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Rewriting magnetic phase change memory by laser heating

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Abstract

Magnetic phase change memory (MAG PCM) consists of bits with different magnetic permeability values. The bits are read by measuring their effect on a magnetic probe field. Previously low permeability crystalline bits had been written in high permeability amorphous films of Metglas via laser heating. Here data is presented showing that by applying short laser pulses with the appropriate power to previously crystallized regions they can first be vitrified and then again crystallized. Thus, MAG PCM is rewriteable. Technical issues in processing the bits are discussed and results on thermal modeling are presented.

Keywords: memory, phase change, magnetic

(Some figures may appear in colour only in the online journal)

I. Introduction

Information in conventional magnetic recording is stored in bits having different directions of residual magnetization. Information stored in this way can be erased by applying a magnetic field or thermal upsets. Thermal upsets [1] occur when the thermal energy overcomes the free energy barrier $K_{\mu}V$ where K_{μ} is the magnetic anisotropy and V is the volume of the bit. The probability of thermal upsets for nanometer-sized bits limits the density of magnetic storage and causes data to become unreliable. In order that thermal upsets are sufficiently infrequent for ten years of storage, it is necessary that $K_{\mu}V > 40$–$60\ k_BT$, where k_B is Boltzmann's constant and T is the absolute temperature [2]. Present efforts to increase the information density involve using FePt, a material with a high anisotropy, and heat assisted magnetic recording (HAMR) [3]. HAMR is done to allow one to use a higher magnetic anisotropy material without increasing the write field. It does this by heating the bit to near its Curie temperature which reduces the anisotropy during the write operation.

We have previously demonstrated a different approach that does not have the above deficiencies of conventional magnetic recording. In our approach, magnetic phase change memory (MAG PCM), information is stored in bits with different values of magnetic permeability [4–6]. Bits with high or low permeability were written into a high permeability film of amorphous Metglas by heating with a laser. Alternatively, low permeability bits were written by heating to cause the Cu in a Cu/permalloy bilayer to diffuse into the permalloy [7]. The permeability of the bits was read using either a magnetic tunnel junction (MTJ) [4] or a spin transfer oscillator [6] to measure the effect of the bit on a probe field. Figure 1 is a schematic view of the reading head and media. The technology of MAG PCM is not affected by a magnetic field or thermal upsets, but writing by diffusing Cu into permalloy is irreversible and is therefore a read only memory.

Another important technology for storing information is based on optical media using phase change media. Wuttig and Yamada [8] have reviewed some phase change materials, such as $Ag_5In_5Sb_{60}Te_{30}$ and GeSbTe, for rewritable data storage. The data has been written either optically or by ohmic heating. By heating these materials above their melting temperature and then cooling them quickly, the crystalline state can be converted to an amorphous state. The materials can be

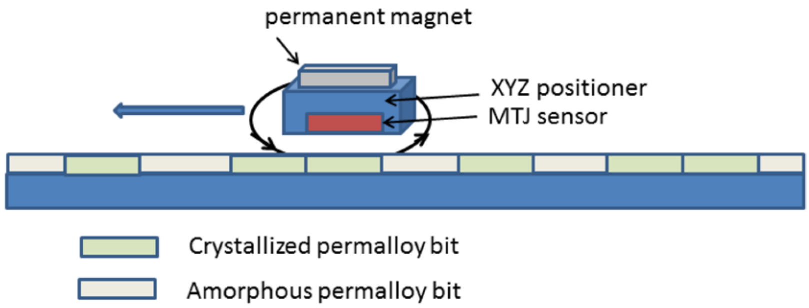

Figure 1. Schematic of the media and the write head used in the experiment. The write head is positioned and translated with an *xyz* positioner. The write head has an MTJ magnetic field sensor and a permanent magnet that provides the probe field.

crystallized from the amorphous state by heating them above their glass temperature. This allows the phase change material to cycle between the two states [9, 10].

