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ScienceDirect
Journal of Magnetism and Magnetic Materials 315 (2007) 46–52
Journal of magnetism and magnetic materials
www.elsevier.com/locate/jmmm

Dual-synthetic magnetic force microscopy tip and its imaging performance

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Received 1 September 2006; received in revised form 17 February 2007
Available online 15 March 2007

Abstract

A multilayer structure magnetic force microscopy (MFM) tip coated with antiferromagnet/ferromagnet/Ru/ferromagnet/Ru/ferromagnet/antiferromagnet on one side of the tip has been fabricated and evaluated. The ferromagnet used was CoFe. The central CoFe layer is antiferromagnetically (AFM) coupled with the two-side CoFe layers via ultra-thin Ru layers through optimizing the Ru layer thickness. The strong antiferromagnetic coupling between the CoFe layers leads to a more stable magnetization configuration and confined tip stray field as compared to that of conventional single-layer coated tips. The former improves the signal-to-noise ratio of the detected signals and the latter leads to an improvement of spatial resolution. The performance of this kind of tip has been evaluated by imaging magnetic patterns and comparing them with the images taken by both ferromagnetically coupled multilayer tips and commercial tips. Micromagnetic modeling has been performed to gain an understanding of the experimental results.

PACS: 75.70.Cn; 07.55.−w

Keywords: Magnetic force microscopy; Multilayer coating; Dual synthetic; Spatial resolution

1. Introduction

Magnetic force microscopy (MFM) has become an effective tool for investigating magnetic-domain structures by detecting the magnetic stray field from magnetic samples [1–5]. Depending on the environmental conditions, MFM can resolve magnetic features down to 10–50 nm [6–8]. However, there has always been a demand to improve the MFM resolution further so as to be able to detect even smaller features. The resolution of a typical MFM is determined by many factors; among them the two most important ones are the size and geometry of the tip, and the tip–sample spacing. Due to the limitation in tip–sample spacing reduction, much effort has been devoted to improving the design and reducing the size of the tips. The approaches that have been taken so far include electron beam-induced deposition [9–16], attachment of carbon nanotubes [17–21], focused ion beam (FIB) modification [22–24], combination of electron beam deposition and ion milling [25], etc. Although all these approaches have successfully produced higher aspect ratio or smaller magnetic volume tips as compared to "non-processed" tips, there are some drawbacks with these methods such as complexity and low throughput of the fabrication process and thermal instability of the magnetic coating due to its ultra-small volume. To address these concerns, we have reported previously on fabrication and characterization of multilayer tips, which are able to provide both a confined stray field distribution and good thermal stability [24,26]. The multilayer-coated tips can be fabricated in a batch process; therefore, it is more suitable for manufacturing. In one of our earlier works, we have demonstrated a synthetic tip with two ferromagnetic (FM) layers coupled antiferromagnetically (AFM) so as to realize an effective dipole at the tip apex [26]. The improvement of resolution by this kind of tip can be readily understood from the point of view that it is equivalent to a differential

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0304-8853/$ - see front matter
doi:10.1016/j.jmmm.2007.02.201

detection technique, which effectively reduces the DC component of the signal and boosts relatively high-frequency components.

In this paper, we report on the fabrication and evaluation of a further modified tip coated with multiple layers consisting of AFM/FM/Ru/FM/Ru/FM/AFM (hereafter, we call it dual-synthetic tip), where the central thicker FM layer is AFM coupled with two thinner FM layers on both sides via an ultra-thin Ru layer. When the thicknesses of individual layers are optimized, this kind of tip produces a more confined field distribution as compared to single-layer tip, which has been confirmed by micromagnetic modeling. As it is with the case of magnetic heads in magnetic recording, a sharper tip stray field naturally leads to a better spatial resolution [27,28]. The performance of the fabricated tips has been evaluated by imaging the magnetic patterns recorded on longitudinal media. It was found that the double-AFM-coupled tips exhibit an evident improvement of spatial resolution over the conventional single-layer coated tips.

