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Quarternary giant magnetoresistance random access memory

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We designed a quarternary memory using weakly coupled giant magnetoresistance (GMR) multilayers based on the fact that there are four stable states when the applied field is zero. Compared with conventional binary memory, the major advantage of the quarternary GMR memory is that we can simply double its capacity. This design's feasibility has been proved by experiments. © *1996 American Institute of Physics.* [S0021-8979(96)13608-1]

I. INTRODUCTION

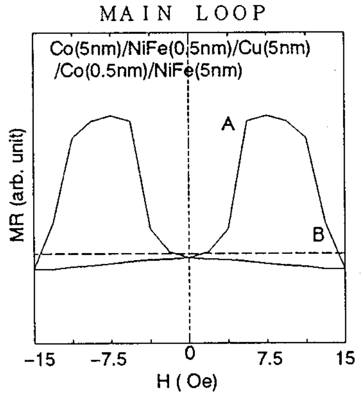
The discovery of giant magnetoresistance (GMR) in magnetic multilayers has led to a large number of studies[1–3] on the giant magnetoresistance system for application. Usually, devices exhibiting giant magnetoresistance are under consideration and development as magnetic field sensors, for instance, in read-back magnetic heads used in magnetic recording technology. Differing from these studies for sensing purposes, we found a storage mechanism in GMR materials and succeeded in fabricating a binary GMR memory.[4] Moreover, the fact that the magnetizations in two ferromagnetic layers of weakly coupled multilayer act independently makes it possible to realize a quarternary data storage by making use of the four combinations of magnetizations. The different coercivities between the two ferromagnetic layers can be just employed to magnetize or remagnetize the two layers, respectively. In this article, we will discuss the mechanism, design, and experimental results of the quarternary GMR memory.

II. QUARTERNARY STORAGE MECHANISM

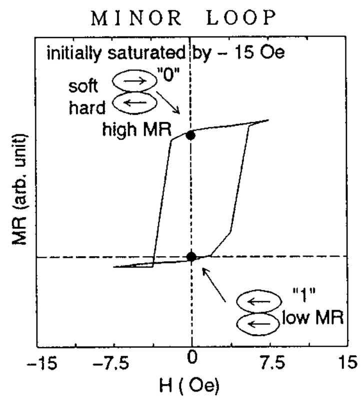
From the viewpoint of application, weakly coupled GMR multilayer,[5,6] with two ferromagnetic components possessing different coercivities, is a hopeful candidate because of its low switching field (smaller than 10 Oe) and relatively large magnetoresistance (MR) ratio (4%–17%). We made samples of Co (5 nm)/NiFe (0.5 nm)/Cu (5 nm)/Co (0.5 nm)/NiFe (5 nm) by rf sputtering. The thinner NiFe and Co layers were formed to enhance interfacial scattering, which increases the MR ratio two times as large as that of Co (5 nm)/Cu (5 nm)/NiFe (5 nm), and the sandwich structure is comprised of two ferromagnetic components: the hard component Co (5 nm)/NiFe (0.5 nm) and the soft component Co (0.5 nm)/NiFe (5 nm). Uniaxial anisotropy, important both for memory storage and for the way that a bit is selected, is induced by a magnetic field of 15.5 Oe applied in the plane of the films during sputtering. Thereafter, an ac magnetic field anneal (300 °C$\times$80 Oe$\times$2 h) was executed and it was found that the ac magnetic thermal treatment helps to increase the slope of the $R(H)$ curve.

The resistance-field transfer curves $R(H)$ of these samples under exciting field of various strength were investigated. The applied magnetic field is along the plane of the samples. The switchings of the double ferromagnetic layers with different coercivities gives rise to the ''double-hump'' shaped curve of the main loop depicted in Fig. 1(a), where the applied field is between $\pm$15 Oe. From Fig. 1(a) we can observe two obvious switching points: point A corresponds to the switching field (about 5.5 Oe) of the soft component and point B corresponds to the switching field (about 14 Oe) of the hard component. Figures 1(b) and 1(c) illustrate the $R(H)$ response's minor loop for the same sample operating in the mode in which only the soft component is switched by limiting an applied field between $\pm$7.5 Oe. In Fig. 1(b) the element is initially saturated to the ''negative'' direction by a field of $-$15 Oe, while in Fig. 1(c) it is initially saturated to the ''plus'' direction by $+$15 Oe.

