have also selected the Bi:RIG film as a recording medium, and succeeded to record and reconstruct data on the Bi:RIG film using the collinear holographic system as shown in Fig. 2(a)[7)]. However, the reconstructed image was dark and unclear due to the low diffraction efficiency of the garnet medium. To improve the diffraction efficiency, we again designed MPM structures for the recording media. Figure 2(b) and (c) show the reconstructed images from the usual single layer garnet film and the MPM medium[8)]. The image reconstructed from the MPM medium had approximately twice the brightness of that reconstructed from the single layer film. These mean that the MPM structure is very attractive recording media.

In addition to these optical applications, we also apply the AML structure to control the magnetostatic waves (spin waves), which is supported by the magnetostatic coupling of spins in a few GHz frequency region. An analogy of photonic crystal, when the propagation medium such as YIG have some periodicity, a magnonic band gap (MBG) can be observed for the spin waves. This MBG can be designed within a excitation frequency band by selecting the appropriate periodicity of the metal strips. We demonstrated experimentally the existence of the MBG using the sample with the one-dimensional periodic structure of Cu strip as shown in Fig. 3. As shown in Fig. 3(b), a clear and deep band gap was observed at approximately 3.00 GHz, and the frequency of the band gap is very sensitive to the magnetic field applied to the crystal[2)]. This high-Q MBG would be used for magnetic sensor. Similar to MPM, the localized mode of spin wave was also observed as shown in Fig. 3(d) by introducing a defect layer in periodic structure[9)]. These results indicate that we can manage the spin wave propagation in the same manner as the light in photonic crystals using AML structure although we have to consider the effect of shape magnetic anisotropy of the spin-wave waveguide.

This work was supported in part by the Grants-in-Aid for Scientific Research (S) 26220902, (A) 15H02240, and Grant-in-Aid for Young Scientists (A) No. 26706009.

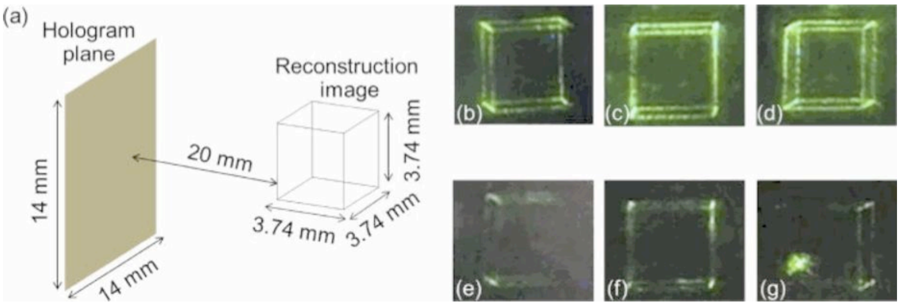

Fig. 1 (a) A model of 3D image for generating the hologram. The wireframe cube was constructed by point light sources. (b)–(d) Reconstructed images from MPC and (e)–(g) those from *a*-TbFe for comparison. The images of (b) and (e) were from left view point of 11°, (c) and (f) were from center, and (d) and (g) were from right view point of 11°.

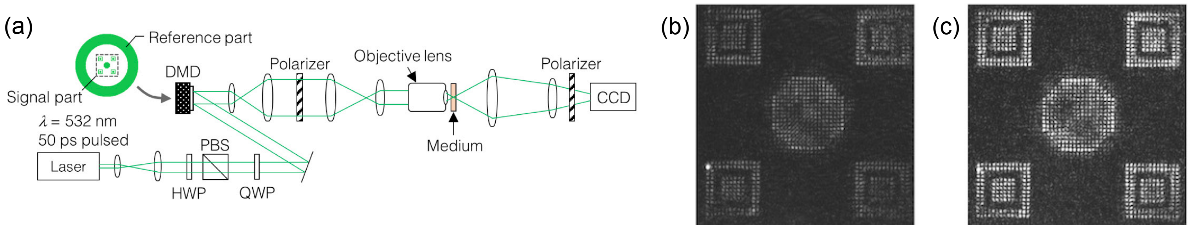

Fig. 2. Experimental setup and reconstructed two-dimensional data patterns. (a) Schematic illustration of the experimental setup for writing and reconstructing magnetic holograms. Reconstructed signal patterns from (b) the single layer Bi:RIG film and (c) the two-pair MPC medium. The MPC medium provided a clear and bright image because the diffraction efficiency of MPC medium was as double as that of the single layer film.

