AIP Applied Physics Letters

Write strategies for multiterabit per square inch scanned-probe phase-change memories

C. D. Wright, P. Shah, Lei Wang, M. M. Aziz, A. Sebastian et al.

Citation: Appl. Phys. Lett. **97**, 173104 (2010); doi: 10.1063/1.3506584
View online: http://dx.doi.org/10.1063/1.3506584
View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v97/i17
Published by the American Institute of Physics.

APPLIED PHYSICS LETTERS **97**, 173104 (2010)

Write strategies for multiterabit per square inch scanned-probe phase-change memories

C. D. Wright,[1,a)] P. Shah,[1] Lei Wang,[1] M. M. Aziz,[1] A. Sebastian,[2] and H. Pozidis[2]
[1]*College of Engineering, Mathematics and Physical Sciences, University of Exeter, Devon EX4 4QF, England*
[2]*IBM Zurich Research Laboratory, Saumerstrasse 4, CH-8803 Rueschlikon, Switzerland*

(Received 30 July 2010; accepted 7 October 2010; published online 25 October 2010)

A mark-length write strategy for multiterabit per square inch scanned-probe memories is described that promises to increase the achievable user density by at least 50%, and potentially up to 100% or more, over conventional approaches. The viability of the write strategy has been demonstrated by experimental scanning probe write/read measurements on phase-change (GeSbTe) media. The advantages offered by adopting mark-length recording are likely to be equally applicable to other forms of scanned probe storage. © *2010 American Institute of Physics*. [doi:10.1063/1.3506584]

Scanning probe based memories have been a subject of intensive recent research due to their potential for achieving ultrahigh storage densities in excess of 1 Tbit/in^2. Several alternatives have been studied, including thermomechanical (or mechanical) writing and reading of indents in polymer media,[1–3] electrical writing and reading of polarization in ferroelectric media[4,5] and, the subject of this paper, the electrical writing and reading of crystalline or amorphous marks in phase-change materials.[6–8] Of these approaches, thermomechanical write/read into polymers is the most advanced, with recent demonstrations of densities and data rates/tip in excess of 4 Tbit/in^2 and 1 Mbit/s, respectively.[1,2,9] However, both ferroelectric and phase-change based systems have also demonstrated at least the potential for multiterabit per square inch data storage.[5,7,8]

Invariably in studies of scanning probe storage the most significant factor in determining the size of a recorded mark is the tip size of the probe itself. This has led to much recent research on the fabrication of probes with ultrasharp tips.[10,11] However, in phase-change probe storage (and most likely in other formats) the requirement for having ultrasharp tips to achieve multiterabit per square inch storage densities can be significantly relaxed by the use of a write strategy in which information is effectively stored in the transitions between marks [so-called mark-length (ML) recording] rather than in the marks themselves (mark-position or MP recording). ML recording is advantageous in storage channels that exhibit a minimum mark size determined by physical limitations in the write/read system (i.e., all practicable channels). ML recording is also attractive for storage systems that exhibit a high degree or write intersymbol interference (ISI) (i.e., where bits written close together affect each other). Write ISI limits how close marks may be written to one another in MP recording, again limiting the achievable density. However, in ML recording we can exploit write ISI to our advantage.

The *de facto* adoption of MP recording in probe memories is a consequence of its origins in scanning probe microscopy, where nanoscale modification of materials is carried out by moving the tip to a particular location, applying some form of excitation, then lifting the tip and imaging the modified region. Concerns about tip wear in probe memories have also no doubt played a role in the continuing use of MP recording. In traditional memory systems, however, such as magnetic or optical disk storage, the benefits of ML recording in terms of increasing the achievable storage density have long been realized. However, a major difference between magnetic and optical disk systems and probe storage is that in the former the write head moves continuously, though out of contact, over the storage medium. In probe storage by contrast, the tip is invariably in contact with the storage medium during writing and, in spite of recent improvements in the design and fabrication of more robust tips,[6,10,11] continuous scanning of the tip on the medium would no doubt lead to excessive tip wear. However, a requirement to avoid continuous tip scanning does not preclude the use of a ML recording approach. In the conventional approach to writing

