Applied Physics Letters

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Cite as: Appl. Phys. Lett. **114**, 243101 (2019); https://doi.org/10.1063/1.5097546
Submitted: 26 March 2019 . Accepted: 24 May 2019 . Published Online: 17 June 2019

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ABSTRACT

In the magnetic hard disk drive industry, a continuous increase in the recording density requires higher anisotropy media in order to maintain thermal stability. However, further advances by scaling have run into a stumbling block due to limitations on the required magnetic fields, particularly for writing, which is currently being addressed by alternative approaches such as heat-assisted magnetic recording and microwave-assisted magnetic recording technologies. In this work, we investigate and demonstrate another alternative approach which is based on the effect of the spin transfer torque (STT). The approach uses tunneling spin-polarized currents, instead of magnetic fields, between a nanoscale magnetic probe and a magnetic recording media, both with a perpendicular anisotropy. Writing is performed by spin polarized electrons injected from the probe into the media, due to the STT effect. Reading is produced by the tunneling magnetoresistance (TMR) effect between the two magnetic layers, in the probe writer and the media substrate, respectively. The energy-efficient switching, with an energy of 3.1 MA/cm^2, is confirmed through the TMR and the magneto-optical Kerr effect. The demonstrated STT-based magnetic recording overcomes the magnetic field limitations to both writing and reading and thus paves the way for the next-generation energy-efficient and extremely high-density recording.

Over the last half a century, the multibillion-dollar magnetic data storage industry has been constantly pushing the technology limits of the imaginable by boldly implementing disruptive technologies.[1,2] Over two decades ago, perpendicular magnetic recording (PMR) replaced the longitudinal magnetic recording technology to further increase the information density which could be written into magnetic media.[3,4] Then, patterning PMR media into bit patterned media (BPM) structures opened a way to store the information at densities above 2.5 Tbit/in.^{2}, requiring a square bit side of 10 nm.[5–7] Further, to overcome the problems of write synchronization and servo technology required for writing into patterned tracks with a pitch as small as 20 nm, shingled perpendicular magnetic recording (SMR) heads have been implemented to write relatively wide alternating pitch tracks at different tilt angles but packed closely together to significantly increase the recording field. In parallel, heat-assisted magnetic recording (HAMR) and microwave-assisted magnetic recording (MAMR) have been proposed to even further increase the information density in magnetic media.[8–12] Arguably, implementation of HAMR and/or MAMR could achieve densities of 10 Tbit/in.^{2}. However, HAMR still faces multiple challenges due to the technical difficulties in coaligning the magnetic recording field with the narrow laser beam in the near field regime and providing the resulting thermal management at temperatures as high as 1000 K.[11–13] MAMR, although it might have fewer challenges in terms of the production reliability and cost, still requires a special head structure with the capability of an adequate spin torque oscillator (STO). Therefore, there is a strong current need to develop an alternative to further advance the technology progress.[12]

Until now, the scaling challenge of generating a sufficiently high magnetic field to write into high-anisotropy magnetic media required for thermal stability at such high areal densities remains an open question. It is noteworthy that using magnetic fields not only limits the requirements on the energy consumption but also significantly limits the spatial and temporal resolutions of magnetic recording. This study aims to exploit the effect of spin-transfer torque (STT) to overcome this stumbling roadblock. Specifically, instead of using magnetic fields, a spin-polarized tunneling current generated by a magnetic nanoprobe in the proximity to a recording media is used to switch the magnetic state of the local region in the media through the STT effect.

To maintain the required quantum-mechanical conditions, e.g., an adequate local spin accumulation in the media, the distance between the nanoprobe and the recording media should be kept as small as possible, preferably in the 1-nm range. It is noteworthy that this goal is not out of reach, because already today the fly height between the recording head and the media can be kept as small as 4 nm throughout the disk surface with the help of special tribology approaches and servo signal processing. Such nanoprobe devices have already been demonstrated to show unprecedented spintronic properties due to the sub-10-nm size, including a significantly reduced STT switching current.[14–18] In this study, a nanoprobe head is used to write into perpendicular magnetic media via the STT effect. As for reading, the tunneling magnetoresistance (TMR) effect, measured with a relatively small tunneling current between the two magnetic layers, in the probe and the media, respectively, is used to distinguish the two local possible magnetization directions in the media.