In this study, we use a higher energy laser than the laser used in our earlier studies [4–6]. The higher energy permits us to melt the bit and to show that the MAG PCM bits can be rewritten using laser heating. Specifically, we have found that Metglas bits that have been crystallized can be returned to their amorphous state by short high energy pulses and then, with lower energy laser pulses, these bits can be crystallized. MAG PCM can store information at a higher density than present optical phase change memory by using a near field transducer. In principle and possibly in practice, one could also write $Ag_5In_5Sb_{60}Te_{30}$ and GeSbTe using a near field transducer. More significantly, MAG PCM is read by a nanometer sized magnetic sensor similar to that in a hard disk read head with the addition of a probe field. Thus, one can read much smaller bits than those read in present phase change memory. MAG PCM would also likely have a longer lifetime than a DVD-RW using GeSbTe because of its higher glass temperature. We also report on our thermal modeling that was performed to address the issue of scaling of the bits to smaller sizes.

II. Laser rewriting to change the phase and permeability of Metglas

To crystallize Metglas 2826MB ($Fe_{40}Ni_{38}Mo_4B_{18}$) one must heat it above its glass temperature [11] of 410 °C. To change crystalline Metglas back into its amorphous state, one must melt it and then quench it. The melting temperatures of two amorphous materials with compositions ($Fe_{40}Ni_{40}P_{14}B_6$ and $Fe_{56}Ni_{16.11}Co_{10.39}B12.49C_{4.54}Si_{0.47}$) similar to Metglas 2826MB are 950 °C [12] and 1060 to 1120 °C [13], respectively. Thus we expect that the melting temperature of Metglas 2826MB to be around 1000 °C.

Here we use Metglas films that were sputter deposited on Si wafers. Two different film structures with different thicknesses were investigated. The first structure consists of 50 nm of Ti followed by 200 nm of Metglas 2826MB. This sample was crystallized by heating to 550 °C for 1.5 h. We used a G4 pulsed fibre laser from SPI Lasers operating at 1060 nm. The laser was translated linearly over the media during the writing process and the spot size on the media was 12 μm, creating a line 12 μm wide. The total exposure time at each spot along the line was roughly 40 ms. In all cases reported here, the rise time of the pulse was 10 ns, its duration was 140 ns, and the fall time was 10 ns. The pulse repetition frequency was 960 kHz. The pulses were approximately square wave pulses. Figure 2(a) shows a microscope image of the Metglas film after different translations of the laser over the media using first pulses with increasing energy and then decreasing energy in the energy range 0.376 to 1.65 W. The effect of the laser heating on the permeability was determined by measuring with a MTJ how the lines affected a probe field of 10 Oe. The structure and performance of these MTJ used was previously described [4]. The separation between the MTJ and the media was a few microns. The size of the MTJ sensor and the separation between sensor and the media must be less than the size of the bit. Figure 2(b) shows the MTJ voltage output reading of the bits as the MTJ was translated near the surface of the Metglas film using an *xyz* positioner from Thorlabs. The positioner can control the position with micrometer resolution. The separation between the film and the MTJ was 1–5 μm. The lines in figure 2(b) are aligned with the lines in figure 2(a). The lower energy pulses had no observable effect. When the MTJ passed over the lines written with higher energy pulses (average power of 0.586 W), the MTJ voltage increased. This result indicates that the laser heating had caused a phase change and that the Metglas line was now amorphous with a higher permeability. The laser heat had melted the Metglas and the rapid cooling had prevented crystallization. At still higher energies (average power of 0.748 W, 0.840 W, 1.65 W) material was ablated. From atomic force microscope (AFM) measurements it was determined that at least half of the material in the 1.65 W line was removed by the ablation. The removal of material decreased the permeability and the MTJ voltage.

