

Four State Magnetoresistive Random Access Memory

FIELD OF THE INVENTION

5 The present invention relates to a magnetoresistive random access memory (MRAM) having four states, and more especially to the MRAM having the capabilities of writing each state by one step.

BACKGROUND OF THE INVENTION

10 Recently, magnetic multilayer structures with two ferromagnetic layers separated by a conductor layer have been utilized to form MRAM which is based on the giant magnetoresistive (GMR) effect. Magnetization vectors of the two magnetic layers are employed as logical states.

15 A two-state MRAM with two logical states indicated by "0" and "1" is achieved by utilizing two magnetic layers in which the magnetization vectors of the two magnetic layers point in a parallel direction under zero field. The magnetization vectors of both magnetic layers can be switched to an opposite direction when an external magnetic field is applied, one direction can be defined as a logic "0", and the
20 other direction can be defined as a logic "1".

Alternatively the magnetization vectors of a first magnetic layer is always maintained in one direction, for example pinned by exchange coupling to an anti-ferromagnetic layer, while the magnetization vectors of the second magnetic layer can be switched between parallel and anti-parallel to the magnetization vectors of the
25 first magnetic layer, representing logic "0" and "1" states. For example, a parallel direction for a logic "0" state and an anti-parallel direction for a logic "1" state.



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A prior art two state MRAM is constructed from a GMR element, a word line that writes data to the GMR and a sense line for reading the data. Typical devices are described in United States patent number US5477482 in the name of Prinz and United States patent number US5774394 in the name of Chen et al. The latter
5 description is incorporated herein by reference.

A four state MRAM is achieved by utilizing two magnetic layers with different coercivity separated by a conductor layer. The two magnetic layers with different coercivity can be obtained by using different magnetic materials or the same material with different thickness. For a four state MRAM cell, a nondestructive
10 readout (NDRO) has been described in a paper entitled "Quaternary Giant Magnetoresistance Random Access Memory" published in J. Appl. Lett. 79 (8), P.6639, (1996). A method of writing and detecting four states in a MRAM has been disclosed in U.S. Pat. No. 5,703,805 issued to Tehrani et al. However, the writing process requires multiple steps to write the anti-parallel states and is therefore
15 complex.

Accordingly, it is a purpose of the present invention to provide new and improved four state MRAM cells with the capabilities of writing each state by one step.

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SUMMARY OF THE INVENTION

The above problems of write complexity in the prior art four state MRAM are solved and the purposes of writing each state in a four state MRAM by one step are realized in new MRAM unit structures comprising a GMR memory cell with two
25 ferromagnetic layers having different coercivity which are separated by a nonmagnetic metallic conductive layer, a word line, a sensor line, and an enable line. Write operation in the MRAM cell is accomplished by using word current and sensor

current to switch the magnetization vectors of a ferromagnetic layer with small coercivity, and followed by using word current, sensor current, and enable current to switch the magnetization vectors of a ferromagnetic layer with large coercivity. No changes in current intensity in the word line, sensor line and enable line are required.

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BRIEF DESCRIPTION OF THE DRAWING

FIG 1 shows a side perspective view of a MRAM unit;

10 FIG 2 shows a schematic of the bit layout of dense arrays of MRAM unit;

FIG 3 is a cross sectional view of a first embodiment of a four state MRAM unit in accordance with the present invention;

15 FIGS 4a-4d illustrate the write operations of the MRAM unit shown in FIG 3;

FIG 5 is a cross sectional view of a second embodiment of a four state MRAM unit in accordance with the present invention;

20 FIGS 6a-6d illustrate the write operations of the MRAM unit shown in FIG 5; and

FIG 7 is a schematic view of an array of the MRAM units of FIG 5.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

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FIG 1 shows a single MRAM unit constructed in accordance with the prior art. The MRAM unit is constructed on substrates 1 which may be common to a number

of MRAM units. An electrically conductive layer forms sensor line 2 in contact with GMR memory cell 5. Insulator layer 3 separates the GMR memory cell 5 and sensor line 2 from a word line 4.

Each GMR memory cell 5 includes a first magnetic layer 6, a nonmagnetic
5 metallic conducting layer 7, and a second magnetic layer 8. The GMR memory cell 5 is rectangular with a width W and a length L , where W is smaller than the width of the magnetic domain walls of layers 6 and 8, L is much larger than W , therefore magnetization vectors of magnetic layers 6 and 8 prefer to align along the length L direction (longitudinal direction). For the four state MRAM cell shown in FIG 1, the
10 two magnetic layers 6 and 8 have different coercivity,

A number of MRAM units may be combined as shown in FIG 2 to form a bit layout for a dense array. Each GMR memory cell in the array of MRAM units is addressable, as will be well known to persons skilled in the art.

In order to write anti-parallel states in the MRAM of FIG 1, a two step
15 operation must be employed. In the first step, large magnetic fields produced by a sensor current flowing in the sensor line 2 and a word current flowing in word line 4 are utilized simultaneously to write the magnetization vectors of the high coercivity layer to a desired direction. At this step, the magnetization vectors of the small coercivity layer inevitably point to the same direction as that of the magnetization
20 vectors of the high coercivity layer. In the second step, a small magnetic field is utilized to switch the magnetization vectors of the small coercivity layer to an opposite direction without switching the magnetization vectors of the high coercivity layer.