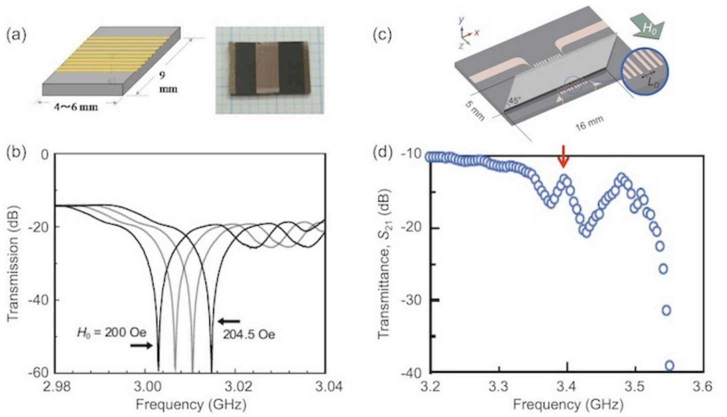

Fig. 3. (a) Schematic illustration and photogragh of the 1D magnonic crystal composed of a YIG single crystal film and a periodical metal strips. (b) Frequency shift in the magnonic band gap corresponding to the change in the bias field from 200 Oe to 204.5 Oe with an interval of 1.5 Oe. (c) Schematic illustration of a magnonic crystal in the shape of a microcavity. (d) Transmission spectrum showing a localized state of spin wave at 3.395 GHz under the applied magnetic field of 400 Oe.

Reference

1) K. Takahashi, M. Inoue, J. Appl. Phys. 101 (2007) 09C523.
2) M. Inoue, A. Baryshev, H. Takagi et al., Appl. Phys. Lett. 98 (2011) 132511.
3) V. M. Bove, Proceedings of the IEEE **100** (2012) 918.
4) H. Takagi, K. Nakamura, T. Goto, P. B. Lim, and M. Inoue, Opt. Lett. 39 (2014) 3344.
5) K. Nakamura, H. Takagi, M. Inoue et al. Appl. Phys. Lett. 108 (2016) 022404.
6) H. Horimai and X. Tan, Opt. Rev. 12 (2005) 90.
7) Y. Nakamura, H. Takagi, P. B. Lim, and M. Inoue, Opt. Exp. 22 (2014) 16439.
8) R. Isogai, Y. Nakamura, M. Inoue et al., Opt. Exp. 23 (2015) 13153.
9) N. Kanazawa, T. Goto, M. Inoue et al., J. Appl. Phys. 116 (2014) 083903.

Ultrafast photo manipulation of magnetization and non-local spin dynamics

Arata Tsukamoto
(College of Science and Technology, Nihon University, Funabashi, Chiba, JAPAN)

For further progress in applications on magnetic magnonic and spintronic technology, ultrafast control of magnetization (ordered spin system) is an issue of crucial importance. Controlling magnetism by light is one of the promising approaches as appealing scenario. For photo manipulation of magnetization, femtosecond laser pulses that are among the shortest stimuli in contemporary technologies could serve as an alternative stimulus to manipulate spin order and trigger magnetization reversal.