The second structure was used in laser processing to recrystallize amorphous regions that had been created by laser pulses The structure consisted of 275 nm SiO_2 on a Si wafer followed by sputtering 300 nm of Metglas 2826MB deposited at 500 °C. To ensure that the initial Metglas film was crystallized, the wafer was heated to 700 °C for 3 min in N_2 gas. Laser heating followed by MTJ reading tests were used to establish that applying an average laser power of 3.65 W created amorphous Metglas regions in this structure. To show that the amorphous regions could be recrystallized, three amorphous lines, separated from each other by 0.1 mm,

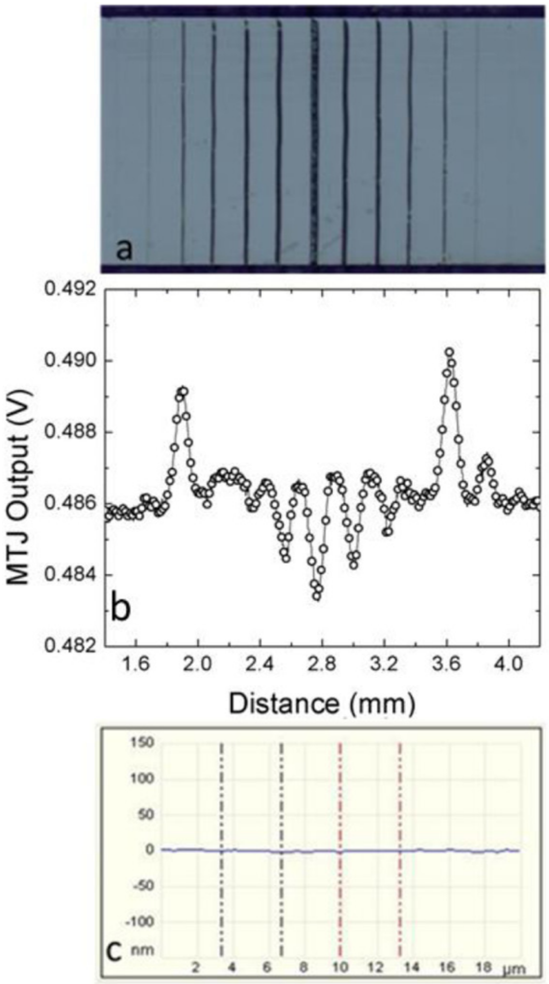

Figure 2. Effect of using thermal laser pulses on film of crystallized Metglas to write lines. Lines towards the center were written with higher powers and lower power was used to write the lines further from the center. (a) Microscope image of the Metglas film after laser writing. The dark lines in the center are due to ablation. (b) Output of MTJ from scans of lines written going from left to right with first increasing laser power and then with decreasing laser power. Increasing values on the vertical axis indicate higher permeability. The strong positive peaks are due to amorphous lines written by laser pulses having an average energy of 0.586 W. Lines in the center show decreased permeability due to ablation. Note that the lines in figure 1(b) align with the lines in figure 1(a). (c) AFM image of the surface of the amorphous line at 3.63 mm in figure 1(b) showing that no discernable roughening occurs during the write operation.

were written in one of these films using laser pulses with an average of 3.65 W. The central line was then rewritten at a lower power (1.61 W) that was high enough to crystallize the Metglas. Figure 3(a) shows a microscope image of the three lines after this processing. Figure 3(b) shows the voltage MTJ output from a scan used to measure the permeability of the three lines. One sees the increased permeability of the outer amorphous lines and, more importantly, the decreased permeability of the crystallized central line. It is not clear why the decrease was not large enough to bring the voltage down to the value of the crystalline baseline. Possible explanations include that not all the line was crystallized or that the crystallized products are different. One also sees that the signal from every the line is broad. The lines in figure 3(b) are also broader than the focused laser spot, 12 μm. This apparent broadening is primarily an experimental artifact. The sensor consists of a chain of MTJs 650 μm long. Thus, both the lines and the MTJ sensor are much longer than the width of the line. Because of this, if the long direction of the sensor and the laser written line are not exactly parallel, a larger translation distance will be required before the sensor no longer detects the line.