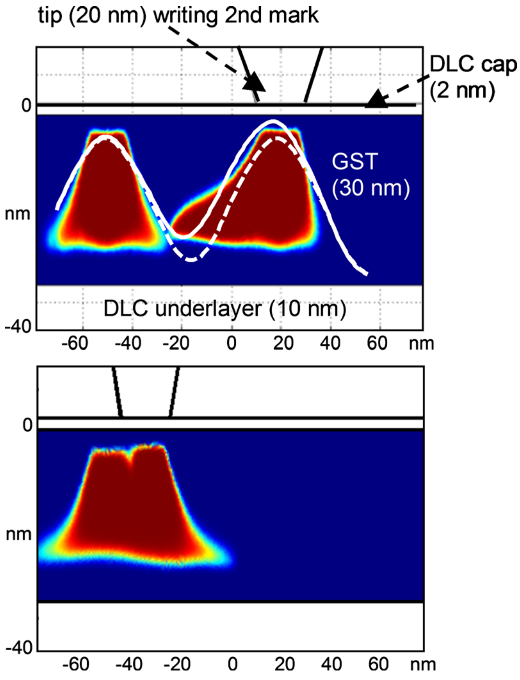

FIG. 1. (Color online) Simulated crystalline marks recorded consecutively into a Si/DLC(10 nm)/GeSbTe(30 nm)/DLC(2 nm) stack using a 20 nm tip and a 7 V, 200 ns pulse. Write ISI is clearly visible in (a-top figure), as is the effect on readout current (simulated as described in Ref. 7) shown in white (solid line—for the two bits shown; dashed line—for the case of no ISI). ML recording exploits ISI to write marks of varying length, as in (b-bottom).

[a)] Electronic mail: david.wright@exeter.ac.uk.

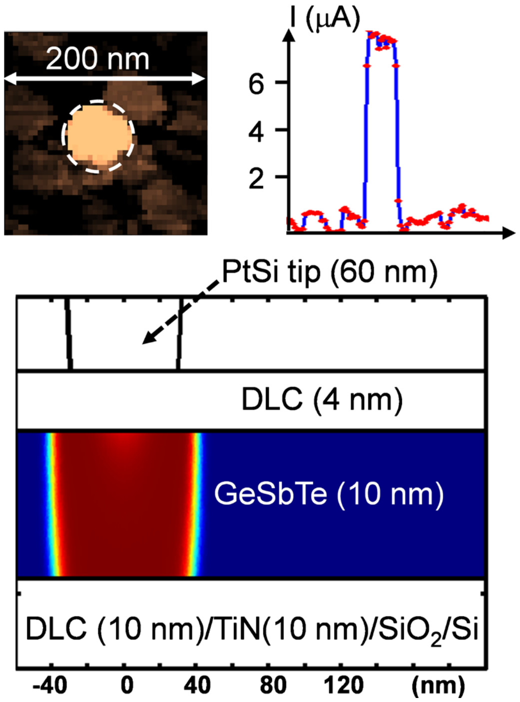

FIG. 2. (Color online) (Top left) Isolated crystalline mark experimentally recorded into a Si/SiO$_2$/TiN(10 nm)/DLC(10 nm)/GeSbTe(10 nm)/DLC(4 nm) stack using a 60 nm tip and 2.8 V, 1 μs pulse. Also shown (top right) is readout current (readout voltage=1 V) when scanning through center of mark and (bottom figure) the simulated written mark.

