Using magnetic permeability bits to store information

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Abstract

Steps are described in the development of a new magnetic memory technology, based on states with different magnetic permeability, with the capability to reliably store large amounts of information in a high-density form for decades. The advantages of using the permeability to store information include an insensitivity to accidental exposure to magnetic fields or temperature changes, both of which are known to corrupt memory approaches that rely on remanent magnetization. The high permeability media investigated consists of either films of Metglas 2826 MB (Fe₄₀Ni₃₈Mo₄B₁₈) or bilayers of permalloy (Ni₇₈Fe₂₂)/Cu. Regions of films of the high permeability media were converted thermally to low permeability regions by laser or ohmic heating. The permeability of the bits was read by detecting changes of an external 32 Oe probe field using a magnetic tunnel junction 10 μm away from the media. Metglas bits were written with 100 μs laser pulses and arrays of 300 nm diameter bits were read. The high and low permeability bits written using bilayers of permalloy/Cu are not affected by 10 Mrad(Si) of gamma radiation from a ⁶⁰Co source. An economical route for writing and reading bits as small at 20 nm using a variation of heat assisted magnetic recording is discussed.

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(Some figures may appear in colour only in the online journal)
increases the bit density by decreasing $V$ [5]. Thus, a more robust method to store information is needed.

To store information in a ‘non-erasable’ format, it is desirable to use an intrinsic property, such as the magnetic permeability, that depends on the microstructure and composition. Metglas, a class of magnetically soft ferromagnetic amorphous alloys [6–9], can be used as a media whose permeability is easily modified. Bits with different permeability can be read by measuring their effect on a probe field. Higher permeability bits modify a probe field by attracting the magnetic flux lines more than lower permeability bits. The changes in the local probe field can be determined with a read head in close proximity to the media. Studies were presented previously on writing and reading micron sized permeability bits of permalloy and Metglas [10, 11]. Metglas is a good material for creating bits with different permeability. Amorphous Metglas has a high permeability. However, above its glass temperature, crystalline anisotropy increases the coercitivity and decreases the permeability.

In [10] and [11], photolithography was used to write permalloy bits and laser heating was used to heat 50 μm lines in uniform film of Metglas to 450 °C, which is above its glass temperature. The laser heating converted high permeability amorphous Metglas bits into low permeability crystalline Metglas bits. The read head used has either been magnetic tunnel junctions (MTJs) or a spin transfer oscillator as a sensor. It was shown that the information stored as permeability bits was not corrupted by exposure to a 1 Tesla field or a temperature of 200 °C. It was found [12] for Metglas, that low amounts of laser heating increases the permeability, whereas large amounts decreases the permeability. Thus, one can have multiple states of permeability.

Here as part of our effort to develop an information technology based on the magnetic permeability we present results on the effect of heat treating 2826 MB Metglas (Fe$_{40}$Ni$_{38}$Mo$_{4}$B$_{18}$) and permalloy/copper bilayers. This Metglas was chosen because of its high permeability in the amorphous state and its low glass temperature. Bilayers of permalloy and copper were investigated because the magnetism of Ni atoms is decreased when they have Cu atoms as nearest neighbors [13]. Permalloy was used because its permeability is higher than Ni. From these studies we find that: (1) a low permeability state can be created by heating bilayers of permalloy and copper either in a furnace or ohmically; (2) these bilayers are radiation tolerant; and (3) Metglas bits can be written with 100 μs pulses and can be as small as 300 nm diameter. In addition, it is suggested that the technology of heat-assisted magnetic recording (HAMR) can be used to write permeability bits 20 nm or smaller.

2. Methods for preparing the media

Films of 2826 MB Metglas (Fe$_{40}$Ni$_{38}$Mo$_{4}$B$_{18}$) and Cu/permalloy bilayers were deposited using DC magnetron sputtering in Ar at 10 mTorr pressure and 200 W onto an adhesion layer of Ti or Cr deposited at the same pressure but at a power of 1000 W. For the Cu/permalloy bilayers, care was taken not to expose the samples to atmosphere between the deposition of the layers to avoid oxidation. For the ohmic heating samples, a layer of SiO$_2$ was deposited using electron-beam evaporation to separate the bilayer from the heater layer.