III. Discussion of laser writing

In this section, the laser writing of the bits is discussed and thermal modeling results are presented. Major concerns are ablation and the possible roughening of the Metglas surface. If the laser heating roughens the surface, it will affect the separation between the media and MTJ and, thus, the MTJ readings. Figure 2(c) shows the result of an AFM line scan of the surface of the Metglas film near the amorphous line at 3.63 mm in figure 2(b). One sees that the peak to peak surface roughness is less than 10 nm. This shows that the transition back to the amorphous phase occurred without observable ablation of the surface. Similar to other studies [14, 15], when ablation occurs, sometimes a deep groove can form at the position of the line and material is deposited at the edge of the line. These grooves and redeposited material affect the MTJ permeability reading, are deleterious to memory performance, and will limit rewriting.

In the case discussed earlier, at least half the material of the center line was removed by ablation, but only a small portion of the removed material was deposited on the edge of the line. The magnitude of the MTJ voltage decrease at the center line is a result of the large amount of material that has been removed. The MTJ voltage increases at the positions of the amorphous lines are of comparable magnitude but of opposite sign. Thus, we can infer from the MTJ voltage increase that a large percentage of the material has been made amorphous.

Another possible concern is that oxidation is affecting our results. In our previous paper, we compared samples heated in an inert atmosphere and crystallized by thermal heating with a laser in air and found similar XRD results. Thus, oxidation does not seem to affect crystallization. With regard to returning to the amorphous state with its increased permeability, it seems unlikely that oxidation will increase the permeability. Nevertheless, it is probable that some oxidation has occurred and that oxidation will limit the number of rewrites of the bits in air. Note, however, that oxidation can be eliminated by writing in an inert atmosphere.

Thermal modeling using ANSYS Multiphysics Release 15.0 was done to investigate the feasibility of scaling MAG PCM to nm sized bits. Specifically, we investigated the laser pulse energy and thermal interface resistance needed such that the edge of a nm bit would reach 1000 °C, our estimate of the melting temperature of Metglas 2826MB. This estimate was based on the melting temperature of similar materials mentioned earlier [12, 13]. Short write time and small thermal spreading are needed for this approach to be relevant for high density memory. In all the modelling, the substrate was silicon. Initially, in the modeling we considered 12 micron

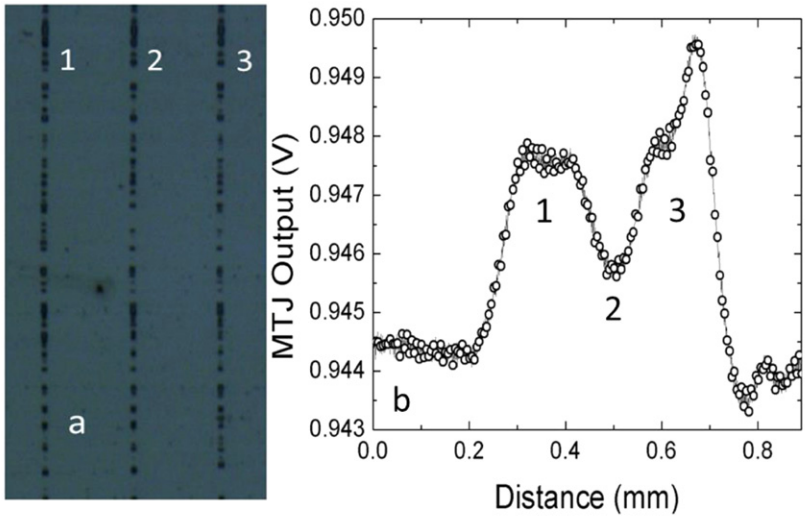

Figure 3. (a) Microscope image of three lines written on crystalline Metglas. First, three amorphous lines were written, and then the middle line was crystallized. (b) Voltage generated by MTJ scan of these three lines after the middle line was crystallized. The decrease in voltage at position 2 is the experimental proof that this line has been crystallized.