An ultrashort laser pulse allows excitation of magnetic systems at time scales much shorter than fundamental quantities such as spin precession or spin-lattice relaxation times. Deterministic magnetization reversal was demonstrated[1)2)] in ferrimagnetic GdFeCo driven by single shot irradiation of laser pulse without the presence of a magnetic field. This All Optical Switching (AOS) phenomena originated from transient non-equilibrium state and sub-lattice nature is fundamentally different from conventional magnetic field driven switching mechanism. Furthermore, from the compositional dependency of all-optical light helicity-dependent magnetic switching (AO-HDS) in ferrimagnetic GdFeCo alloy, it is found that AO-HDS is associated with the collinear sub-lattice magnetization and an explanation of the AO-HDS based on magnetic circular dichroism exactly matches the above features of experiments[3)].

Recently, it is revealed that further extraordinary spin dynamics in ultrashort time scale such as bellow ps region by ultrafast diffraction experiments with an X-ray probing[4)]. In particular, we observed Gd spin reversal in Gd-rich nano-regions within the first picosecond driven by the non-local transfer of angular momentum. These results suggest that a magnetic microstructure can be engineered to control transient laser-excited spins, potentially allowing faster spin reversal. Furthermore, AOS depends on the non-adiabatic energy dissipation of electron system in the GdFeCo layer from the incident surface in the depth direction during a few picoseconds[5)]. It will be also shown that employing plasmonic gold nano-antennas placed above TbFeCo magnetic layer it should be possible to confine photo-magnetic excitation in a spot well below diffraction limit as the order of 50 nm[6)]. Ultrashort non-local phenomena in magnetic material will be discussed.

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Reference

1) T. A. Ostler, et. al., Nature Comm., 3, 666 (2012).
2) C. D. Stanciu, F. Hansteen, A. V. Kimel, A. Kirilyuk, A. Tsukamoto, A. Itoh, and Th. Rasing, Phys. Rev. Lett., 99, 047601 (2007).
3) A Tsukamoto and Th. Rasing, In chapter 13 of “Spintronics for Next Generation Innovative Devices”, Wiley series in materials for electronic and optoelectronic applications, (2015).
4) C. E. Graves et. al., Nature Materials 12, 293 (2013).
5) H. Yoshikawa,S. E. Moussaou, S. Terashita, R. Ueda, A. Tsukamoto, Jpn. J. Appl. Phys, (2016) (Accepted).
6) T. Liu et. al., Nano Letters, 15 (10), 6862 (2015).

All-optical investigation of coherent magnon propagation in metallic films

Shigemi Mizukami
WPI-Advanced Institute for Materials Research, Tohoku University

Dipolar spin-wave frequency is typically in GHz microwave range and its lifetime is quite long in some materials, such as yttrium iron garnet (YIG), thus spin-wave have been widely studied to apply passive and active microwave devices in early days. Most of them could not be commercialized since those were not beyond semiconductor devices. Nowadays, spin-wave or its quantum, *magnon*, is studied with renewed interest as a basis for Magnonics, spin-based information processing technology without electric charge to reduce power consumption.[1)] The Magnonics research is still fundamental, where various basic building blocks have been discussed from the various aspects.[2)] The light-induced coherent magnon may be one of such building blocks, which has been studied during the past few years,[2,3)] because it is applicable to a light coupling for magnon circuit interconnection.[2)] It is also interesting to seek light-induced coherent magnon in metallic films, because magnon dispersion in metallic film hetero-structure can be tuned by the interfacial anti-symmetric exchange interaction and also the externally applied electric field.[4)] However, there have been few reports on the light-induced coherent magnon in metallic films.[5,6)]

Here we present our recent results on the propagating magnon excited in films of magnetic metals by the micro-focused fs pulse laser with the spot diameter of μm scale. The magnon-propagation induced by the laser pulse was detected via the magneto-optical Kerr effect for another weak laser pulse with varying position and delay-time using all-optical scanning pump-probe technique (Fig. 1). The pulse laser-induced coherent magnons propagation was clearly observed and its propagation were highly anisotropic with respect to the direction of magnetization (Fig. 2), being consistent with the anisotropic dispersion of magneto-static surface or backward volume wave. Excitation mechanism of magnon is discussed in terms of ultrafast change of magnetization induced by the pulse laser.[7)] This work was partially supported by KAKENHI No. 16H03846, Nano-spin conversion science No. 26103004, and the center of Spintronics Research Network.

