The Transpinnor: An Active Spin-Based Device*

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Abstract We report the operation at room temperature of an all-metal, active device based on electron spin, which we call the transpinnor[1,2]. A transpinnor is a bridge of four electrically connected GMR (giant magnetoresistive) films whose resistance is controlled by the magnetic field from the current in one or more input striplines electrically isolated from the GMR films. The GMR elements are also connected to power terminals. When the transpinnor is resistively balanced its output remains zero even with power applied to it. A current in an input stripline unbalances the bridge and produces an output that depends on the power current. Transpinnors can be used as selection-matrix elements for magnetic memories, for logic elements of all kinds (e.g., AND, OR, XOR, NAND, NOT), for amplifiers, differential amplifiers, and magnetometers. Experimental results on integrated transpinnors will be presented, demonstrating its utility for logic, analog circuits, and amplification. We have also simulated the function and performance of various small-scale-integration (SSI) logic elements, based on measured GMR film properties. The aim was to verify functionality for a representative set of the SSI elements and to characterize all properties needed to design systems. Simulation results established that transpinnor logic gates are suitable as building blocks in large systems. The all-metal aspect of the transpinnor is unique. Unlike the mixed-technology systems that implement spin-based logic using both semiconductors and ferromagnets, transpinnor-based circuits are fabricated using only metal depositions on a monolithic chip; mixed technology requires fabricating semiconductor and magnetic elements on the same chip. All-metal devices have significant cost, design, manufacturing, and performance advantages over mixed ferromagnetic/semiconductor systems: higher performance, lower power, low costs, inherent radiation hardness; the number of masking steps in all-metal magnetic-RAM processing is about one-third that in its mixed-technology counterpart. Transpinnors have been used to design a number of different all-metal logic gates and circuits, as well as amplifiers and selection circuitry for a 1 Mbit all-metal (support circuitry as well as memory array) magnetic RAM presently being fabricated.

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1. INTRODUCTION

A transpinnor is a bridge of four giant magnetoresistive (GMR) films, to which a field is applied via one or more input striplines electrically isolated from the films. A GMR film contains layers of magnetic films separated from each other by layers of nonmagnetic conductors; e.g. one or more periods consisting of permalloy separated from cobalt by copper. When the permalloy and cobalt are magnetized parallel to each other, the resistance is low; when magnetized anti-parallel, the resistance is high. Figure 1 shows the resistance vs. applied magnetic field of such a film. At high fields, both cobalt and permalloy layers are saturated parallel to the field. As the field is reduced to zero and increased in the opposite direction, the permalloy reverses and the resistance goes up. If the field is increased further in the negative direction, the cobalt also switches and the resistance decreases. If, instead, the field is reduced to zero again, and then increased in the original direction, the permalloy switches back to its original direction, and the resistance falls. Films like this are used for making transpinnors. Other compositions are reported in references 3-5

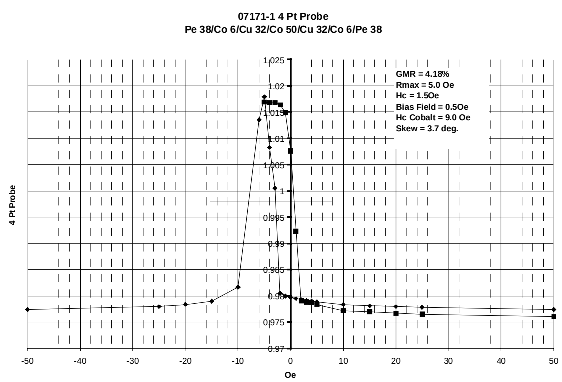

Figure 1: R-H curve of typical film used for transpinnors. Composition is given above.

Transpinnors can be used as selection-matrix elements for magnetic memories, for logic elements of all kinds (e.g., AND, OR, XOR, NAND, NOT), for amplifiers, differential amplifiers, A-D converters and magnetometers.

