Journal of Magnetism and Magnetic Materials 332 (2013) 52–55

Contents lists available at SciVerse ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Letter to the Editor

Layer-resolved readout of magnetic signals using ferromagnetic resonance effect

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ARTICLE INFO

Article history:
Received 20 June 2012
Received in revised form
30 November 2012
Available online 10 December 2012

Keywords:
Three-dimensional magnetic recording
Ferromagnetic resonance
Coplanar waveguide

ABSTRACT

We introduce a method to read the data stored in a three-dimensional (3D) magnetic recording medium comprising plural storage layers. The readout is realized by selecting the storage layer with the ferromagnetic resonance frequency, and detecting the magnetization orientation with the ferromagnetic resonance absorption. This concept is experimentally confirmed with magnetic media comprising NiFe and CoFe layers. The feasibility of applying this method to a realistic 3D magnetic recording medium is discussed by calculating the absorption spectra of several storage layers with different perpendicular magnetic anisotropy constants.

1. Introduction

By continuously reducing the size of the recorded bit in the magnetic recording medium as well as the size of the writing/reading element in the magnetic head, the storage capacity of the hard disk drive (HDD) has been increasing rapidly in past years. However, neither the bit nor the head could be squeezed forever, because of the so-called trilemma, i.e. it is becoming more and more difficult to simultaneously have enough signal to noise ratio (SNR), enough thermal stability, as well as enough writability.

Nevertheless, there are still great efforts to improve the recording density limit. Among these efforts, high frequency phenomena are playing important roles. The microwave field has been found to assist the magnetic reversal [1,2], and thus suggested to be employed to reduce the writing field for a magnetic recording medium with a very high anisotropy [3]. The assisting microwave field can be generated with a spin torque oscillator (STO) element, in which the magnetization precession in GHz frequency range is driven by a dc current [4,5]. The STO element is also proposed as a reading sensor, which is less susceptible to thermal agitation and responds faster compared with a current read head based on magneto-resistance effect [6–8]. In addition, the shingled-writing recording (SWR) [9] is attracting extensive attention as a recording method to pack the bits closely along not only the track direction but also the radial direction. These efforts are expected to put off the appearance of the ultimate recording density limit.

Another conspicuous approach is the three-dimensional (3D) magnetic recording, by which the data is stored not only in a two-dimensional (2D) plane, but also in the thickness direction of the medium comprising several storage layers [10–12]. In this way, the areal recording density in a magnetic disk is expected to be improved by several times, corresponding to the number of storage layers. However, unlike in 2D recording, where the bit is recorded and read one by one through moving the head, it is difficult to resolve the magnetic signals from different storage layers in a 3D magnetic recording medium. Therefore a new readout scheme is necessary, different from the current one detecting the fringe field of the bit.

Such a new readout concept employing the ferromagnetic resonance (FMR) effect has been put forward just recently by some of the authors of this article [13]. The readout of the information stored at any position in a 3D medium is realized by firstly selecting the storage layer with the FMR frequency, and then detecting the magnetization orientation from the FMR absorption.

In this article, we experimentally investigate this readout concept with a magnetic medium comprising only one storage layer and a magnetic medium comprising two storage layers. The feasibility to apply to a 3D magnetic recording medium comprising practical storage layers is also discussed.

2. Experimental methods

In the experiments, two storage layers having different FMR frequencies are designed and fabricated by using NiFe and CoFe alloys. Exchange coupling with an antiferromagnetic IrMn layer is utilized to adjust the coercivity. The storage layers have the

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http://dx.doi.org/10.1016/j.jmmm.2012.12.004

following multilayered structures. Storage layer 1, [IrMn(2 nm)/CoFe(5 nm)]$_4$/IrMn(2 nm), and storage layer 2, IrMn(2 nm)/NiFe(10 nm)/IrMn(2 nm). All the layers are deposited onto the Si substrate with thermally oxidized surface in an ultra-high vacuum magnetron sputtering system. In storage layer 1, IrMn(2 nm)/CoFe(5 nm) double layers are repeated for 4 times to improve the FMR signal as well as the squareness of the magnetization-field (M–H) loop. A magnetic field is applied on the substrate plane during the deposition.

The M–H loops of the media are measured with a vibrating sample magnetometer (VSM). To carry out the FMR experiments, the sample is placed flip-chipped on a standard 50 Ω coplanar waveguide (CPW) line with one end connected to a port of a vector network analyzer and the other end being open. The sample is placed in such a way that the CPW line is parallel to the direction of the field applied during the deposition, which is also the magnetic easy axis. The reflection of CPW is measured by injecting a microwave electrical signal of -3 dBm and sweeping the frequency from 10 MHz to 20 GHz. The power absorbed by the sample, P_{abs}, is estimated by subtracting the background reflection, which is measured when the sample magnetization is saturated in the direction orthogonal to the CPW line.

3. Results and Discussions

We firstly demonstrate how to use FMR absorption to detect the magnetization orientation of a single storage layer. For this purpose, the FMR spectra are measured for the medium comprising only storage layer 1. Fig. 1 shows the dependence of the FMR frequency f_R on the external field H_e, applied along the CPW line.

