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J. R. Petrie

U.S. Army Research Laboratory

K. A. Wieland

U.S. Army Research Laboratory

R. A. Burke

U.S. Army Research Laboratory

G. A. Newburgh

U.S. Army Research Laboratory

J. E. Burnette

Spin Transfer Technologies

See next page for additional authors

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Authors

J. R. Petrie, K. A. Wieland, R. A. Burke, G. A. Newburgh, J. E. Burnette, G. A. Fischer, and A. S. Edelstein

A non-erasable magnetic memory based on the magnetic permeability

J.R. Petrie^a, K.A. Wieland^a, R.A. Burke^a, G.A. Newburgh^a, J.E. Burnette^b,
G.A. Fischer^a, A.S. Edelstein^{a,*}

^a U.S. Army Research Laboratory, 2800 Powder Mill Rd, Adelphi, MD, USA

^b Spin Transfer Technologies, 33 Arch Street # 3200, Boston, MA, USA

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ABSTRACT

A non-erasable memory based on using differences in the magnetic permeability is demonstrated. The method can potentially store information indefinitely. Initially the high permeability bits were 10–50 μm wide lines of sputtered permalloy ($\text{Ni}_{81}\text{Fe}_{19}$) on a glass substrate. In a second writing technique a continuous film of amorphous, high permeability ferromagnetic Metglas ($\text{Fe}_{78}\text{Si}_{13}\text{B}_9$) was sputtered onto a similar glass substrate. Low permeability, crystalline 50 μm wide lines were then written in the film by laser heating. Both types of written media were read by applying an external probe field that is locally modified by the permeability of each bit. The modifications in the probe field were read by a nearby set of 10 micron wide magnetic tunnel junctions with a signal-to-noise ratio of up to 45 dB. This large response to changes in bit permeability is not altered after the media has been exposed to a 6400 Oe field. While being immediately applicable for data archiving and secure information storage, higher densities are possible with smaller read and write heads.

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1. Introduction

Current magnetic memory technology stores and reads information using an extrinsic property of the media and the direction of the remanent magnetization of domains [1]. This method of encoding information has two major disadvantages. First, since the information is written by applying a magnetic field, the information can also be erased by inadvertent exposure to an external magnetic field. For example, archival magnetic tape, hard disks, and magnetic stripes in credit cards, hotel cards, and ID cards, are corrupted by fields of 300–4500 Oe [2]. One could minimize the loss of information from accidental exposure to a magnetic field by increasing the coercivity, but this would increase the cost of writing and reading the media. In addition, stray field interference from the write head or from the neighboring bits of data can corrupt the bits [3,4]. Secondly, the remanence of the bits changes over time because of thermal instabilities. For single domain bits in archival tape and hard drives, the thermal stability is constrained by the superparamagnetic limit [5,6]. To reliably store information at room temperature for 7 years, domain sizes above 5–50 nm are required to satisfy the Néel–Arrhenius relation i.e., $K_u V / k_B T > 50$, where V is the volume of the bit, K_u is the crystalline anisotropy, k_B is the Boltzmann constant, and T is the absolute

temperature. Heat-assisted magnetic recording (HAMR) allows lower bit sizes by using materials with higher K_u values, but there still must be a compromise between recording density and stability against thermal upsets [7,8]. Non-magnetic methods of information storage do not presently possess the density of magnetic memory and generally do not retain information indefinitely [9–15]. Though magnetic storage is still the primary method of information storage, considerable effort is spent each year duplicating the magnetic data to maintain data reliability.

To improve data stability and security, we are investigating a new technology that stores information in the form of regions (i.e., bits) of high and low magnetic permeability [16]. This approach has the major advantages that information is neither erased by applying a magnetic field nor will it be affected by thermal upsets because the changes in permeability due to temperature are small and reversible. To read the stored information, an external magnetic probe field is applied to the media. Modifications of the probe field near the high permeability bits are read by a magnetic sensor in close proximity to the media. Instead of using a hard magnet, the high permeability bits are regions of a soft ferromagnet. Because the magnetization of a soft ferromagnet is an intrinsic and reversible property [17], a soft ferromagnet returns to its original demagnetized state after the field is removed. Thus, information written in the form of high and low permeability bits is not erased by a magnetic field. This is a significant advantage for applications such as storing high value information in identification cards, and credit cards. Further, the magnetic permeability is not affected by thermal instabilities because

* Corresponding author. Tel.: +1 301 394 2162.