2. TRANSPINNORS

Figure 2 shows an example of a single-input transpinnor. There are four GMR resistors that form a bridge. Power current flows into R_1 and R_4. The current from R_1 flows into R_2, and the current from R_4 flows into R_3. One output terminal is the connection between R_1 and R_2. The other is between R_4 and R_3. If $R_1/R_2 = R_4/R_3$, the bridge is balanced and there is no output. If a current in the field-current line switches the permalloy in two of the GMR resistors, so that the bridge is no longer balanced, there is an output. Transpinnors can be made very small or, if a large output is desired, large.

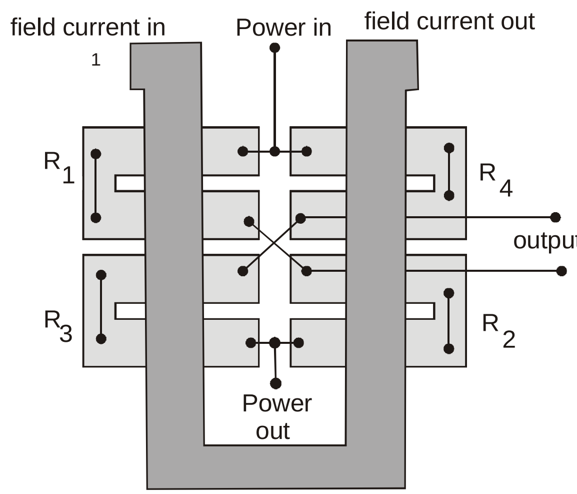

Figure 2: A single-input transpinnor. There are four GMR films (light gray) and a field-current stripline (dark gray) that is insulated from the GMR film.

The output of the transpinnor depends on the size of the transpinnor, the magnitude of power current flowing through the GMR resistors, and the current in the input stripline. Figure 3a shows the output response vs. input current for a large integrated transpinnor amplifier at small drive. The GMR resistors are 80 µm wide and ~ 32 sq long (each) with resistance of 160 ohms. The input stripline is 20 microns wide. Figure 3b shows the output of the same transpinnor at large drive and large power current. Figure 3c shows the peak output as a function of power current. The output increases linearly as a function of power current.

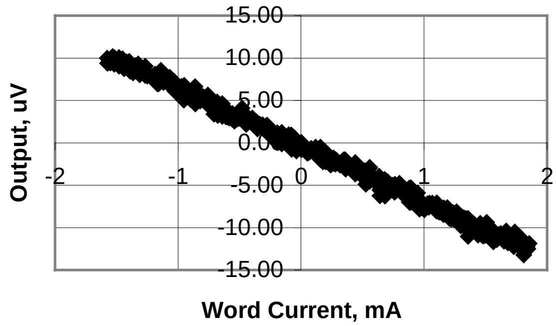

Figure 3a: Output of a transpinnor at low drives (see text). The power current is 5 mA. The output is linear and small in magnitude.

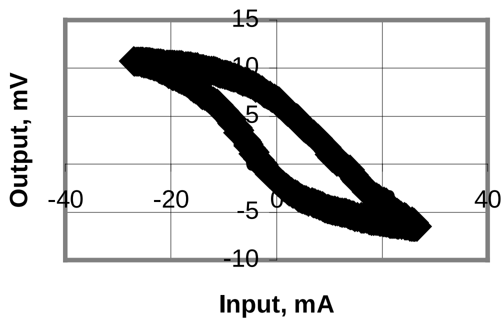

Figure 3b: Output of a transpinnor (see text) at high drive and power input (48 mA). The output has hysteresis.

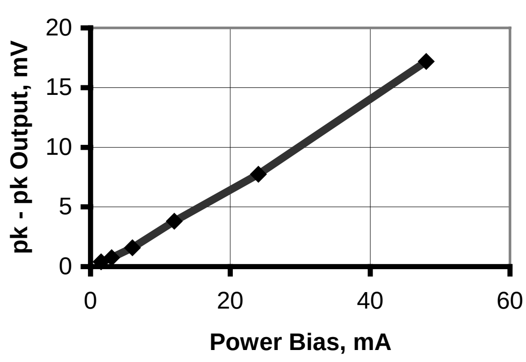

Figure 3c: The output of the transpinnor of 3a and 3b increases with the magnitude of the power current.