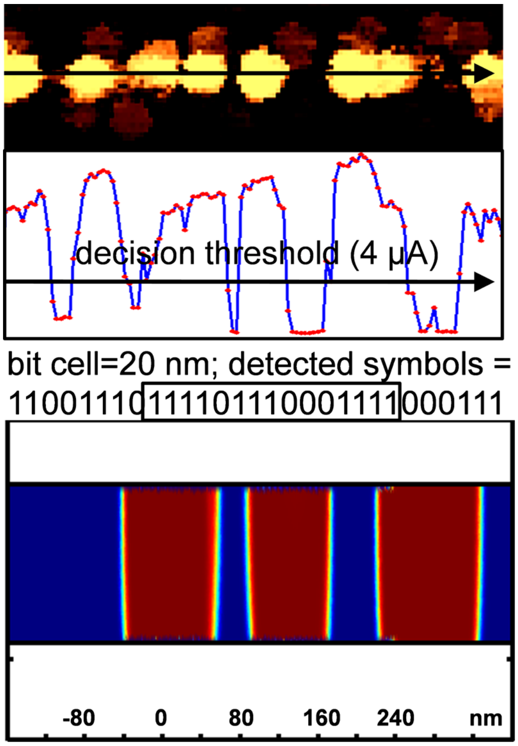

FIG. 3. (Color online) ML recorded bits written in Si/SiO$_2$/TiN(10 nm)/DLC(10 nm)/GeSbTe(10 nm)/DLC(4 nm) stack using a 60 nm tip and a 2.8 V, 1 μs pulse. Top figure (a) shows current image (580 × 140 nm^2) of the bits themselves, as well as current for scanning along center of the track (readout voltage=1 V). Bottom figure (b) shows simulation results for writing the highlighted part of the full data sequence.

marks in scanned probe systems, the tip is brought into contact with the medium and an excitation applied to form a mark; the tip is then retracted from the medium, moved laterally and subsequently brought back into contact to write an adjacent mark. The marks should be spaced far enough apart so that they do not interfere with each other. Assuming a written mark is associated with a logical "1," the avoidance of this write induced ISI leads to the insertion of a minimum number of logical '0s (absence of a mark) between the ones; in coding terminology this is a channel with a run-length limited (RLL) constraint. In the mark-length recording case the tip moves a small (submark) distance between writing events, so using write induced ISI beneficially to write marks of "arbitrary" length (see Fig. 1).

The basic processes involved in scanning probe storage using phase-change media have been described elsewhere.[6–8] Essentially the writing of bits involves an electrothermal process in which a voltage applied between the tip and the storage medium induces Joule heating to crystallize or amorphize the "active" phase-change layer. The readout process is electrical and relies on sensing the large difference in electrical resistivity between the two phases. A typical medium stack and tip geometry is shown in Fig. 1. In this case the medium is a tri-layer stack of DLC(10 nm)/Ge$_2$Sb$_2$Te$_5$(30 nm)/DLC(2 nm) on a silicon substrate, as previously described.[7] The figure shows the results of a finite-element simulation of the MP writing of two consecutive crystalline marks in an amorphous background. In Fig. 1(a) the effects of write induced ISI are clearly visible, with the shape of the second bit (and the readout current) being affected by the presence of the first bit, even though the tip has moved 70 nm between the writing of the two marks. Indeed, for this configuration a separation of more than 80 nm is required before write ISI is eliminated. However, by moving a sub-tip width distance (15 nm in this case) between writing events, as shown in Fig. 1(b), write ISI can be used advantageously to merge marks together for use in ML recording.