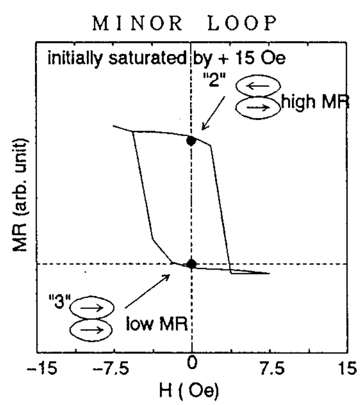
Theoretical analysis[7] indicates that the minor loop is primarily determined by the hysteresis of the soft component. But we found that these minor loops were shifted since the initially polarized hard component blocks the spins of the soft component through the ferromagnetic exchange interaction. In this case, the exchange field is about 1.5 Oe, smaller than the coercivity (4 Oe) of the soft component. So that the remanent state of the soft component cannot be influenced, although the exchange field is present. For this reason this type of GMR material is called weakly coupled. It is apparent that the soft component will act independently as long as the exchange field is smaller than its coercivity, and the lower the exchange field becomes the more stable the working point is. In fact, the exchange field will decrease with increasing Cu's thickness but, unfortunately, the MR ratio will also decrease with increasing Cu's thickness. We have to balance these two requirements and we found that for a Cu thickness of about 5 nm, the MR change ratio stays large and the exchange field is still relatively small. As a result, there are four stable states for the sample we used when the applied field is zero, which correspond to four combinations of



(a)Main loop in which the applied field is between ±15 Oe.



(b)Minor loop in which the applied field is between ±7.5 Oe but the sample is initially saturated by the field of −15 Oe.



(c)Minor loop in which the applied field is between ±7.5 Oe but the sample is initially saturated by the field of +15 Oe.

FIG. 1. Quarternary storage mechanism.

magnetizations, as shown in Fig. 1. In GMR multilayers the resistance is lower when alternate magnetizations are parallel than when they are antiparallel. This rule is also shown in the same figure.

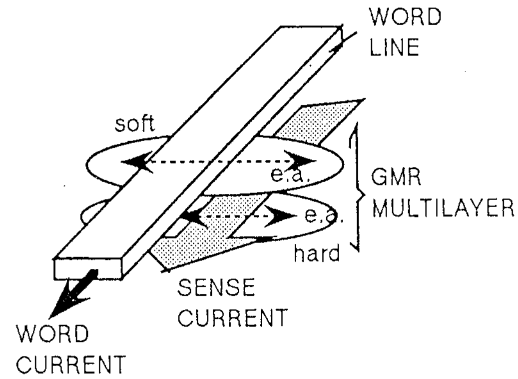


FIG. 2. Schematic diagram for quarternary memory cell.

The above description gives a quarternary storage mechanism. For any uniaxial anisotropic ferromagnetic film, there are two stable states: the magnetization will tend to point in one of two easy directions, and the fact that the magnetizations in two ferromagnetic layers act independently in weakly coupled sandwiches makes it possible to use these directions to represent a quarternary data.

III. EXPERIMENTAL RESULTS

We have fabricated a one-bit quarternary GMR memory cell with a storage/sense line and a word line on to neoceramic substrate. Its schematic diagram is illustrated in Fig. 2. A brief outline of the fabrication method is given in the following. The material of the storage/sense line was the GMR multilayer, as described in the above section. This sandwiches were patterned into a rectangular shape whose size is 5 μm$\times$10 μm by optical lithography and ion milling techniques. The storage/sense line was covered with a 0.5 μm thick SiO_2 layer, which served as an insulator, and a Cr (10 nm)/Cu (1000 nm)/Cr (30 nm) multilayer was deposited onto the SiO_2 and patterned into the word line. Contact holes were etched in the SiO_2 by a lift-off technique, followed by the structuring of electrodes for the storage/sense line. The use of the Cr/Cu/Cr structure was to make mechanically strong contacts. The word line was parallel to the storage/sense line, and both of them were orthogonal to the easy axis because the preferred easy axis is chosen to lie along the transverse direction of the GMR stripe. A combination of a sense current flowing along the GMR line itself (the sense current is assumed to pass primarily through the intermediate layer Cu because of its high conductivity), together with an exciting current flowing along the word line, make it possible for a 2D selective storage/sense function to be realized.

