Perpendicular GMR Random Access Memory Using Magnetic Tunneling Effect

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Abstract

Results obtained on current-perpendicular-to-plane (CPP) giant magnetoresistance (GMR) effect show a low-field magnetoresistance change ratio as high as 30 %, superior to conventional current-in-plane (CIP) GMR effect. A storage mechanism in CPP GMR artificial lattice is also found, similar to that in CIP structure. Based on this storage mechanism, we designed an advanced perpendicular GMR random access memory (RAM). These CPP GMR elements provide an excellent means of storing information as a remanent magnetization on the hard components with high density, whereas low impedance output drivers offer extremely high signal-to-noise ratio (SNR) readout signal at low power, by suppressing such as Johnson noise from normal metal. In other words, it is expected that the problem of low SNR of signal, existing in magnetoresistance random access memory for a long term, will be solved by our scheme.

1.Introduction

The discovery of giant magnetoresistance in magnetic multilayers has led to a large number of studies^{[1] [2]} on 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 sense purpose, we found a storage mechanism in both CIP^[3] and CPP GMR materials: the small-field response's slope is dependent on its past magnetic history. It is taken for granted that we can design a binary solid state memory element based on this storage mechanism.

From a fundamental point of view, the CIP configuration suffers from several drawbacks. First, the CIP magnetoresistance is diminished by shunting and channeling. In particular, uncoupled multilayers or sandwiches with thick spacer layers^[4] suffer from this problem, whereas the switching field in such system is usually small. Moreover, diffusive surface scattering reduces the MR for sandwiches and thin multilayers. Finally, fundamental parameters of the effect, such as the relative contributions of interface and bulk spin-dependent scatterings, are difficult to obtain using the CIP geometry. Measuring with the CPP solves most of these problems, mainly because the electrons cross all magnetic layers, but a practical difficulty is encountered, the perpendicular resistance of ultrathin multilayers is too small to be measured by ordinary techniques. One of the good methods to enhance the perpendicular resistance^{[5] [6]} is introducing the magnetic tunneling effect to GMR devices. Experimental results show that a relatively large resistance (a few Ω) between two magnetic electrodes through the thin Al_2O_3 insulator can be obtained. This work attracts much attention not only from the point of view of

physics, but also from the point of application of the films as an electronic devices.

2.Storage Mechanism in Magnetic Tunneling Junction

The magnetic tunneling junction $\text{Co}/\text{Al}_2\text{O}_3/\text{80NiFe}$ was prepared by RF sputtering in a background vacuum of 2×10^{-7} Torr. The temperature of the substrates was set at 30°C by water cooling. The structure of the measurement apparatus is shown in Fig.1. First a $\text{Cr}(10 \text{ nm})/\text{Cu}(1000 \text{ nm})/\text{Cr}(30 \text{ nm})$ multilayer was sputtered onto the whole glass substrate whose size is $6 \times 6 \text{ mm}^2$ as down electrode. As regards to $\text{Cr}/\text{Cu}/\text{Cr}$ structure, the usage of Cr is to make conductor pads strong as Cu's mechanical strength is soft. Then a 100 nm thick Co layer and a 8.5 nm thick Al layer was formed on the center in the circular form with a diameter of 4.5 mm. The surface of Al was oxidized in air at room temperature for 28 hours. The Al layer below 10 nm thick would be oxidized thoroughly into Al_2O_3 . On the Al_2O_3 layer, a 100 nm thick NiFe layer was sputtered in the same circular form. Finally, a $\text{Cr}(10 \text{ nm})/\text{Cu}(1000 \text{ nm})/\text{Cr}(30 \text{ nm})$ multilayer was sputtered onto the top as upper electrode. Uniaxial anisotropy, important both for memory storage and for the way that a

Fig.1 Schematic cross section of current-perpendicular-to-plane GMR element.

bit is selected^[7], was induced by a magnetic field of 15.5 Oe applied during sputtering.

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 switching of the double ferromagnetic layers with different coercivities gives rise to the "double-hump" shaped curve depicted in Figure 2 (a), where the applied field is between ± 80 Oe.

Figure 2 (b) and (c) illustrates the $R(H)$ response for the same sample operating in the mode in which only the soft component is switched by limiting an applied field between ± 40 Oe. In Figure 2(b) the element is initially saturated to the "negative" direction by field of -80 Oe while in Figure 2(c) initially saturated to the "plus" direction by $+80$ Oe. In fact the above description gave a storage mechanism: the small-field response's slope is dependent on its past magnetic history. That is to say, after being magnetically polarized to negative direction the response's slope will be plus whereas after being polarized to plus direction the slope will be minus. In CIP element we observed the same mechanism^[3]. The magnetization in the hard component tends to point in one of two easy directions, and these directions can be used to represent a binary data. The plus slope and minus slope can be used to produce a polar signal and hence we can distinguish the stored data according to the polarity of the voltage response. This was proved to be true by the experiments. That is to say, in a GMR memory cell, the GMR materials is used not only for reading but also for storage. With such a compact structure, complex and time-consuming fabricating processes, for example fabrication of semiconductor memories, are no longer needed.

3. Two Schemes for Perpendicular GMR RAM

As a comparison, the configuration of GMR RAM using CIP elements is illustrated in Fig.3. For one bit, this mode requires just a GMR storage/sense line with shorting bars between memory elements and a word line, orthogonal to each other. Appropriate selection of fields leads to a method of writing a particular bit in a two-dimensional (2D) array where neither the easy direction field (with selected value) nor the hard direction field (with selected value) by themselves are able to switch the material, but the two in combination will. The above memory mode, which uses 2D selection for writing, also provides a possibility of 2D nondestructive read out (NDRO). NDRO can be achieved by applying a field below the hard layer's threshold with the word line^[3].