E-mail address: alan.s.edelstein.civ@us.army.mil (A.S. Edelstein).

the magnetic permeability is relatively insensitive to environmental influences. Because of this long term stability, our approach of using the magnetic permeability would be ideal for archiving information if one could achieve acceptable information density. Here we report our initial results on (1) writing high and low permeability lines by two techniques, lithography and thermal patterning with a laser and (2) reading these lines using an external probe field and a linear set of magnetic tunnel junctions (MTJ). Our approach protects the stored information from accidental exposure to a magnetic field, and thus, eliminates the need of increasing the coercivity and the problems that result from increasing the coercivity.

Zheng et al. previously employed [18] laser interference lithography to create media consisting of periodic arrays of Co-rich nanodots in a Co–C film. The resulting magnetic media was then written via a magnetic field to create magnetic domains. Our approach is quite different in that the laser is used to do the writing on a uniform media and that the information is stored in the form of regions of high and low permeability. In our method, no magnetic field is required to write the information.

2. Writing information

Initially, the high permeability bits were sputtered permalloy ($\text{Ni}_{81}\text{Fe}_{19}$) lines the glass substrates. These lines were patterned by optical lithography and had track widths (i.e., recording widths) that varied from 10 to 1000 μm . The length of the lines was 2500 μm . The substrate was low permeability, 1.2 mm thick optical grade soda lime glass. The track widths of these lines are comparable to that used in current magnetic card storage and tape archival systems [19]. The lines consist of six, 70 nm permalloy ($\text{Ni}_{81}\text{Fe}_{19}$)/2.25 nm Cr bilayers. During deposition, the working Ar gas pressure was less than 10 mTorr and a bias voltage of -150 V was applied to the substrate. The base pressure of the magnetron sputtering system was 4.6 μT . The deposition produced soft, ferromagnetic permalloy films with high permeabilities ($\mu_r \sim 1000$) at $H=0$ Oe, low coercivities (~ 0.1 Oe) and low intrinsic stress [20,21]. The surface roughness was on the order of nanometers, as determined by a Veeco Nanoman atomic force microscope (AFM).

An alternative, more economical method of writing the information through thermal annealing was also investigated. In the second method, low permeability, crystalline regions in an otherwise high permeability, amorphous Metglas continuous film were written thermally using a laser. First, an amorphous Metglas 2605SA2 ($\text{Fe}_{78}\text{Si}_{13}\text{B}_9$) film of thickness 400 nm was sputtered onto the same type of low permeability glass used in the lithographic writing. With the exception of no added substrate bias, the

sputtering conditions were similar to those used to deposit the permalloy. The deposition produced an amorphous, ferromagnetic film that was relatively soft, with a high permeability ($\mu_r \sim 1000$) and a coercivity of ~ 30 Oe. Low permeability lines were written into this amorphous, high permeability Metglas film by heating small regions with a 1.966 μm Thulium fiber laser. By focusing the laser by a cylindrical lens, linear regions that were 1000 μm long and had track widths of approximately 50 μm were written using 3 s pulses at 2.9 W.