Both the nanoprobe and recording media were made of CoFeB with perpendicular magnetic anisotropy (PMA). The only difference was the fact that the anisotropy field of the probe media was made higher (by varying the thickness of the CoFeB and MgO layers) to ensure that the probe magnetization direction could be used a reference orientation. A programmable point contact mounted on a scanning probe microscopy (SPM) system was designed for high sensitivity transport measurements. By applying a constant current, the probe was brought into a tunneling contact with the recording media using a nanoscale piezo-electric manipulator. The "tunneling contact" was established when the tunneling current reached 105 nA, which corresponded to a separation below 3 Å.

Figure 1(a) shows images of thin film stacks used to define the two main components, the nanoprobe writer and the recording media, respectively, both made of a CoFeB magnetic layer and a MgO layer. The standard stack of the head consisted of the Si/CoCr (10 nm)/Ta (5 nm)/CoFeB (1.1 nm)/MgO (0.9 nm)/Ta (1 nm) composition. As for the media substrate, the thickness of the CoFeB and MgO layers was approximately 1.5 and 2 nm, respectively. It is noteworthy that the purpose of the capping Ta layer was to protect the stack during the fabrication process. It was assumed that the layer would be significantly thinned down to an insignificant value as a result of the process. The optimal structures were deposited using the sputtering system and the detailed process is described later. The general composition of the final structure is confirmed in the enclosed TEM image as shown in Fig. 1(a).

Figure 1(b) shows m-H loops of the thin film stacks measured with the above focused magneto-optical Kerr effect (f-MOKE) system. Both directions in the in-plane and out-of-plane components were measured. The results confirm a PMA orientation in the both CoFeB layers, deposited on the writer probe and the media substrate, respectively, with the coercivity on the order of 10 and 20 Oe for the media and the probe, respectively.

Figure 1(c) shows an atomic force microscopy (AFM) topography of the final media bit. The roughness of the final film surface is less than 3 Å. Again, the same conditions were used for both the writer and the media films. The right side of Fig. 1(c) presents a magnetic force microscopy (MFM) image of the structure which confirms a single-domain PMA behavior throughout the bit.

State-of-the-art He-ion focused ion beam (FIB) trimming was performed to develop a nanoscale magnetic structure on top of the tip as shown in Fig. 2. The CoFeB structure was trimmed through FIB etching with an Orion NanoFab system using He and Ne ion beams. From the pristine Si probe, several thin film stacks were deposited on tips of the probes and milled to isolate the region through FIB. The technology has been proven in other studies elsewhere to prevent further ion implantation effects.[19]

Figure 3(a) illustrates the studied concept of the memory/recording system made of the two main components, the probe writer and the media substrate, respectively. When the writer was brought sufficiently close to the media (∼3 Å) to generate an adequate tunneling current, the effective point contact was established. The distance between the writer and the media was controlled by the nanoelectromechanical (NEM) switching component of the SPM system with an angstrom precision. Then, spin polarized electrons from the probe were used to switch magnetization in the patterned bit in the region of the recording media under the probe. In this demonstration, writing and reading processes could be studied separately.

To demonstrate the reading mechanism, Fig. 3(b) shows the magnetic field dependence of the resistance of the junction. The dependence, due to the TMR effect, can be explained by the change of the relative orientation of the magnetizations in the probe and the media. As expected, the resistance in the antiparallel case is higher

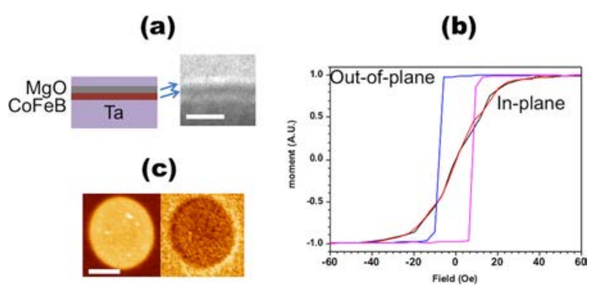

FIG. 1. Deposition of PMA thin film stacks. (a) Illustration of the deposited thin film stack and a TEM image of the stack. The scale bar is 4 nm. (b) m-H loops of a thin film stack in "easy" and "hard" magnetic orientations taken by a focused magneto-optical Kerr effect (f-MOKE) system. (c) AFM and MFM images of the nanoprobe structure taken from the air-bearing surface (ABS). The scale bar is 50 nm.