The change of magnetic field direction in a MRAM is achieved by changing
25 the direction of the word current. The change of strength of the magnetic field is achieved by changing the magnitude of the word or sensor current. The above mentioned two step operation, especially the requirement of change of current

magnitude, makes the operation of writing anti-parallel states in a four state MRAM complex.

Referring now to FIG 3, a preferred embodiment of a MRAM unit according to the principles of the present invention is illustrated. The MRAM unit comprises a
5 suitable substrate 21, such as glass, ceramic, or a semiconductor, a first electrically conductive layer forming a transverse enable line 22, a first insulator layer 23, a second electrically conductive layer forming sensor line 24 which is in electrical contact with GMR element 27, a second insulator layer 25, and a third electrically
10 conductive layer forming a word line 26. The GMR element 27 includes a bottom ferromagnetic layer 28 with small coercivity, a nonmagnetic metallic conductive layer 29, and a top ferromagnetic layer 30 with large coercivity.

As in the prior art, the GMR element 27 is rectangular with width smaller than the width of the magnetic domain walls, which results in the alignment of magnetization vectors along the length (longitudinal direction), as shown by vectors
15 31 or 31', and 32 or 32' for magnetic layers 28 and 30, respectively. The write operation is accomplished by simultaneously applying a longitudinal field and a transverse field. The longitudinal field is induced by a positive ($\oplus$) or a negative ($\otimes$) word current I_w in word line 26. The transverse field is induced by sensor current I_s which mainly flows in the nonmagnetic metallic conductive layer 29, as shown by
20 right arrow 33, (representing current flows to the right, defined as positive sensor current I_s), or enable current I_e in the first electrically conductive layer forming enable line 22, (as shown by right arrow 34, defined as positive enable current I_e), or both of them. The magnetic field produced by any of I_w , I_s or I_e alone in the region of GMR element 27 is less than the magnetic field required to change the magnetic
25 states of the magnetic layers 28 and 30. The combination of magnetic fields from I_w and I_s is sufficient to change the magnetization vectors of small coercivity layer 28, however, it is not enough to change the magnetization vectors of large coercivity

layer 30. The further combination of magnetic fields from I_w , I_s and I_e is sufficient to change the magnetization vector of large coercivity layer 30 due to a larger transverse field produced by the combination of I_s and I_e than that produced by I_s alone, and is not sufficient to change the magnetization of small coercivity layer 28 because the transverse fields in layer 28 produced by I_s and I_e are mutually canceling.

Referring now to FIGs 4a-4d, an embodiment is shown of the operations of writing four states represented by logic "00", "11", "10", and "01" in the MRAM cell shown in FIG 3. For ease of explanation, the magnetization vector of the low coercivity layer 28 is shown in the figures by arrow 28' and the magnetization vector of the high coercivity layer 30 is shown in the figures by arrow 30'.

The magnetic fields are produced by square wave current I_w in word line 26, I_s in the layer 29, and I_e in enable line 22. The positive square wave current I_w ($\oplus$) in word line 26 makes the magnetization vectors of layer 28 point to the right when positive square wave sensor current I_s is applied simultaneously, as shown in FIG 4a. On the contrary, the combination of negative square wave current I_w ($\otimes$) in word line 26 and positive square wave current I_s in layer 29 makes the magnetic vectors of layer 28 point to the left, as shown in FIG 4b. Similarly, to make the magnetization vectors of layer 30 point to the left or right can be achieved by applying positive or negative square wave current I_w while applying positive square wave currents I_s and I_e simultaneously.

The anti-parallel states "10" and "01" are generated by reversing the current I_w in word line 26 without any change in magnitude. The required square wave currents are shown in FIG 4c and FIG 4d. It will be appreciated that the current magnitude of I_w , I_s and I_e is the same for all states with only the waveform of I_w changing to write the different states. This represents a significant simplification compared to prior art four state MRAM.

It is obvious that the write operations are similar to the above write operations when both the sensor current I_s in layer 29 and the enable current I_e in enable line 22 flow to the left in FIG 3, i.e., negative square wave current.

Another embodiment of a MRAM cell according to present invention is shown in FIG 5, portions of FIG 5 that have the same reference numbers as FIG 3 are the same as the corresponding FIG 3 elements. The difference between FIG 3 and FIG 5 is that in FIG 5 the large coercivity layer 30 is at the bottom and small coercivity layer 28 is at the top, and the directions of square wave current 34 in layer 22 and square wave current 33 in layer 29 are in opposite direction (positive I_s , negative I_e). The write operations for the four states of "00", "11", "10", and "01" are shown in FIG 6a, 6b, 6c, and 6d, respectively.

The MRAM units of FIG 3 or FIG 5 can be built into an array of MRAM units by extending the substrates 21, enable lines 22, insulator layers 23, sensor lines 24, and insulator layers 25 in the lateral directions and extending the word lines 26 in the transverse directions, as shown in FIG 7. Applying square wave currents to the enable, write and sensor lines allows each GMR cell in the array to be addressed.