The different coercivities of the two ferromagnetic layers can be used to polarize the two layers, separately. In our experiments, we first use a strong magnetic field of 15 Oe to polarize the hard component whose switching field is 14 Oeand then use a weak field of 7.5 Oe to polarize the soft

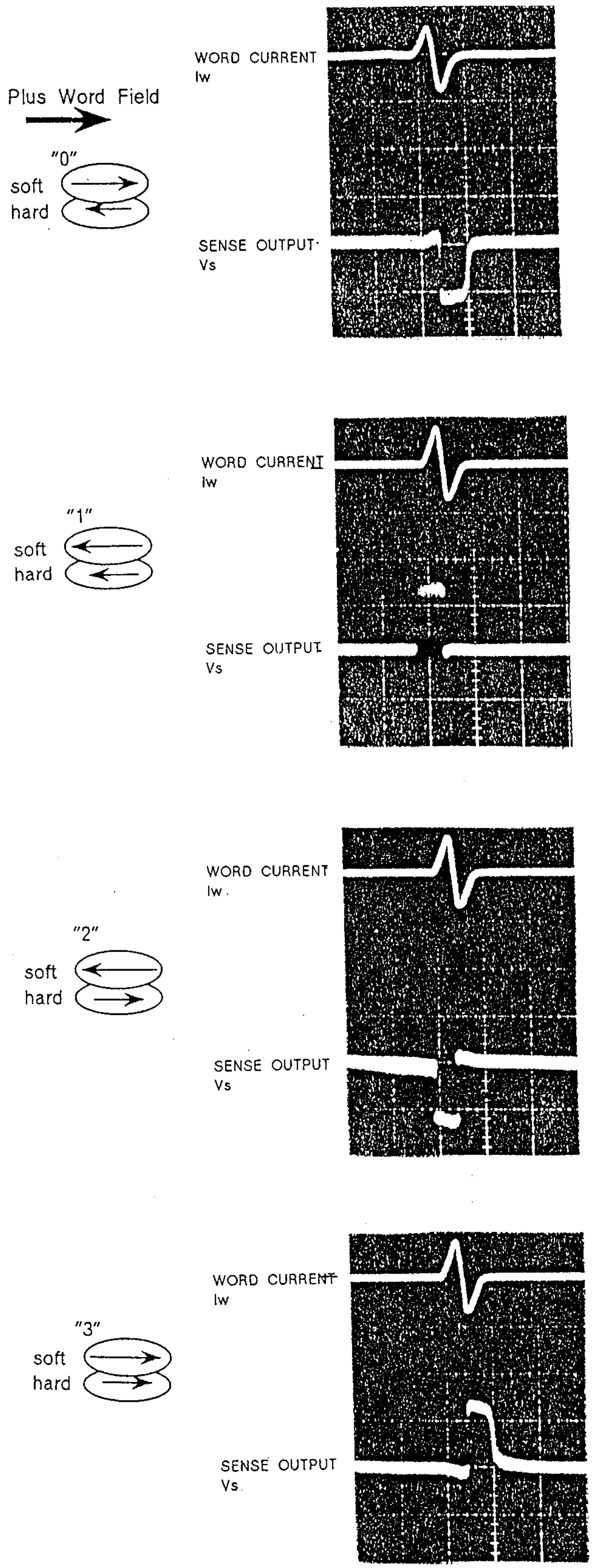


FIG. 3. Reading timing sequences. The vertical scale for sense voltage output Vs is 5 mV/div.

component. (In this mode the remanent magnetization of the hard component cannot be altered but the soft component can be switched since its switching field is about 5.5 Oe.)

For reading method, a bipolar excitation pulse current was used, and the strength of the corresponding magnetic field is limited to be smaller even than the coercivity of the soft component to confirm a nondestructive readout (NDRO) capability. It is easy to understand that the magnetization parallel to the excitation field could not rotate while the magnetization anti-parallel could. When a bipolar pulse word current Iw passes through the word line, a voltage-pulse combination should appear across the GMR line, in which a plus pulse corresponds to increasing resistance, and a minus pulse corresponds to decreasing resistance, and zero voltage corresponds to no resistance change. Figure 3 is the measured result, in which four kinds of pulse combinations corresponding to the remanent states arise, and therefore data readout can be performed by monitoring these pulse combinations against the plus–minus word current (field). The word current Iw is 15 mA and the sense current is 5 mA. The voltage difference between plus and minus pulses is 12 mV. Furthermore, the continuous test indicates that a stable readout waveform can be held for a long time. That is to say, this element has NDRO ability, and an additional rewrite operation after reading is not needed.

IV. CONCLUSIONS

We succeeded in fabricating a quarternary memory cell. In this structure, the multilayer is used not only for data storing but also for data sensing. The major advantage of the quarternary GMR memory is that we can simply double its capacity compared with conventional binary memory. NDRO capability was also confirmed.

ACKNOWLEDGMENTS

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