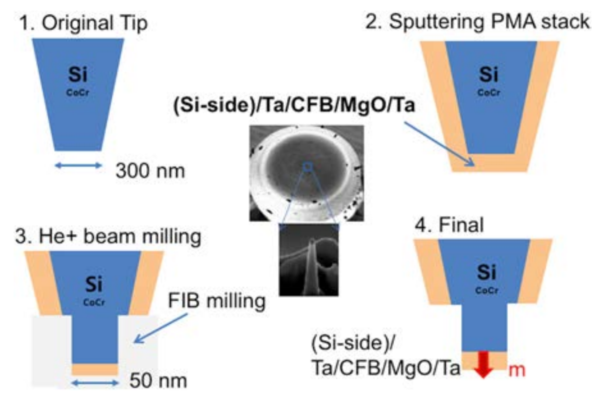

FIG. 2. Fabrication of a probe writer.

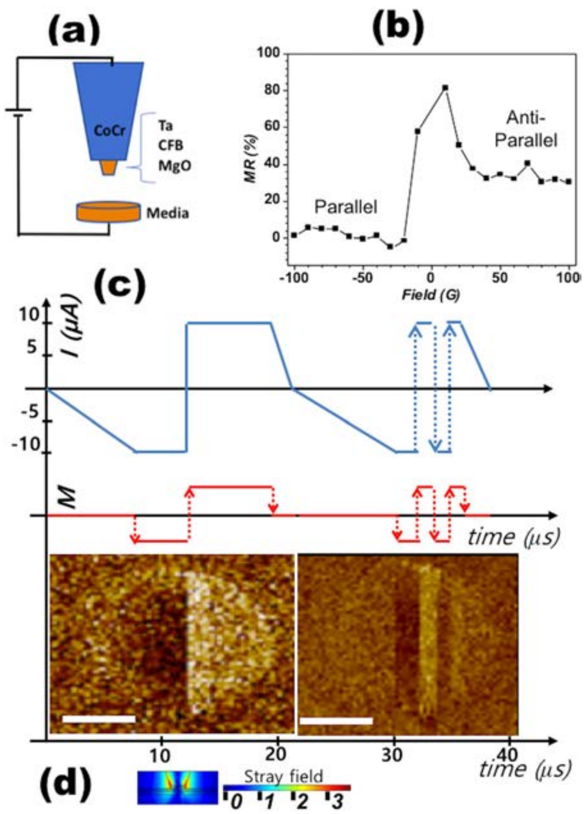

FIG. 3. STT recording system. (a) An illustration of a STT recording system. (b) Demonstration of the reading mechanism: field dependence of the magnetoresistance (MR, %) of the effective point junction between the probe and media illustrating a binary state of the system. (c) Writing with spin polarized currents through the STT effect as confirmed through MFM imaging. The scale bar is 50 nm. (d) COMSOL simulation of stray field effects which shows stray field distribution around the probe head and the unit of the scale bar is 1 Oe. The maximum stray field is less than 4 Oe in this case.

than that in the parallel case. Perpendicularly oriented parallel and antiparallel configurations of the magnets were clearly observed with the average TMR of 35%, consistent with state-of-the-art demonstrations of the TMR effect in similar junctions.[20,21] The zero field resistance value was 350 kΩ.