We have implemented a ML recording scheme experimentally for a phase-change probe memory. We used a PtSi tip that combines excellent electrical conduction and wear characteristics.[6,12] The storage medium comprised a Si/SiO$_2$/TiN(10 nm)/DLC(10 nm)/Ge$_2$Sb$_2$Te$_5$(10 nm)/DLC(4 nm) stack, which has been shown to have superior recording properties to the simpler stacking used in the simulations of Fig. 1. An experimentally recorded isolated mark is shown in Fig. 2, along with the readout (current) signal, as well as the results of a finite-element simulation of the written crystalline 'bit'. In this case the phase-change layer was initially amorphous, and a 2.8 V, 1 μs write pulse was used. The tip diameter was approximately 60 nm (as measured by SEM imaging—not shown here but see Ref. 9) and it can be seen that the recorded crystalline mark is approximately the same size. There is a peak readout current amplitude of ~8 μA and a good contrast between the current for amorphous and crystalline regions, implying that the crystalline mark (most probably) extends through the whole thickness of the Ge$_2$Sb$_2$Te$_5$ layer. The results of the simulation also show a mark size of approximately 60 nm and a mark extending through the whole phase-change layer, in good agreement with the experimental observations. In Fig. 3 we show the results of writing a series of crystalline marks using our proposed ML strategy. In this case the bit cell was chosen to be 20 nm, i.e., one third the width of the PtSi tip. To implement the ML scheme the tip was moved along the track in 20 nm steps. At each step the data to be recorded is used to determine whether or not a write pulse is applied. Figure 3 shows the current image and readout signal for a section of the track corresponding to approximately 29 bit cells (580 nm) for the data sequence [11001110111101110001111000111]. Also shown is the simulation of the recorded mark structure for the highlighted portion of this sequence. It is clear from both experiment and simulation that marks of varying lengths corresponding to (approximately) integer multiples of the bit cell length can indeed be recorded in this way, and, as shown in Fig. 3(a), it is possible to recover the data sequence correctly by setting an appropriate threshold current (here 4 μA) in the "detection" process.

We now turn our attention to the potential density improvements that might be achieved using a ML write strategy. A simplistic interpretation of the results of Fig. 3 is that using the ML approach we have recorded 30 bits in 600 nm, whereas using MP recording only 10 bits could be recorded in the same distance (for a 60 nm mark), implying a $\times 3$ density increase. However, such a simplistic approach ignores the effect that run-length constraints (RLL codes) have on usable density. Indeed, for a valid comparison of density we should compare the achievable "user density" (i.e., the number of *user* bits per unit area) in ML and MP recording, taking into account the efficiency of any RLL codes required in each case. RLL codes convert user bits into *channel* bits (or more properly *symbols*), and it is these channel symbols that are transcribed to the storage medium.

Consider then a ML scheme in which two channel symbols are written per tip width (so a slightly more "pessimistic" case than in Fig. 3 where we had three channel symbols per tip width). Also let us assume that the minimum "gap" that can be discerned (on readout) between two consecutive marks is one symbol long. In this case the minimum number of consecutive zeros is one (i.e., $d_0=1$ in coding terminology) and the minimum number of consecutive ones is two ($d_1=2$). A practical code for this case is an "asymmetric-RLL" code of the form (d_0,k_0,d_1,k_1), where k is the maximum run-length. A suitable example would be a (1,7,2,7) code,[13] which has a capacity (maximum possible efficiency) of 0.7966 and for which a practical code exists with a rate (efficiency) of 0.75. Given that the symbol is half the tip width, the density gain with respect to the uncoded case (i.e., assuming one bit per tip width and no RLL constraints) is 2×0.75, or 1.5. Turning now to MP recording, let us first consider the case where (as in our previous overly simplistic comparison) we keep the symbol length equal to the tip-width. The only RLL constraint in this case is that there cannot be two ones in succession. Therefore, we have a $d_0=d_1=1$ code, which has a rate of 2/3. Since in this case the symbol length is equal to the tip width, the density is actually reduced by the factor 2/3 as compared to the uncoded case. Therefore, from this comparison, the use of ML recording would increase the user density by a factor of 2.25 $(1.5\div 2/3)$ over the MP case. However, this comparison has not used RLL coding to maximum effect in the MP case, possibly leading to an overly optimistic view of the density gain of ML recording. For example if, as above, we assume that the minimum readable "gap" between two symbols is equal to half the tip width, then it makes sense to halve the symbol-length to half the tip width in the MP case. Now a recorded mark can be used to represent *two* consecutive channel "ones" (i.e., a mark represents the channel symbols "11"). In this case the RLL constraints are $d_1=k_1=2$, and a suitable code would be (1,7,2,2) with a capacity of 0.5293. If we assume that a practical (1,7,2,2) code with a rate of 0.5 can be constructed, we then have a density "gain" for MP recording, as compared to the uncoded case, of $2\times 0.5=1$. On the basis of this more realistic comparison, ML recording increases the user density by 50% over the MP case. Such advantages of the ML scheme might be partially eroded by a decrease in readout signal amplitude, and hence SNR, at smaller bit cell sizes. However, very significant density increases are still expected by adopting ML recording in probe storage.