Following the laser writing, x-ray diffraction (XRD) studies on the Metglas were performed with a Bruker-AXS D8 diffractometer equipped with a general area detector diffraction system (GADDS). These studies indicated that the laser heating of the amorphous Metglas induces crystallization. As an example, Fig. 1(a) shows x-ray diffraction scans of one of our amorphous sputtered films, a laser heated region, and a 1×1 mm section of Metglas film annealed in N_2 for 30 min at 600 $^\circ\text{C}$. Note that this temperature is well above the $\alpha\text{-Fe(Si)}$ crystallization temperature of ~ 450 $^\circ\text{C}$ [22]. The peak in Fig. 1(a) occurs near the (110) 2θ value for Fe and is also near the (110) peak that is observed when $\alpha\text{-Fe(S)}$ is crystallized [23]. The amplitude of the laser induced crystalline peak in Fig. 1(a) is reduced because the x-ray beam diameter is larger than the width of the laser written crystalline lines. Fig. 1(b) shows a comparison of magnetization versus field measurements, made with a Micromag alternating gradient magnetometer (AGM), of the as deposited, amorphous Metglas and a 600 $^\circ\text{C}$ annealed Metglas section characterized by XRD. There is a significant increase in coercivity and decrease in permeability near $H=0$ Oe in the annealed Metglas. Though the small size of the laser heated regions prevented us from obtaining high quality M – H data, the reading results presented in the next section indicate that the laser heating also causes a large decrease in the magnetic permeability near $H=0$ Oe. Note that higher density and faster writing are possible using arrays of hot, sub-micron cantilever tips [24,25].

3. Reading information

The data written by the two methods described above was read by measuring the changes in an external probe field H_{probe} near the bits using magnetic tunnel junctions (MTJ). The fabrication of these MTJ was done as follows: First, a multilayer stack was deposited onto a thermally oxidized silicon substrate in a magnetron sputtering system with a base pressure of 5×10^{-9} Torr. The stack consisted of Ta(5)/Ru(20)/IrMn(5)/Co₅₀Fe₅₀(4)/Ru(0.8)/Co₄₀Fe₄₀B₂₀(3.5)/MgO(2)/Co₂₀Fe₆₀B₂₀(1.8)/NiFeCuMo(50)/Cu(10), where the number in parenthesis is the thickness in nanometers. The two layers above the

Fig. 1. a) XRD scans of laser heated Metglas, Metglas annealed at 600 $^\circ\text{C}$ in N_2 for 30 minutes, and sputtered amorphous Metglas. The peak occurs near the (110) 2θ value for Fe. and (b) magnetization versus magnetic field of the amorphous Metglas before and after it is thermally crystallized.

MgO insulator comprise the free layer, and the three layers below are part of the synthetic antiferromagnetic (SAF) reference layer [26]. Optical lithography was used to pattern a chain of ten $40 \times 10 \mu\text{m}$ MTJ ellipses with each major axis aligned along the chain length. The magnetic sense direction of these MTJ is in the plane of the film and perpendicular to the MTJ chain. A constant current of 1 mA was passed through the MTJ chain and the voltage across the chain was sampled at 1 kHz. The MTJ reader has a tunneling magnetoresistance (TMR) of 22% and a maximum sensitivity of 0.48%/Oe in a field of 22 Oe. The reason that the maximum sensitivity in MTJ is often shifted from zero applied field has been attributed to film roughness and edge effects that give rise to stray fields from the reference layer [27]. An external probe field H_{probe} of 32 Oe was applied. The magnetoresistance of the reader changed by 11% with no media present when this probe field was applied. No significant hysteretic effects were observed.

The experimental setup for reading the two kinds of media is shown in Fig. 2. The media is held parallel to the plane of the reader and is located between the reader and the lens of a VHX 1000 Keyence microscope. Thus, for lines on transparent glass one can see the position of the lines relative to the reader. A permanent magnet (below the reader and not shown) provides the H_{probe} oriented along the sense direction of the MTJ. Both the MTJ reader and the magnet are attached to the moveable stage of the microscope. The setup allows us to accurately control the separation or fly height d between the media and the reader. The fly height d varied between $0 \mu\text{m}$ and $100 \mu\text{m}$. The media is read by moving the MTJ reader by translating the base of the microscope. The reading of the bit is done by determining whether the probe field is modified by material with high permeability. In Fig. 2(a), the media consists of the high permeability lines of permalloy on the low permeability glass substrate. In Fig. 2(b), the media consists of high permeability amorphous Metglas (a-Metglas) and low permeability crystalline Metglas (c-Metglas) lines on the glass substrate. The permalloy lines in Fig. 2(a) shunt the probe field away from the reader, decreasing the detected field when the reader is located at the '1' position near the high permeability bit. Conversely, the magnetic field lines tend to emerge from the crystalline Metglas lines shown in Fig. 2(b). This increases the detected field when the reader is located at the '1' position near a low permeability bit. The magnetic field lines in Fig. 2 are calculated using a finite element code Maxwell 3D.

