Nanoelectromechanical Magnetic Storage and Memory: A Scalable, Energy-Efficient Approach to Next-Generation Nonvolatile Storage

Chuncheng Wang[1] and Jeongmin Hong[1,2]

[1]School of Sciences, Hubei University of Technology, Wuhan, 430068, China, jehong@hbut.edu.cn
[2]Department of Physics, University of California, Berkeley, CA 94720, USA, jehong@berkeley.edu

Increasing the recording density of magnetic hard disk drives (HDDs) and demands high-anisotropy media to ensure thermal stability. However, conventional scaling faces fundamental limits because generating sufficiently strong magnetic fields for writing becomes impractical, even as technologies like heat-assisted (HAMR) and microwave-assisted magnetic recording (MAMR) seek to address this challenge. Here, we demonstrate an alternative approach using spin-transfer torque (STT) to manipulate tunneling spin-polarized currents—rather than magnetic fields—between a nanoscale magnetic probe and the recording media. Writing is achieved by injecting spin-polarized electrons from the probe into the media via the STT effect, while reading leverages the tunneling magnetoresistance (TMR) effect between the probe and media layers. This STT-based recording method overcomes magnetic field limitations for both writing and reading, enabling energy-efficient, ultrahigh-density recording for next-generation nonvolatile storage.

***Index Terms*—Spin Transfer Torque, Probe Switching, Magnetic Memory, Magnetic Storage**

I. Introduction

ACHIEVING higher areal densities in magnetic recording requires writing into high-anisotropy media to maintain thermal stability, yet scaling is fundamentally limited by the challenge of generating sufficiently strong magnetic fields for writing. Beyond increased energy demands, magnetic field-based writing inherently restricts spatial and temporal resolution. This study explores spin-transfer torque (STT) as a strategy to overcome these limitations by replacing magnetic fields with spin-polarized tunneling currents. Specifically, a magnetic nanoprobe positioned in close proximity to the recording media injects spin-polarized electrons to locally switch the media's magnetization through the STT effect.

To ensure effective spin-transfer, maintaining an extremely small probe-to-media separation—ideally within ~1 nm—is critical for adequate local spin accumulation. This target is practically achievable, given current HDD technologies already achieve fly heights as low as 4 nm across the entire disk surface using advanced tribology and servo control. Nanoprobe devices with sub-10 nm features have previously demonstrated exceptional spintronic properties, including significantly reduced STT switching currents. In this work, the nanoprobe writes to perpendicular magnetic media via STT, while reading is performed by measuring the tunneling magnetoresistance (TMR) effect, which distinguishes local magnetization directions through small tunneling currents between the probe and media layers.

II. Results and Discussion

Both the nanoprobe and the recording media were fabricated using CoFeB-based perpendicular magnetic films. The key difference was that the probe's anisotropy field was engineered to be higher—by adjusting the thickness of the CoFeB and MgO layers—so that the probe's magnetization could serve as a stable reference orientation. A programmable point contact mounted on a scanning probe microscopy (SPM) system enabled high-sensitivity transport measurements. By applying a constant current, the probe was brought into contact mode with the recording media using a nanoscale piezoelectric manipulator. A "tunneling contact" was established once the tunneling current exceeded a threshold, indicating a separation below 3 Å.

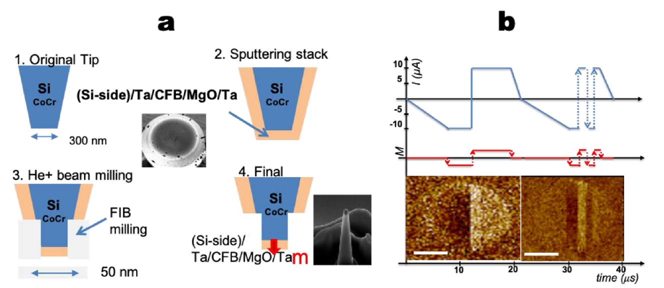

Fig. 1 (a) Fabrication of a probe writer. recording system. (b) Writing with spin polarized currents through the STT effect as confirmed through MFM imaging. The scale bar is 50 *nm*.

To fabricate the nanoscale magnetic probe structure, state-of-the-art helium-ion focused ion beam (He-FIB) trimming was performed, as illustrated in Fig. 1(a). CoFeB thin-film stacks were deposited onto pristine silicon probes and milled using an Orion NanoFab system with helium and neon ion beams to isolate the active region. This fabrication approach has been validated in prior studies to avoid detrimental ion implantation effects.

Figure 1(b) shows the writing process using spin-polarized currents via the STT effect. The top graph presents the time-dependent sequence of the applied spin-polarized current. Simultaneously, the magnetic state of the media was imaged using magnetic force microscopy (MFM), with the bottom row showing the resulting MFM images and the middle row illustrating the corresponding magnetization directions. A clear correlation was observed between the programmed current sequence and the magnetization state in the media. Magnetization switching consistently occurred whenever the applied current exceeded the STT switching threshold, directly confirming local magnetization reversal in the media by spin-polarized currents injected from the nanoprobe.

III. Conclusion

This work demonstrates that spin-transfer torque (STT) magnetic recording offers a promising pathway for next-generation ultrahigh-density data storage. By replacing magnetic fields with spin-polarized currents for writing and tunneling magnetoresistance (TMR) for reading, this approach drastically reduces writing energy while overcoming fundamental scaling limitations of conventional magnetic recording. Moreover, the elimination of external magnetic fields simplifies the potential integration of three-dimensional (3D) stacks of magnetic bits into nonvolatile memory devices.

Looking ahead, this technology could be extended to record and read information in next-generation magnetic media based on antiferromagnetic (AFM) materials. Because AFM media lack stray fields and exhibit significantly higher spin exchange energies compared to the anisotropy energies of traditional ferromagnets, they offer the potential for processing information at unprecedented densities and data rates, with bits encoded in the AFM order parameter (the Néel vector).

References

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