For patterning of the micron sized features, photolithography was used. The photolithography was done via a lift-off process, using an image reversal photoresist AZ5214E. For submicron features electron beam lithography was used. The 300 nm diameter Metglas circles that had a thickness of 29 ± 2 nm were produced using electron-beam lithography with the photoresist PMMA 495 A4 spun at 2000 rpm (~2100 Å). Instead of lift off, ion milling was used to remove the Metglas and produce the desired structure. An end point detector was used to determine when to stop the etch. The thickness was measured with a Veeco Dimension 3100 atomic force microscope.

3. Writing and reading permeability bits

3.1. Using bilayers of permalloy and copper

This section describes our investigations using bilayers of permalloy (78% Ni, 22% Fe) and Cu to write permeability bits. All the measurements were taken at room temperature. This work uses the result of earlier studies of nickel showing that nickel atoms lose their magnetic properties if they have too many copper nearest neighbors atoms [13]. A film consisting of 20 nm Cr, 100 nm of Cu, and 80 nm of permalloy was deposited on a Si wafer via sputtering. Photolithography was used to prepare samples with various numbers of bilayer lines and other portions of the wafer were diced into 3 mm by 3 mm squares suitable for alternating gradient magnetometer (AGM) measurements. Figure 1 shows magnetization versus applied field $H$ before and after the bilayer was heated to 500 °C for 1 h in a tube furnace in argon. Clearly the heating that
causes the Cu to diffuse into permalloy drastically reduces the magnetization and permeability of the permalloy.

The effect of the diffusion on the permeability of the bilayers was measured using the same technique described in [10]. A magnetic sensor, consisting of multiple MTJs in series, was biased by a permanent magnet to optimize its sensitivity. The sensor was brought close to the surface and then scanned over the features using a mechanical translation system. Since the system did not record position, time was used as the recorded parameter in the scans. A constant current from a Keithley 2400-LV was passed through the MTJs and the voltage was measured via an analog to digital converter. A 32 Oe probe field was applied in the plane of the film and the MTJ sensor was moved over the lines at a height of 10 μm. The sensor measured the modification of the probe field near the surface of the permalloy/Cu bilayer lines. The voltage increase or decrease when the magnetic field increases depends on the relative orientation of the sensors and the probe field. Except the last figure, an increase in voltage corresponds to an increase in field. An increase in permeability decreases the field, because it draws in flux. Figure 2 shows a microscope picture of a sample with several bilayer lines of different widths and the voltage output of the MTJ as they are moved over the lines. One sees that heating to 550 °C has reduced the permeability of the lines. One also sees that before annealing, the wider lines have a larger effect on the probe field.

The effect of exposing the bilayer to gamma radiation from a 60Co source was investigated. AGM measurements were made after each exposure. Figure 3 shows that even an exposure of 10 Mrad(Si) gamma radiation has no effect on the magnetization and the permeability. This provides clear evidence that the permeability bits are very tolerant to ionizing radiation exposure and could survive decades in a space radiation environment.

Other samples were prepared for testing whether ohmic heating could be used to change the permeability. In these samples, the permalloy/copper bilayer lines were deposited on a borosilicate glass wafer and microprobes were connected at each end of one of the permalloy/copper bilayer lines. The average resistance between the microprobes on different lines was 40 Ω. A current of 0.1 A or, alternatively, at a voltage of 2V for 10 s, was large enough to cause sufficient diffusion to decrease the permeability of the bilayer. Figure 4 shows MTJ scans before and after the right most line was heated via ohmic heating pulses. One sees that the ohmic heating has greatly decreased the permeability of this line.

3.2. Laser heating of Metglas

Previously [10, 11], we have described using laser heating to change the permeability of Metglas. Subsequently, it was shown [12] that by using different levels of heat treatment one could write bits with three different values for their permeability. Here we find that the area around the crystalline region created by laser heating is annealed and has a higher permeability. This result is shown in figure 5. One sees the MTJ signal decrease, corresponding to an increase in permeability, on both sides of the central peak. This type of structure has been observed in previous local heating studies [14].

In the present study, electron-beam lithography was used to create two 0.9 nm square arrays of Metglas, shown in figure 6(a), of 300 nm diameter bits of amorphous Metglas that had a thickness 29 ± 2 nm. The area around the arrays is the initial as deposited Metglas. Figure 6(b) shows a scanning electron microscope image of the 300 nm amorphous bits. Because of diffraction effects, one cannot directly write individual 300 nm bits with our 980 nm wavelength laser. Instead we used the laser to heat and therefore crystalize all of the bits in one of the arrays. Figure 6 shows the result of two MTJ scans made to read the permeability of the arrays before and after the left array in figure 6(a) was crystallized with a 980 nm wavelength laser. Before heating,
the permeability of the arrays is larger than the Metglas film. This increased permeability is a result of the heating that occurs due to processing with e-beam lithography and ion milling. It has been established that low temperature annealing can increase the permeability of Metglas [12, 15].