Reference

1) A. A. Serga et al., J. Phys. D. Appl. Phys. **43**, 264002 (2010).
2) B. Lenk et al., Phys. Rep. **507**, 107 (2011).
3) T. Satoh et al., Nat. Photo. **6,** 662 (2012).
4) K. Nawaoka et al., Appl. Phys. Express **8,** 063004 (2015).
5) Y. Au et al., Phys. Rev. Lett. **110,** 097207 (2013).
6) S.-J. Yun et al., Appl. Physics. Express. **8,** 063009 (2015).
7) S. Iihama et al., arXiv: 1601.07247 (2016).

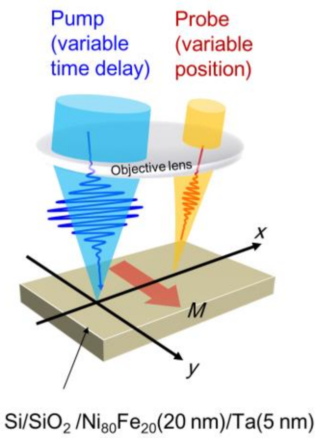

Fig. 1 Schematic illustration of the all-optical spatio-temporal pump-probe measurements for magnetic film under microscope.

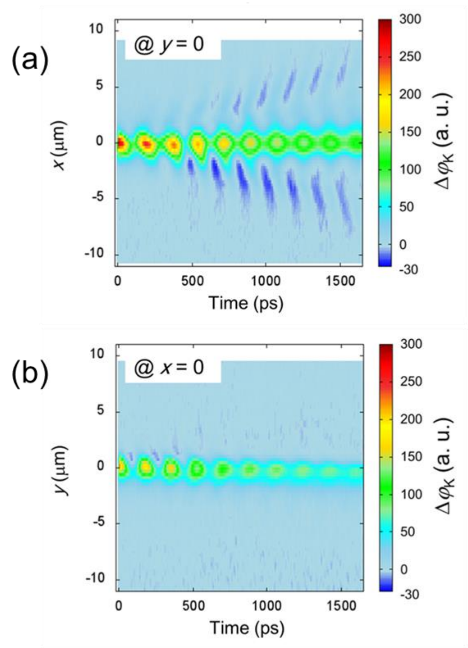

Fig. 2 Spatio-temporal mapping of the experimental data of the pump-pulse-induced change of Kerr rotation angle. The scanning direction of probe beam is (a) *x*- and (b) *y*-axis.

Accumulative magnetic switching of FePt granular media by circularly polarized light

Y.K. Takahashi[1], R. Medapali[2], J. Wang[1], S. Kasai[1], K. Ishioka[1], S.W. Wee[3], O. Hellwig[3], K. Hono[1] and E.E. Fullerton[2]
(NIMS[1], UCSD[2], HGST[3])

Deterministic control of magnetization by light, often referred to as all-optical switching (AOS), is an attractive recording method because magnetization control becomes possible without the need of an external magnetic field[1-5]. The first demonstration of AOS was in ferrimangnetic GdFeCo film where the Gd and FeCo spin sub-lattices are antiferromagnetically exchange coupled. Since the mechanism determined for GdFeCo films required antiparallel exchange of two sublattice systems, it was believed that AOS occurs only in ferrimagnetic materials including synthetic structures[1-4]. However, recently Lambert *et al*. reported that the optical control of the magnetization occurs in ferromagnets including Co-based multilayer thin films and FePtAg-C granular thin film materials[5]. Therefore the potential mechanisms for AOS in ferromagnetic materials must be reexamined. Here, we report the observation of accumulative magnetic switching from multiple circularly polarized light pulses on FePt-C HAMR media.