The output of the transpinnor of figure 2 can be calculated as follows. Consider first the case where all four GMR resistors are of identical dimensions. Then when all resistors are saturated and have a resistance R, the bridge is balanced and there is no output. When R1 and R3 have their permalloy reversed, their resistance is R(1+gmr) where gmr is the decimal value of the GMR effect. Let i_0 be the total power current. Let there be a resistor of magnitude r across the terminals of the output leads, and let the output current be δi. It can then be shown, using Kirchoff's laws, that

$$\delta i = gmr\ i_0/\{2(1+r/R+gmr/2)\} \qquad (1$$

In this case the output can be either positive or negative, depending on whether the input current reverses the permalloy on R_1 and R_3 or on R_2 and R_4.

Consider next the case where the GMR resistors are not equal in size, but are such that the output is zero when R_2 and R_4 have their permalloy reversed. Then, when an input current saturates R_2 and R_4 and reverses the permalloy on R_1 and R_3 the output becomes double that of equation 1.

$$\delta i = gmr\ i_0/(1+r/R+gmr/2) \qquad (2$$

Note that the output is unipolar if the polarity of the power current is unchanged, but the sign of the output does change if the polarity of the power current is reversed.

This shows the importance of high GMR values and the importance of obtaining high power currents through use of thick lattice GMR stacks and wide GMR resistors.

If the transpinnor is to be used for switching another identical transpinnor, low coercivity is desired. The figure of merit is the product of the thickness, the value of gmr, and the inverse of the coercivity.

3. LOGIC ELEMENTS

Transpinnors can be used for logic elements, amplifiers, differential amplifiers, and selection matrices. The single-input-line transpinnor of figure 2 can be used as an AND gate for the word or digit selection matrix for a GMR random access memory. If power current alone, with no field current, is applied, the bridge is balanced and the output is zero. If field current is applied with no power current, there is no output. Thus if one has a 32x32 matrix of such gates, one can apply current to one row and one column, and get output from only one of the 1024 transpinnors.

Transpinnors can be built with two field-current input lines instead of one. This is illustrated in figure 4.

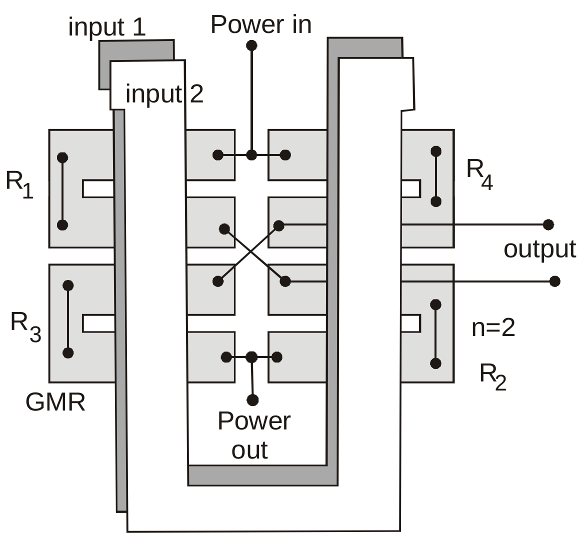

Figure 4: A transpinnor with two field-current input lines, insulated from each other and from the GMR resistors.

In order to make an OR gate, one adjusts the parameters so that a logic-level signal on either input is sufficient to switch the permalloy and cause a "1" output.

In order to make an XOR gate, one chooses the GMR film so that a signal on either the first input line or the second input line is sufficient to switch the permalloy and cause an output, but signals on both lines at once cause the cobalt layer to switch, resulting in a balanced bridge and zero output. The gate then has to be reset.

4. AMPLIFICATION

One would like to have an amplification factor of better than 1 in order to have a series of logic gates, each switchable by the previous gate.