According to the Kittel equation, the FMR frequencyf_R of the storage layer with in-plane anisotropy is written as

$$f_R = \frac{\gamma}{2\pi}\sqrt{(H_a+H_e)(H_a+H_e+4\pi M_s)}, \text{ for } M>0 \tag{1}$$

and

$$f_R = \frac{\gamma}{2\pi}\sqrt{(H_a-H_e)(H_a-H_e+4\pi M_s)}, \text{ for } M<0 \tag{2}$$

Here, $\gamma$is the gyromagnetic ratio. H_a is the in-plane anisotropy field, induced by the exchange coupling with the IrMn layer as well as the field applied during the deposition. M_s is the saturation magnetization.

Eq. (1) explains the decrease in the FMR frequency shown in Fig. 1, when the external field is reduced from 2 kOe. However, the FMR frequency jumps to a larger value and starts to increase after the external field is reduced to beyond the switching field, i.e. the negative coercivity $-H_C$ indicated in the M–H loop. This transition is attributed to the reversal of magnetization. Therefore, following Eq. (2), f_R increases with further reduction in the external field. Similar field dependence of f_R is also observed when the external field is increased from -2 kOe, as plotted in the same figure.

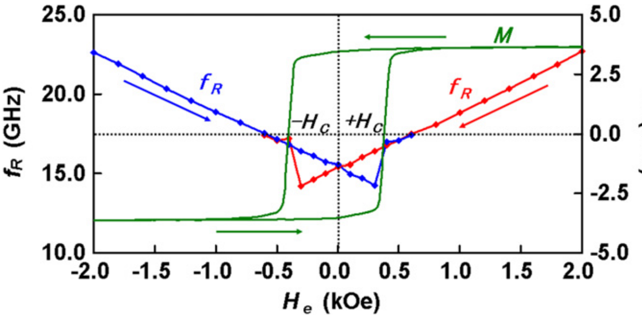

Fig. 1. M–H loop and field dependence of the FMR frequency for storage layer 1. The arrows indicate the directions of sweeping the field.

Notably, there are two FMR frequencies for any nonzero external field between $+H_c$ and $-H_c$. For example, when H_e=300 Oe, there are two resonance frequencies $f_R^{\leftarrow}$=14.5 GHz and $f_R^{\rightarrow}$=16.4 GHz, the corresponding FMR peaks of which are plotted in Fig. 2(a). The arrows "→" and "←" represent "+" and "−" magnetizations respectively. This duality of f_R is the result of magnetic hysteresis, and is also reported elsewhere [14]. Interestingly, if measured at $f_R^{\rightarrow}$=16.4 GHz and H_e=300 Oe, the absorption is 1.6 when the magnetization is "+", but drops to about 0.7 when the magnetization is "−", as shown in Fig. 2(a). This result indicates that the magnetization orientation could be detected from the level of FMR absorption, suggesting that the recorded bits in a magnetic recording medium may be read in the same way. In such a readout scheme, the external field H_e serves as a reading field, thus we denote it as H_r hereafter. Similarly, the frequency at which the absorption is measured is hereafter denoted as reading frequency f_r. According to Eqs. (1) and (2), the reading field causes the difference in FMR absorption between the two magnetization orientations. It can be seen from Fig. 2(b) that this absorption difference is improved by increasing H_r, favoring a large SNR if being used in a read head. However, the reading field should not exceed the coercive field.

Different from the traditional reading methods detecting the fringe field from the medium, this new readout method excites the bit to be read and detects FMR absorption. Therefore, it is possible to read the data stored in the different storage layers in a 3D magnetic recording medium, if each storage layer has its own FMR frequency different from the frequencies of other storage layers.

To testify this idea, a magnetic medium is prepared, comprising both storage layer 1 and storage layer 2 described previously. The two storage layers are separated by a 15 nm-thick Ta layer. A thickness of 10 nm is chosen for the NiFe layer in storage layer

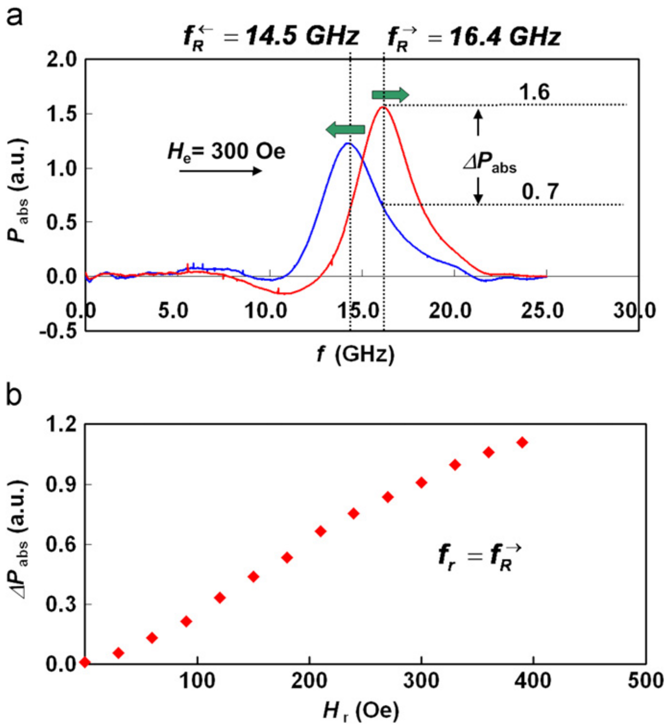

Fig. 2. (a) The power absorption spectra measured when a 300 Oe field is applied. The thick green arrows indicate the magnetization orientation. (b) Reading field dependence of the power absorption difference between the two opposite magnetization orientations, measured at $f_R^{\rightarrow}$.