diameter bits that were 200 nm thick Metglas on 50 nm titanium. This geometry is the same as the film structure used in our first laser writing experiments described above. We considered heating a circular region on the top surface that was the size of a bit. It was assumed that the thermal conductivity of Metglas is temperature independent, isotropic, and is equal to 9 W $(\text{m K})^{-1}$ [16]. The specific heat of Metglas, estimated from its components, was a temperature independent value of 0.445 J $(\text{g K})^{-1}$. Having cylindrical symmetry greatly simplifies the modeling and decreases the run time. Convection was included in the model, but it did not have much of an effect. We assumed that all the incident energy was absorbed. By varying the incident energy of the 140 ns pulse we were able to identify how much power is required so that most of the bit volume exceeds 1000 °C. The irradiance of the model pulses needed was 4.3×10^{10} W m^{-2} instead of the experimental value of 3.9×10^{10} W m^{-2} needed to return the crystallized bits to their amorphous state. In the model results there were large temperature gradients, e.g. the temperature at the top center of the bit was 1900 °C whereas at the bottom center of the bit the temperature was 1000 °C. The lateral spreading of the heat predicted by the model is less than 3 μm. The large predicted temperature gradient was probably a result of neglecting the interface thermal resistance.

Further modeling was done on 200 nm diameter bits consisting of a bilayer of Ti (50 nm)/ Metglas (50 nm). Again no thermal resistance at the interface was included. The laser pulse length is 20 ns and the irradiance needed to reach 1000 °C at the top edge of the bit was 5.2×10^{11} W m^{-2}. Figure 4 shows the temperature of the Metglas on the top surface as a function of time at the following displacements from the center of the laser spot: 0, 100, 150, and 200 nm. One sees that the maximum temperature decreases rapidly as one moves away from the center. Though there is not significant lateral spreading of the heat beyond the edge of the bit, there is an undesirably large temperature gradient in the bit in the lateral direction and between the top and bottom surfaces of the bit. Different values for the interface thermal barriers between the

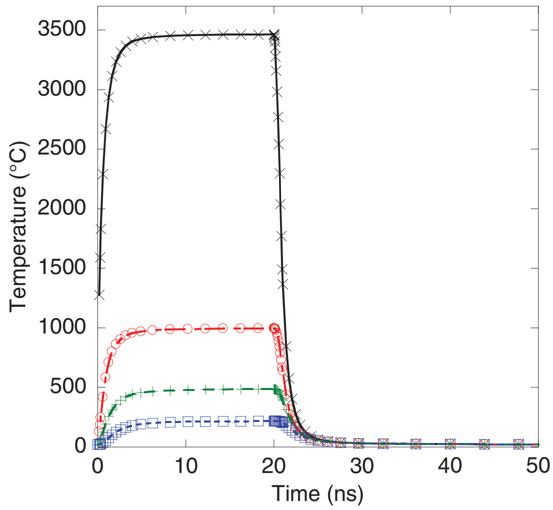

Figure 4. Modeled time dependence of the temperature at the top surface of a 200 nm diameter Metglas bit at the center (×), at the edge of the heated region (○), 50 nm from the edge of the irradiated region (+), and 100 nm from the edge of the irradiated region (□).

Metglas and titanium and between the titanium and the silicon were added to investigate their effect on this temperature gradient. We are not aware of experimental values for the interface thermal barriers for these materials. The thermal resistance of both barriers was taken to be 10^{-6} m^2 °C W^{-1}. This choice of thermal resistance is larger than typical measured values [17] for other systems processed in a similar manner. The modeling results of including the thermal resistance at the interface are shown in figure 5. Comparison of figures 5 and 4 shows that one can reach the same temperature at the edge of the bit with less power (7.0×10^{10} W m^{-2}) when interface thermal resistance is included. One also sees that the flat portion of the curve in figure 4 is not present in figure 5. This change occurs because the increased thermal resistance prevents the bits from reaching equilibrium during the time of the pulse. Of more importance, adding the interface resistance decreased the temperature gradients but does require doubling