However a severe practical problem is encountered: $N \times N$ ultra-dense GMR RAM will probably be limited by the signal-to-noise ratio. At this limit, the noise

(a) Main loop in which the applied field is between ± 80 Oe.

(b) Minor loop in which the applied field is between ± 40 Oe but the sample is initially saturated by the field of $- 80$ Oe.

(c) Minor loop in which the applied field is between ± 40 Oe but the sample is initially saturated by the field of $+ 80$ Oe.

Fig.2 Measured magnetoresistance vs. field responses.

Fig.3 Configuration of current-in-plane GMR random access memory.

generated by a storage/sense line can be determined from the real part of the line impedance. Johnson noise (often called thermal noise) [8] is associated with all lossy mechanisms that can be modeled as linear resistors. The common way for dealing with Johnson noise is to represent a noisy resistor R in thermal equilibrium at absolute temperature T by a noiseless resistor of the same value in series with a noise voltage generator with value:

$$\text{noise} = (4 k_B T R B)^{1/2} = (4 k_B T N r B)^{1/2} \quad (1)$$

where k_B is Boltzmann's constant, $1.38 \times 10^{-23} \text{ J/K}$, B is the bandwidth in Hertz, r is the resistance of one cell. Hence the greater the resistance becomes, the greater the Johnson noise.

On the other hand, the effective signal is given by

$$\text{signal} = d I_{\max} (\Delta \rho / \rho) r \quad (2)$$

where d is a factor depending on the mode of stored data, $I_{\max}$ is the maximum current allowed by the sense line. Contrary to the requirement to reduce noise, for a given magnetoresistance change ratio $\Delta \rho / \rho$, we have to increase r in order to increase signal. The SNR is given by

$$\text{SNR}_{\text{CIP}} = \text{signal} / \text{noise} = \frac{d I_{\max} (\Delta \rho / \rho) r^{1/2}}{(4 k_B T N B)^{1/2}} \quad (3)$$

From the above formula we found that SNR in the CIP GMR RAM is very low since N is usually a large number.

For CPP GMR RAM, we designed two schemes. One is 2D configuration, in which both of the array of current-perpendicular-to-plane magnetic tunneling junctions and lead lines locate on one plane of the substrate, as shown in Fig.4. Its fabrication process will be similar to that of the measurement apparatus in Fig.1 we described above. In this configuration those lead lines orthogonal to each other just provide a 2D selective writing method, similar to the CIP case. The other is 3D configuration, shown in Fig.5. This method

is proposed to suit the needs of so-called electrochemical method [9] [10]. Those CPP GMR columns will be electrodeposited onto a porous membrane with an ultra-high density of $10^9 \sim 10^{11} \text{ bits/cm}^2$. Those X, Y lead lines will be distributed on the top and bottom planes of that membrane, respectively.

Fig.4 2D configuration of perpendicular GMR random access memory.

Fig.5 3D configuration of perpendicular GMR random access memory.

The sensing methods are same for these two configurations. Let's discuss this important problem according to Fig.6, in which the resistances of all the lead lines are assumed to be zero. This assumption should be acceptable because the tunneling junction's resistance will be much larger than these lead lines's. Instead of conventional constant current driving method, we propose a constant voltage driving method. The main advantage of this driving method is to avoid ambient flowing of sense current. Although there are countless possible circumstantial circuit in that array, the sense current will flow along dotted paths drawn in the same figure because of the symmetry of the potentials of each contact point along X direction. By the way, this is a collective readout since all the cells in the selected X line will give their outputs simultaneously. We deduce the output signal as following:

$$V_0 = \frac{R'}{R' + r} V_R \quad (4)$$

where V_R is the driving voltage applied to selected X line, R' is the sensing resistor, r is the memory cell resistance. Differentiating both sides, we get

$$\Delta V_0 = \frac{V_R R'}{(R' + r)^2} \Delta r \quad (5)$$

Fig.6. Readout method of perpendicular GMR random access memory.

It is easy to prove that when the resistance R' of the sensing resistor is equal to the resistance r of each cell the output voltage achieves its maximum value. Therefore

$$\text{signal} = d V_0 = \frac{d V_R}{4} \left(\frac{\Delta r}{r} \right) \quad (6)$$

Similarly, Johnson noise in this case can be given by

$$\text{noise} = (4 k_B T R B)^{1/2} = (2 k_B T r B)^{1/2} \quad (7)$$

Thus, SNR in the CPP case results in

$$\text{SNR}_{\text{CPP}} = \text{signal} / \text{noise} = \frac{d V_R (\Delta \rho / \rho)}{4 (2 k_B T r B)^{1/2}} \quad (8)$$

Obviously, V_R and $I_{\text{max}} r$ are in the same order. Because SNR_{CPP} is regardless of enormous N , we have the following relationship:

$$\text{SNR}_{\text{CPP}} \gg \text{SNR}_{\text{CP}} \quad (9)$$

The theoretical analysis has confirmed the large SNR for the CPP configuration.

4. Conclusions

The experiment confirmed that there is a storage mechanism in current-perpendicular-to-plane giant magnetoresistance tunneling junction. Based on this mechanism, a perpendicular GMR random access memory with extremely high signal-to-noise is designed. These facts seem to speed up the pace of the practical application of GMR memory.

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