The top left image shows the media structure made of a Ta/CoFeB/MgO thin film stack. The electronics allowed to sweep the spin polarized current of 50 μA in both directions. The measured switching current was on the order of 10 μA. The images in Fig. 3(c) indicate that the spin polarized current could indeed change the magnetization direction of the substrate. As shown in Fig. 3(c), we observed a current induced magnetization change to randomly switch the media. The SPM results on the bottom show the change of the magnetization by sweeping the current. Above the switching current, the magnet clearly switched as shown in Fig. 3(c). According to this measurement, the magnetization in the media could be easily controllable with the probe head to switch CoFeB thin films with a PMA. Using this geometry, high anisotropy materials could be switched as reported in our previous report.[22]

Figure 3(c) demonstrates the mechanism of writing into the media with spin polarized currents through the STT effect. The top graph shows the time dependence of the value of the spin polarized current, programed in some random sequence. Simultaneously, the magnetic state of the media was imaged via MFM, as shown in the bottom row. The middle row illustrates the direction of the magnetization in the media according to the MFM imaging. A direct correlation between the electric current sequence and the MFM sequence could be clearly observed. It can be noted that the switching takes places every time the electric current is above the STT switching threshold value. This experiment directly showed switching of the local magnetization in the media using spin polarized currents in the probe via the STT effect. We assessed that the stray field was less than 4 Oe as shown in Fig. 3(d).

STT magnetic recording has been shown here as a potential next generation technology capable of continuing to scale hard-disk capacity. This study has demonstrated magnetic recording via the STT effect. Using spin polarized currents, instead of magnetic fields, to write and read information promises a next paradigm shift in magnetic recording to further increase information storage densities. In addition, such a recording system could be translated from the disk form factor to a nonvolatile memory device in which STT and TMR are used for writing and reading information into densely packed three-dimensional (3D) stacks of magnetic bits.[7,23–25]

The elimination of the need for magnetic fields to control the write and read mechanisms makes 3D integration of magnetic devices relatively straightforward. Last but not least, such a technology could be used to write/read into/from next-generation magnetic media made of antiferromagnetic (AFM) materials. Because of the lack of stray fields for both writing and reading and the unprecedented high spin exchange energies, compared to the anisotropy energies in traditional ferromagnetic materials, AFM based magnetic media, with bits coded as the AFM order parameter, also known as Neel vector, can be used to process information at extremely high densities and data rates.

Ta, CoFeB, and MgO layers were deposited through a 7-gun-sputtering system, respectively. The base pressure was as low as 2.0×10^{-8} Torr, and the optimal process pressure range was varied from 2×10^{-4} to 5×10^{-3} Torr. The annealing temperature was increased to 800 K. A high-quality high-density MgO target was provided by Ube Industries Co., Ltd. (Japan). The process pressure, gas flow, power, and time were optimized for the deposition conditions. After the film deposition, the media substrate was further patterned using standard electron beam lithography techniques.

A high sensitivity magneto-optical Kerr effect (MOKE) measurement was performed using a focused MOKE (f-MOKE) system in the polar mode, considering the perpendicular orientation of the magnetic media, with a focusing beam spot on the order of 10 μm. To conduct the polar f-MOKE measurements, a 635-nm diode laser beam was directed normal to the sample. In turn, the sample was placed between the two poles of a vector magnet. The magnetic field at the sample location was calibrated by a three-axis Hall probe sensor (C-H3A-2m Three Axis Magnetic Field Transducer, SENIS GmbH Zurich, Switzerland). The accuracy of the magnetic field measurement was on the order of 0.1 Oe.

The required scanning probe microscopy (SPM) was performed in the noncontact mode using a Bruker-Nano atomic force microscopy (AFM) system. The magnetic force microscopy (MFM) measurements were conducted in the dynamic lift mode with a scan height of 20 nm.

This work was supported by the National Natural Science Foundation of China under Award No. 61674062. This work was also supported by the U.S. Department of Energy, Office of Basic Energy Sciences, Division of Materials Sciences and Engineering under Contract No. DE-AC02-05CH11231. The authors acknowledge financial support from the National Science Foundation (NSF) Center for Energy Efficient Electronics Science (E3S) under Award No. 0939514 and the Air Force Office of Scientific Research (AFOSR) Nos. FA9550-18-1-0527 andNSF-ECCS-1810270.

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