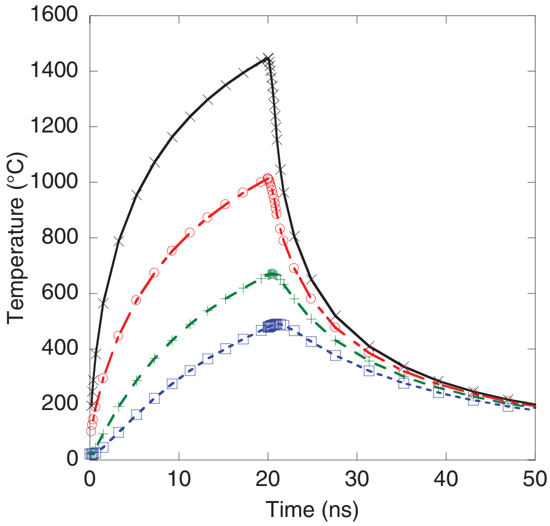

Figure 5. Modeled time dependence of the temperature, when thermal interface resistance is 1×10^{-6} m^2 K W^{-1}, at the top surface of a 200 nm diameter Metglas bit at the center (×), at the edge of the heated region (○), 50 nm from the edge of the irradiated region (+), and 100 nm from the edge of the irradiated region (□).

the spacing between bits to avoid writing neighboring bits. Unless the interface resistance is exceptional high, a cell size of $4F^2$ is expected where the feature size (F) is determined by the laser spot. The thermal modeling results for the nm sized bits are qualitatively similar to those of the micron sized bits. The predicted write time and write energy required are both acceptably small. Based on the thermal modeling results, scaling to smaller sized bits is promising.

IV. Possible applications and conclusions

Data has been presented demonstrating that micron sized MAG PCM bits can be rewritten by laser heating with a commercially available laser. Specifically, amorphous bits can be converted to crystalline bits, then to amorphous bits, and finally to crystalline bits. Thermal modeling results indicate that interface resistance decreases the thermal gradients in the bits and scaling to nm sized bits is feasible, but lateral spreading of the heat is an issue. A possible route to decrease the lateral thermal spreading would be patterning the media to minimize the lateral thermal conductivity. In this case, the bit size would be limited by the lithography rather than the laser spot size.

MAG PCM has potential applications in several areas. For example, MAG PCM has an advantage over optical phase change memory in that it can have much higher density since the reading is not limited by the optical wavelength. For most memory applications, it is desirable to reduce the bit size. Clearly further work is required. For example, it is necessary to determine the best conditions for rewriting and to determine how often the bits can be rewritten. A route for reducing the size of the bit is to use the techniques being developed in HAMR. The temperature being used in HAMR is sufficiently high to crystallize amorphous Metglas bits, but not high enough to convert crystalline bits to amorphous bits. It is not clear whether the higher temperatures needed to return nm sized bits to the amorphous state can be achieved using near field transducers.

MAG PCM can also be used to produce secure identification (ID) cards. Current ID cards use a radio frequency (RF) chip or magnetic strips that can be erased by accidental exposure to a magnetic field. The information on an ID card with an RF chip can be read by someone nearby with an RF chip reader. Carrying the card in a metallized envelope provides protection, but the data is exposed when the card is read or if the user neglects to use the envelope. ID card using MAG PCM will not have these deficiencies.

Another potentially very important application of MAG PCM is archiving. Magnetic tape is still used extensively for archiving, but magnetic tape must be copied about every 10–30 years [18] and must be used in an area with temperature and humidity control. MAG PCM, unlike magnetic tape, provides fast access to the stored information. If MAG PCM is used, the data should last decades and the temperature and humidity does not have to be controlled. MAG PCM has the potential of high density, long life, and rapid access.

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