The FePt-30vol%C (hereafter, FePt-C) granular film was deposited by co-sputtering of FePt and C targets on a MgO(001) single crystal substrate by DC magnetron sputtering at 600°C. 10-nm-thick C was deposited as a capping layer at RT. 15-μm-width Hall crosses were used for the measurement of the magnetization change by the light exposure and the applied magnetic fields.

Figure 1(a) shows the magneto-optical image of an initially demagnetized FePt-C granular film after scanning it with both right and left circularly polarized (RCP and LCP) light pulses. The optical pulses induce a net magnetization in the FePt-C and the sign of the magnetization is determined by the helicity of the light. To quantify the optically-induced magnetization changes, we exposed the laser over the Hall cross region. The initial state is remanence after applying saturating magnetic fields of -7 T (Fig. 1c)) and 7 T (Fig. 1d)). Figure 1(c) shows the normalized Hall resistance change after the exposure to RCP, linearly polarized and LCP. For RCP light, the normalized magnetization gradually decreases to zero, then reverses and saturates at about -0.5. This indicates that ~3/4 of the FePt grains switch to the opposite direction. On the other hand, the exposure to LCP light decreases the magnetization to about half of the initial value, corresponding to the switching of ~1/4 of the FePt grains. For exposure to linearly polarized light, the normalized Hall resistance gradually approaches zero. In the case of the opposite initial state (negative saturation) shown in Fig. 1d), RCP, LCP and linearly polarized light exposures result in the same final normalized magnetization of -0.5, 0.5 and zero, respectively. Thus, the magnetization state after exposure to polarized light only depends on the helicity of the light. Fitting Fig. 1(c) and (d) to a simple accumulative model, the switching probability by a single pulse is very small, less than 1%. However, accumulating the small switching probabilities results in a continuous change in the magnetization until the final equilibrium state[6].

(1)C.D. Stanciu et al., PRL99, 047601 (2007). (2) A. Hassdenteufel et al., Adv. Mater25, 3122 (2013). (3) S. Alebrand et al.,APL101, 162408 (2012). (4) S. Mangin et al NMAT13, 287 (2014). (5) C-H. Lambert et al., Science345, 1337 (2014). (6) Y.K Takahashi et al., arXiv:1604.03488.

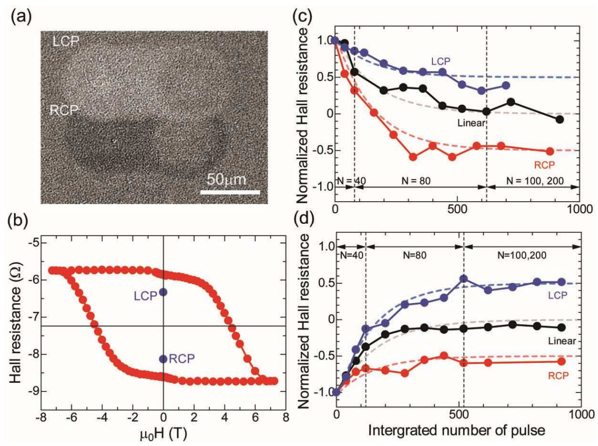

Fig. 1 Magnetization change observed from a FePt-C granular film by exposure to circular polarized light. (a) Magnetic image after exposure to RAP and LCP. (b) AHE curve for the FePt-C granular film. (c,d) Normalized Hall resistance after applying circular and linear polarized light.