A view of the permalloy media and the reader beneath it, as seen through the microscope, is shown in Fig. 3(a) and (b) which shows the microscopic image of the laser heated Metglas lines on the amorphous Metglas film. At a constant fly height, the

moveable stage was used to manually translate the reader under the media. During this translation, when the probe field is shunted by the permalloy or enhanced by the crystalline Metglas lines the result is designated as a '1' bit. Regions of lesser field change i.e., the glass or amorphous Metglas, are designated as '0' bits. The measurement system allows one to visually correlate positions of the reader and media to changes in the detected field due to the media's permeability.

Fig. 4(a) shows changes in the tunneling magnetoresistance ΔTMR that result from translating the reader under the three permalloy lines shown in Fig. 3(a), with bit width $w=10 \mu\text{m}$, a lateral separation of the lines of $50 \mu\text{m}$, and a fly height $d=5 \mu\text{m}$. The observed signal-to-noise ratio (SNR) for ΔTMR due to field shunting by the permalloy is $\sim 45 \text{ dB}$. There is a small increase in ΔTMR due to field enhancement around each TMR valley that occurs as the reader passes under the edge of each line where the field becomes concentrated. Fig. 4(b) shows the values of ΔTMR that result from sweeping the reader under the group of three crystallized Metglas lines written in the Metglas shown in Fig. 4(b), with $w=50 \mu\text{m}$, a lateral separation of the lines of $200 \mu\text{m}$, and $d=5 \mu\text{m}$. Since these crystalline lines are low permeability lines, magnetic flux emerges from the highly permeable amorphous Metglas surrounding each line. This increases the field near the crystalline lines and, consequently, increases ΔTMR . These changes in ΔTMR due to either field shunting of H_{probe} in the permalloy lines or field enhancement of H_{probe} in crystalline Metglas indicate that both kind of changes can be used to read a bit. Although the magnitude of ΔTMR in the crystallized Metglas lines is comparable to the magnitude of ΔTMR at the permalloy lines, the SNR for the crystallized Metglas lines is below 10 dB because the noise is much higher. The increase in noise as seen in Fig. 4(b) is attributed to oxidation causing deterioration of the high permeability of the Metglas.

Fig. 5 shows ΔTMR expressed in percent observed from placing the reader directly under the center of individual permalloy lines of varying track width w as a function of fly height d and $H_{\text{probe}}=32 \text{ Oe}$. Generally, at progressively larger widths w and decreasing fly height d , the shunting effect increases as more flux is diverted into the permalloy and away from the reader. The shunting effect reaches a maximum ΔTMR of -5% near a width of $100 \mu\text{m}$ at $d < 5 \mu\text{m}$. By calibrating the MTJ reader, we can infer from this value for ΔTMR that $\sim 13.5 \text{ Oe}$, or over 40% of the probe field, is shunted. The shunting effect is much smaller for $w=500 \mu\text{m}$ and $d > 100 \mu\text{m}$ because flux lines near the reader position at the center of the permalloy lines are less affected. We find both experimentally and through modeling with the finite element code MAXWELL 3D that the detected change in the probe