While the present invention has been particularly shown and described with reference to the preferred embodiments, it will be understood by those skilled in the art that various changes in form and detail may be made without departing from the spirit, and scope of the invention.

What is claimed is:

1. A four state magnetoresistive random access memory unit comprising:
a substrate;
5 a first electrically conductive layer forming an enable line adjacent the substrate;
a first insulating layer adjacent the enable line;
a four state GMR memory cell formed adjacent the first insulating layer;
a second electrically conductive layer forming a sensor line in electrical contact with
said GMR memory cell;
10 a second insulating layer adjacent said GMR memory cell and said sensor line; and
a third electrically conductive layer forming a word line adjacent the second
insulating layer.
2. The magnetoresistive random access memory unit of claim 1 wherein said
GMR memory cell includes a first ferromagnetic layer having a first coercivity, a
15 second ferromagnetic layer having a second coercivity, and an electrically
conductive layer separating said first and second ferromagnetic layers.
3. The magnetoresistive random access memory unit of claim 2 wherein the
sensor line is in electrical contact with said electrically conductive layer separating
said first and second ferromagnetic layers of said GMR memory cell.
- 20 4. The magnetoresistive random access memory unit of claim 2 wherein the
width of the GMR memory cell is less than the width of magnetic domain walls of
said first and second ferromagnetic layers so that magnetization vectors in said
ferromagnetic layers point substantially along the length of said layers.
5. The magnetoresistive random access memory unit of claim 2 wherein said first
25 ferromagnetic layer is adjacent said first insulating layer and has lower coercivity
than said second ferromagnetic layer.

6. The magnetoresistive random access memory unit of claim 2 wherein said second ferromagnetic layer is adjacent said first insulating layer and has higher coercivity than said first ferromagnetic layer.

7. The magnetoresistive random access memory unit of claim 1 wherein the
5 substrate is formed from ceramic, glass or semiconductor material.

8. In a magnetoresistive random access memory unit comprising a GMR memory cell, sensor line, enable line, and word line, a method of writing data including the steps of :

writing a magnetization state in a layer of said GMR cell having a high coercivity by

10 passing a current through said word line, said enable line and said sensor line; and

writing a magnetization state in a layer of said GMR cell having a low coercivity by passing a current through said word line and said sensor line;

wherein the current in said word line, said enable line and said sensor line act cooperatively to align the magnetization vectors with a magnetic field generated by
15 the current flowing in said word line.

9. The method of claim 8 wherein the step of writing a magnetization state to the layer having low coercivity is performed before the step of writing a magnetization state to the layer having high coercivity.

10. The method of claim 8 wherein the step of writing a magnetization state to the
20 layer having high coercivity is performed before the step of writing a magnetization state to the layer having low coercivity.

11. The method of claim 8 wherein currents passed through said sensor line and said enable line are parallel.

12. The method of claim 8 wherein currents passed through said sensor line and
25 said enable line are anti-parallel.

13. A four state MRAM unit comprising:
a four state GMR memory cell;

a word line arranged to generate a longitudinal magnetic field in said GMR memory cell when current is passed through said word line;

a sensor line arranged to generate a transverse magnetic field in said GMR memory cell when current is passed through said sensor line, such that a magnetization vector
5 in a low coercivity layer of said GMR memory cell aligns with said longitudinal magnetic field when said transverse magnetic field and said longitudinal magnetic field are present; and

an enable line arranged to generate a further transverse magnetic field in said GMR memory cell when current is passed through said enable line, such that a
10 magnetization vector in a high coercivity layer of said GMR memory cell aligns with said longitudinal magnetic field when said transverse magnetic field, said further transverse magnetic field and said longitudinal magnetic field are present.

14. The MRAM unit of claim 13 wherein said transverse magnetic field and said further transverse magnetic field are arranged to be mutually canceling in said low
15 coercivity layer and mutually enhancing in said high coercivity layer.

15. A four state memory array including a plurality of four state GMR memory cells, a plurality of word lines, a plurality of sensor lines and a plurality of enable lines, said GMR memory cells, word lines, sensor lines and enable lines being arranged to form a plurality of MRAM units, each MRAM unit comprising:

20 one of said four state GMR memory cells;

part of said word line arranged to generate a longitudinal magnetic field in said GMR memory cell when current is passed through said word line;

part of said sensor line arranged to generate a transverse magnetic field in said GMR memory cell when current is passed through said sensor line, such that a

25 magnetization vector in a low coercivity layer of said GMR memory cell aligns with said longitudinal magnetic field when said transverse magnetic field and said longitudinal magnetic field are present; and

part of said enable line arranged to generate a further transverse magnetic field in said GMR memory cell when current is passed through said enable line, such that a magnetization vector in a high coercivity layer of said GMR memory cell aligns with said longitudinal magnetic field when said transverse magnetic field, said further
5 transverse magnetic field and said longitudinal magnetic field are present.

16. The four state memory array of claim 15 wherein said word line, said sensor line and said enable line are arranged such that each said MRAM unit is individually addressable.