Time-resolved imaging of spin wave transmission through an air gap

T. Satoh[1], I. Yoshimine[2] and T. Shimura[3]
[1]Department of Physics, Kyushu University, Fukuoka 819-0395, Japan
[2]AIST, Tsukuba 305-8565, Japan
[3]Institute of Industrial Science, The University of Tokyo, Tokyo 153-8505, Japan

Magnetization control using ultrashort optical pulses has been extensively studied in recent years. One of the nonthermal control of magnetization is based on the inverse Faraday effect, where circularly polarized pulses generate the effective magnetic field along the propagation vector in a transparent material, leading to spin wave generation[1,2]. Spin wave reflection at the sample edge or transmission through an air gap has been reported in finite-size samples[3,4]. In the present study, we report on time- and phase-resolved imaging of photo-induced spin wave's transmission through an air gap using pump-probe technique with a CCD camera.

In the experiment, a bismuth-doped rare earth iron garnet crystal with a thickness of 110 μm was used as a sample. Circularly polarized pump pulses with a time duration of 150 fs were employed to excite the sample via the inverse Faraday effect. Faraday rotation of time-delayed probe pulses was measured. Figure 1 shows the transmission of spin wave excited in the left hand sample through an air gap to the right hand sample, where the gap width was 40 μm and the time delay was 1000 ps. The center wavelength of the spin waves was observed to be 100-200 μm meaning that the spin waves were dipolar-dominated magneto-static waves. The relation between transmission, phase and the gap width was analyzed. The experimental results were compared with simulation results.

Reference

1) T. Satoh *et al.*, Nature Photon. **6** (2012) 662.
2) I. Yoshimine *et al.*, J. Appl. Phys. **116** (2014) 043907.
3) M. P. Kostylev *et al.*, Phys. Rev. B, **76** (2007) 184419.
4) T. Schneider *et al.*, EPL **90** (2010) 27003.

Acknowledgements

This work was partly supported by JST PRESTO, Grant-in-Aid for Young Scientists (A), and Grant-in-Aid for Scientific Research on Innovative Areas.

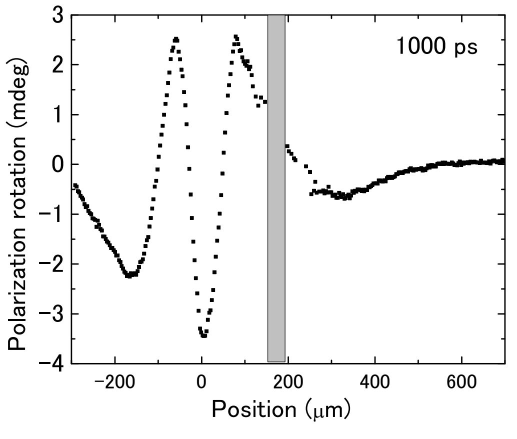

Figure 1　Spin wave transmission through an air gap with a width of 40 μm.

Time resolved magneto-optical Kerr effect and spin transfer torque switching of GdFeCo / TbFe exchange coupled bilayers

T. Kato[1], T. Higashide[1], B. Dai[2], D. Oshima[3], S. Iwata[3]
[1]Department of Electrical Engineering and Computer Science, Nagoya University, Nagoya 464-8603, Japan
[2]Center for Comosite Materials and Structures, Harbin Institute of Technology, Harbin 150080, P.R.China
[3]Institute of Materials and Systems for Sustainability, Nagoya University, Nagoya 464-8603, Japan

Spin transfer torque (STT) switching is considered as a promising technology to realize Gbit class magnetic random access memories (MRAMs). However, there still remains a challenge to develop high-density MRAMs with densities of several Gbit and beyond, since it has a conflicting requirement, i.e., a reduction of critical current density J_c to switch the memory cell while keeping a sufficient thermal stability of the cell. One of the solutions for this challenge is so-called thermally assisted MRAM in which the memory layer is heated during the writing[1)]. We have studied amorphous TbFe[2), 3)] and GdFeCo[4), 5)] as a memory layer of the thermally assisted MRAM cell. In this paper, we discuss the STT switching of GdFeCo single layers and GdFeCo / TbFe exchange coupled bilayers. Moreover, Gilbert damping constant α of GdFeCo / TbFe bilayers is discussed to compare the product of Gilbert damping and perpendicular anisotropy with the switching current density J_c.