Fig. 2. Diagram of the reader system showing the microscope, media, probe field (H_{probe}) lines (calculated using MAXWELL 3D), and the MTJ reader (red disks) in two different positions encoded as either a '0' or '1'. The MTJ reader and the permanent magnet (not shown) that provides the probe field H_{probe} are on the movable base of the microscope. (a) H_{probe} lines are attracted to high permeability permalloy lines and shunted away from the reader and (b) Low permeability crystalline Metglas (c-Metglas) allows the magnetic flux lines of H_{probe} to emerge from the high permeability amorphous Metglas (a-Metglas) and increase near the reader. The bit width w and fly height d are labeled in (a). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 3. Microscope view at $500\times$ magnification (a) of $10\ \mu\text{m}$ wide permalloy lines on glass and of the MTJ reader beneath the glass and (b) of three $50\ \mu\text{m}$ wide crystalline lines written into amorphous Metglas using a focused $1.966\ \mu\text{m}$ (Tm fiber) laser. The binary encoding of the media is labeled at the top of each figure.

Fig. 4. Percentage change in TMR resulting from sweeping the reader (a) under three $10\ \mu\text{m}$ wide permalloy lines and (b) under three $50\ \mu\text{m}$ wide crystallized Metglas lines. The reader was at a fly height d of $5\ \mu\text{m}$ and the probe field $H_{\text{probe}} = 32\ \text{Oe}$. The separation between permalloy lines was $50\ \mu\text{m}$ and between the crystalline Metglas lines was $300\ \mu\text{m}$. Shaded regions indicate the times when the reader is swept under permalloy lines and crystalline Metglas lines. The binary encoding of the signal is labeled at the top of each figure.

Fig. 5. Percentage change in TMR versus fly height d for different widths w of a single permalloy line centered over the reader in a probe field $H_{\text{probe}} = 32\ \text{Oe}$.

field is limited by the media permeability, the sensitivity of the reader to the probe field, the size of the reader relative to the width of the lines in the media, and the fly height.

To test whether the information can be erased by a magnetic field, the reader was moved under three permalloy lines before and after the media was exposed to a $6400\ \text{Oe}$ field in the plane of the media for $60\ \text{s}$. This field is higher than the coercivity of nearly all hard disk media. The width of the lines was $50\ \mu\text{m}$, their lateral separation was $50\ \mu\text{m}$, and the fly height was $10\ \mu\text{m}$. As seen in Fig. 6, within experimental error, the measured ΔTMR is unaffected by being exposed to this large magnetic field. Also no change was observed after exposure of the media to a $6400\ \text{Oe}$ field in different orientations. Thus, information stored in the form of high and low magnetic permeability is not erased in large magnetic fields. The measured ΔTMR was also unaffected by exposure to $200\ ^\circ\text{C}$ or by changing the rate that the reader was swept under the media.

4. Conclusion

We have demonstrated a new, non-erasable method for storing information based on using the magnetic permeability. We have shown that we can write and read high permeability, non-erasable lines of permalloy and low permeability crystalline Metglas lines in high permeability amorphous Metglas. The $10\ \mu\text{m}$ wide permalloy lines were read with a SNR of $45\ \text{dB}$. Writing information in

Fig. 6. Percentage change in TMR before and after a 60 s media exposure to a 6400 Oe field. The change was measured by sweeping the reader under 50 μm wide permalloy lines at a fly height d of 10 μm and in a probe field $H_{\text{probe}} = 32$ Oe. The separation between the lines is 50 μm . The sweeps are slightly offset on the time axis for clarity.

the form of permalloy lines was done using lithography and in Metglas films the writing was done thermally with a laser. Thermal writing is a practical method for writing. Although our SNR levels and information densities are already sufficient for archiving and card storage applications, the write and power should be decreased. To achieve these goals, we are varying the laser writing parameters. Changing the media composition can facilitate writing and decrease noise from metal oxide formation in the bulk of the media. Note one can adjust the probe field to optimize performance. To increase the bit density for other applications, we are using e-beam lithography to fabricate smaller MTJs and investigating alternative approaches for writing at a nm scale. Using the permeability provides a potential method for dealing with the thermal upsets of bits near the superparamagnetic limit. The ability to write and read non-erasable media can fulfill the growing need to store data indefinitely.

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