Another potential advantage of ML recording is that it can alleviate the requirement for very sharp tips, since the same (linear) density can be achieved in the ML approach for larger tips as compared to the MP case. Larger tips are potentially more robust than very sharp tips, and easier to fabricate. Of course the ML approach can also be used with small diameter tips, where the additional advantage of having a higher track density is also gained. Recent advances in the fabrication of robust conductive tips[10,12] promise viable contact radii in the range 10 to 20 nm. With such tip sizes user densities to 10 Tbit/in^2 and beyond are potentially achievable using a mark-length recording strategy. The use of ML recording would, however, require precise, high-resolution positioning systems, otherwise jitter in the location of mark edges would lead to increased errors. Similarly very high densities would require media with ultrasmooth surfaces, so that a reliable tip-media contact could be maintained during writing and reading.

We are grateful to Dr A Pauza (Plarion Ltd) for the GeSbTe samples, and to the EC for supporting this work via the ProTeM project No. 2005–IST-5–34719.

[1] D. Wiesmann, C. Rawlings, R. Vecchione, F. Porro, B. Gotsmann, A. Knoll, D. Pires, and U. Duerig, Nano Lett. **9**, 3171 (2009).
[2] H. Pozidis, G. Cherubini, A. Pantazi, A. Sebastian, and E. Eleftheriou, IEEE J. Sel. Areas Commun. **28**, 143 (2010).
[3] A. Jo, W. Joo, W.-H. Jin, H. Nam, and J.-K. Kim, Nat. Nanotechnol. **4**, 727 (2009).
[4] Y. Hiranaga, T. Uda, Y. Kurihashi, H. Tochishita, M. Kadota, and Y. Cho, Jpn. J. Appl. Phys. **48**, 09KA18 (2009).
[5] M. Forrester, J. W. Ahner, M. D. Bedillion, C. Bedoya, D. G. Bolten, K. Chang, G. Gersem, S. Hu, E. C. Johns, M. Nassirou, J. Palmer, A. Roelofs, M. Siegert, S. Tamaru, V. Vaithyanathan, F. Zavaliche, T. Zhao, and Y. Zhao, Nanotechnology **20**, 225501 (2009).
[6] H. Bhaskaran, A. Sebastian, A. Pauza, H. Pozidis, and M. Despont, Rev. Sci. Instrum. **80**, 083701 (2009).
[7] C. D. Wright, M. Armand, and M. M. Aziz, IEEE Trans. Nanotechnol. **5**, 50 (2006).
[8] H. Satoh, K. Sugawara, and K. Tanaka, J. Appl. Phys. **99**, 024306 (2006).
[9] R. Cannara, B. Gotsmann, A. Knoll, and U. Duerig, Nanotechnology **19**, 395305 (2008).
[10] H. Bhaskaran, B. Gotsmann, A. Sebastian, U. Drechsler, M. A. Lantz, M. Despont, P. Jaroenapibal, R. W. Carpick, Y. Chen, and K. Sridharan, Nat. Nanotechnol. **5**, 181 (2010).
[11] N. Tayebi, Y. Narui, R. J. Chen, C. P. Collier, K. P. Giapis, and Y. Zhang, Appl. Phys. Lett. **93**, 103112 (2008).
[12] H. Bhaskaran, A. Sebastian, U. Dreschsler, and M. Despont, Nanotechnology **20**, 105701 (2009).
[13] C. Menyennett, L. Botha, and H. C. Ferreira, IEEE Trans. Magn. **28**, 2901 (1992).