GdFeCo (10 – x nm) / TbFe (x nm) exchange coupled bilayers were deposited on thermally oxidized Si substrates by RF magnetron sputtering, where the TbFe thickness x was varied from 0 to 5 nm. Time resolved magneto-opcical Kerr effect (TRMOKE) measurements were carried out to estimate Gilbert damping α and anisotropy field H_k of the bilayer. For STT switching, giant magneto-resistance (GMR) films with GdFeCo / TbFe memory layers were sputtered, and the GMR films were microfabricated into the size of 120 × 180 nm^2.

Figure 1 (a) shows TbFe thickness dependence of Gilbert damping constant α of the bilayer. The damping constant α of the GdFeCo / TbFe was relatively low 0.051 for x = 0, and it significantly increased to 0.23 for x = 1. TbFe thickness dependence of the anisotropy field H_k estimated from the TRMOKE measurements was shown as closed circles in Fig. 1 (b). The H_k gradually increased with increasing TbFe. The H_k estimated from TRMOKE agreed well with the H_k estimated from hysteresis loops which is shown as open circles in Fig. 1 (b). We compares the product $\alpha \times M_sH_k$ of the as-deposited GdFeCo / TbFe bilayers with the J_c of CIMS as shown in Fig. 1 (c), since the J_c is known to be proportional to the product, $\alpha \times M_sH_k$, in a single memory layer. The J_c of the GdFeCo (9 nm) / TbFe (1 nm) was confirmed to increase by 1.6 times compared to that of the GdFeCo (10 nm), while the product $\alpha \times M_sH_k$ was confirmed to increase by a factor of 10. This suggests that an empirical relation, $J_c \propto \alpha \times M_sH_k$, does not hold in the exchange coupled bilayer system.

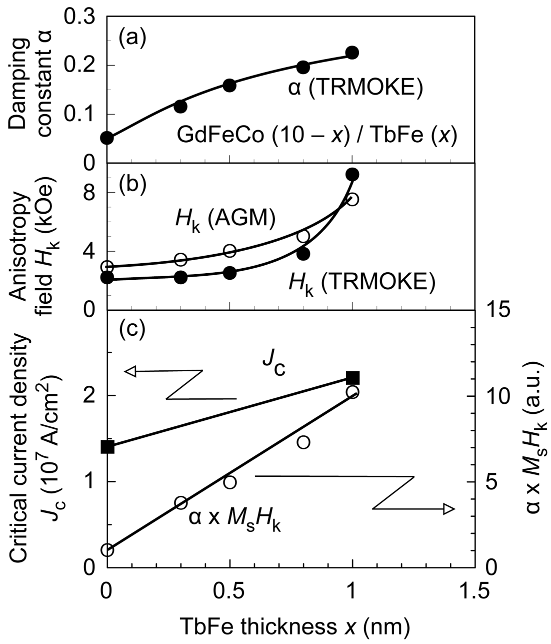

Fig. 1 (a) TbFe thickness dependence of the damping constant α of the GdFeCo / TbFe bilayer. (b) TbFe layer thickness dependence of the anisotropy field H_k estimated from TRMOKE and hysteresis loops, (c) TbFe thickness dependence of the critical current density J_c of the GMR nano-pillars with GdFeCo / TbFe bilayers and the product $\alpha \times M_sH_k$ of the bilayers.

Reference

1) I. L. Prejbeanu *et al.*, J. Phys. D: Appl. Phys., **46**, 074002 (2013).
2) L. You *et al.*, Jpn. J. Appl. Phys., **47**, 146 (2008).
3) L. You *et al.*, J. Magn. Magn. Mater., **321**, 1015 (2009).
4) B. Dai *et al.*, IEEE Trans. Magn., **48**, 3223 (2012).
5) B. Dai *et al.*, IEEE Trans. Magn., **49**, 4359 (2013).