After laser heating the left array with 200 mW that crystalizes the Metglas, the permeability has been decreased such that it is smaller than the original Metglas film as demonstrated by the peak in figure 7. Thus, the smaller 300 nm bits change their permeability when crystallized in the same way as micron sized bits [10, 11].

On a different unpatterned film, the time required to write bits with different permeability was investigated. Figures 8(a) and (b) show microscope images of lines written by applying different length pulses from the 980 nm laser. The large black lines were written by applying the laser continuously as we changed the position of the laser. These lines are markers for finding the position of the features written with the short pulses such as those written with the 100 micro second pulses that are difficult to see visually. The laser power was approximately 200 mW and laser spot size was 16 μm in diameter. Pulses as short as 100 μs produce discernible features with lower permeability. The MTJ scans in figure 8(c) show that one can detect the change in permeability caused by 100 μs pulses. It is likely that shorter pulses can be used for smaller sized bits.
Figure 7(a) using the magnetic tunnel junction sensor.

(c) Voltages measured during scans over the features shown in figure 7(a) using the magnetic tunnel junction sensor.

4. Potential applications

The information density obtained by direct laser writing of information is limited by the diffraction limit and the availability of short wavelength lasers. Nevertheless, direct laser writing could be used for credit and security card applications. With 1 micron wide bits, there would be 25 kilobits/in in a magnetic strip. For a high density hard disk memory, one needs to circumvent the diffraction limit. This can be done via evanescent waves like those used in HAMR. HAMR is being developed by the major hard disk companies [16, 17] to avoid the density constraint imposed by the superparamagnetic limit. In HAMR [1], high magnetic anisotropy media, such as FePt, are heated to near their 477 °C Curie temperature with an evanescent wave when writing the bits to reduce the write field. For writing 2826 MB Metglas, we need to reach the glass temperature 410 °C. Note, in this approach there is no need for lithography of the media.

There is also the possibility of developing a type of RAM, written ohmically, that will be a one-time programmable non-volatile memory. Doing this will require having a permeability bit, heater element, sensor, and logic gates at each cell. As discussed above, the heating only has to be done for microseconds. The short heating time makes it easier to avoid damaging the sensor and logic gates during heating. If necessary, heat sinks can be added. By changing the microstructure while reading magnetically, this type of RAM would be a hybrid incorporating features of both state-of-the-art phase change [18] and magnetic random access memories (MRAM) technology [19].

5. Summary and conclusions

We have discussed the development of a technology based on bits with different values for their permeability that can be used to safely store information in credit and identification cards and in high density hard disks. This information is a read only memory that is unaltered by exposure to a magnetic field or temperature changes. Using the permeability for card applications has the advantages that it cannot be easily erased and that it cannot be read by someone passing by with an RF reader. There are no clear technological barriers to writing and reading permeability information cards. Data was presented that demonstrated that bilayers of permalloy and copper can be used to write readable permeability bits. The permeability bits written on the bilayers can be written by ohmic heating and are radiation hard. One can use laser writing to create bits with higher and lower permeability than the as deposited Metglas. The Metglas bits can be written in 100 μs and can be as small as 300 nm.

We wish to emphasize that the technology of heat assisted magnetic recording should provide a route for writing 20 nm or smaller permeability bits. We have discussed a potential technology for high density memory with different challenges than the superparamagnetic limit. Though the permeability bits can be very small, there are many technical issues and scientific questions that need to be addressed before one can produce practical nanosized bits and read these bits at an acceptable rate. For example, the read head must be able to reliably read the bits’ alteration of the probe field. As the bits get smaller, the probe field may have to be increased and the sensor will likely have to detect small changes in this larger field. Some scientific questions that need to be considered are: How abrupt is the change in permeability and atomic arrangement in nanosized regions of Metglas after one has applied a temperature gradient? How abrupt is the change in permeability in nanosized regions of permalloy/Cu with a composition gradient? What temperature and time will be needed to write permalloy/Cu bits?

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