2. Micromagnetic modeling

To understand how the dual-synthetic tips could improve the resolution of MFM, we first calculated the stray field distribution using micromagnetic modeling and then compared it with those of a single-synthetic tip as well as a multilayer tip with the same structure as that of the dual-synthetic tip, but with all magnetizations aligned in parallel via replacing the 1 nm thick Ru with a 2 nm thick Cu (hereafter, we call it dual-FM-coupled tip). The micromagnetic modeling was performed using a home-developed micromagnetic simulator [29]. In this simulator, a rectangular element is used to reduce the nodes and calculation time of the demagnetizing field. The energy minimization method is used to obtain the magnetization distribution at the equilibrium state. The energy terms that have been taken into account include exchange energy, anisotropy energy, external field (Zeeman) energy, demagnetizing (magneto-static) energy and the interlayer exchange coupling energy. The tip shape was simplified as a slab with height H, width W and thickness d. The simulation volume was chosen as $200 \times 100 \times 2$ nm for the single-layer tip and as $200 \times 100 \times 18$ nm for the multilayer tips, where the numbers are corresponding to the height, width and thickness of the tip, respectively. Although the dual-synthetic tip and dual-FM-coupled tip consist of many layers, only the FM layers' magnetizations contribute to the MFM response. Therefore, in order to simplify the problem without loss of generality, in this simulation we assumed that the tip consists of three FM layers with a rectangular shape. The discretized cells are $10 \times 10 \times 2$ nm for the single-layer structure, and $10 \times 10 \times 4$ nm for the dual-synthetic and dual-FM-coupled tips, respectively. The thickness of the FM layer for the single-FM layer tip is chosen to be 2 nm so that the magnetic moment of the single-layer tip will be approximately the same as that of the net moment of the double-AFM-coupled tip. The magnetic parameters used in the simulation are (i) saturation magnetization M_s: 1.3×10^3 emu/cm^3, (ii) anisotropy constant K_u: 5.0×10^3 erg/cm^3, and (iii) interlayer coupling constant A_{ex}: $\pm 8.0 \times 10^{-8}$ erg/cm. The plus and minus signs correspond to the AFM and FM coupling, respectively.

Fig. 1 shows the normalized stray field distribution of a dual-synthetic tip with a structure of IrMn(10 nm)/CoFe(4 nm)/Ru(1 nm)/CoFe(10 nm)/Ru(1 nm)/CoFe(4 nm)/IrMn(10 nm) and a single-synthetic tip with a structure of IrMn(10 nm)/CoFe(4 nm)/Ru(1 nm)/CoFe(10 nm)/IrMn(10 nm) at a tip–sample spacing of 10 nm. The inset is the schematic structure of the dual-synthetic tip in which the bottom Ta(5 nm)/NiFe(2 nm) layers serve as seed layer to improve the exchange coupling strength, while the top Ta(10 nm) layer is used to protect the tip coatings from oxidation. It is apparent that the stray field of the dual-synthetic tip is more confined than that of the single-synthetic tip at this tip–sample spacing. In addition to a more confined stray field distribution, a simple estimation suggested that the stability of AFM-coupled structure can be improved over the FM-coupled counterpart by a factor of $[(M_{s1}t_1 + M_{s2}t_2 + M_{s3}t_3)/(M_{s1}t_1 - M_{s2}t_2 - M_{s3}t_3)]^2$, where M_{s1} and t_1 denote the saturation magnetization and thickness of the central FM layer, while M_{s2} and t_2, M_{s3} and t_3 denote the saturation magnetization and thickness of the two-side FM layers, respectively [30].

Fig. 2 compares the calculated stray field distributions (H_z in x-direction) of the single-FM layer tip, dual-synthetic tip, and dual-FM-coupled tip, at different

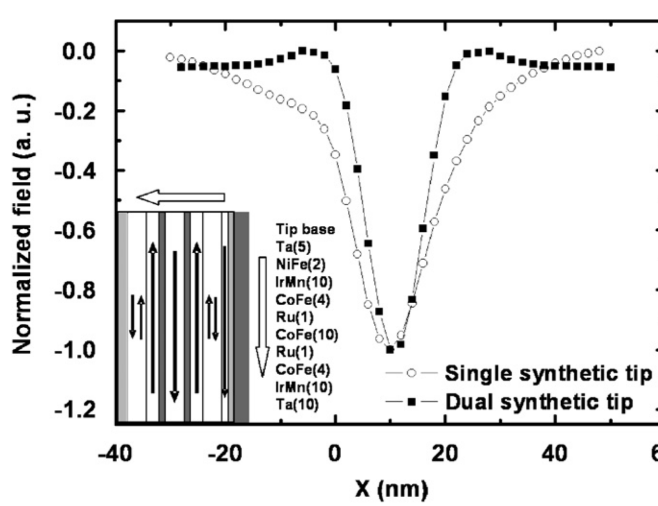

Fig. 1. Calculated z component of the tip stray field distribution of a dual-synthetic tip with a structure of IrMn(10 nm)/CoFe(4 nm)/Ru(1 nm)/CoFe(10 nm)/Ru(1 nm)/CoFe(4 nm)/IrMn(10 nm) (solid square) and single-synthetic tip with a structure of IrMn(10 nm)/CoFe(4 nm)/Ru(1 nm)/CoFe(10 nm)/IrMn(10 nm) (open circle) at a tip–sample spacing of 10 nm. To facilitate the comparison, the amplitude is normalized to between −1 and 0. Inset is the schematic of the multilayer tip with the structure: tip base/Ta(5 nm)/NiFe(2 nm)/IrMn(10 nm)/CoFe(4 nm)/Ru(1 nm)/CoFe(10 nm)/Ru(1 nm)/CoFe(4 nm)/IrMn(10 nm)/Ta(10 nm).