It is desirable to have a mathematical expression for the gain of a transpinnor that takes into account the electromigration limit of the GMR and the width, length and thickness of the GMR layer and the field-input layer. It is also desirable to have a formula that specifies the design parameters required to construct the highest-gain transpinnor.

It is possible to adjust the resistance of the field input by changing the number of turns of the copper field coil. The maximum current gain is shown to occur when the resistance of the field coil equals the resistance of each of the four GMR resistors in the bridge. The transpinnor is found to have maximum gain when both the GMR film and field-coil films are as thick as possible, the gmr value is as high as possible, and the coercivity of the permalloy layer is as small as possible. An expression is derived for current amplification. The number of transpinnors that can be simultaneously switched by an identical transpinnor is equal to the square of the current amplification. For typical parameters, this fanout is 16.

The transpinnor that is to be optimized is shown in figure 4. It has a GMR film (light gray) with N_g bars per resistor (2 bars per resistor are shown), and a copper layer (dark gray) with N_c turns (three turns are shown). The width of a GMR bar is W_g, and of a copper line is W_c. These parameters are shown in figure 5.

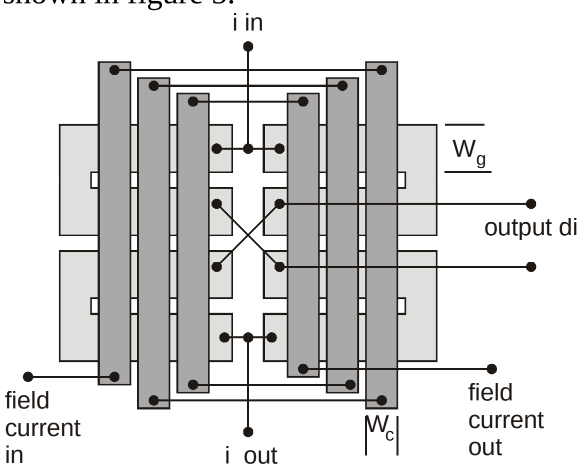

Figure 5: Illustration of a transpinnor showing parameters used in calculation.

Let the current into the GMR bridge be i. Roughly half the current goes in the right leg and half in the left leg. Let the current in the copper field coil be δi. If the transpinnor has unity current gain and is able to switch another identical transpinnor, the field current equals the output current δi and must be equal to or larger than the coercive field Hc.

The magnetic field H produced by a current δi in the copper field line can be shown, using Maxwell's equations, to be given by equation 3a if there is no keeper on top, or by equation 3b if there is a keeper deposited on top of the copper:

$$H = 2 \pi \delta i / W_c \quad (3a$$

$$H = 4 \pi \delta i / W_c \quad (3b$$

The output of a transpinnor with four resistors R into a load r is, from equation 2 (ignoring second order terms),

$$\delta i = gmr\, i / (1 + r/R) \quad (4a$$

which creates a field

$$H = 4 \pi\, gmr\, i / [(1 + r/R) W_c] \quad (4b$$

The output of the transpinnor is proportional to the power current. However the allowed power current is limited by the electromigration limit β for GMR films. This is much larger than for aluminum. The maximum i is proportional to the line width and thickness, so that:

$$i = \beta\, T_g\, W_g \quad (5$$

Expressions for the Resistance of Field and GMR Lines

In example 1 we found that the copper field line should be narrow so a given current would produce more field. However, the resistance of the line increases quadratically, because the resistance per unit length of a line is inversely proportional to the width, and because to cover the same area the number of turns must increase, which increases the length of the line. Let ρ_c be the resistivity of the copper, T_c the thickness of the copper, n_g the number of bars per resistor, and λ the length of each bar. There are four resistors in a transpinnor. Then

$$r = c / W_c^2 \quad (6$$

where

$$c = \rho_c W_g n_g 4 \lambda / T_c \quad (7$$

and similarly

$$R = \rho_g n_g \lambda / (W_g T_g) \quad (8$$

Finding the proper resistances to maximize the gain: General Case

If one inverts equation 6 to solve for W_c and substitutes that into equation 4b, the result is

$$H = 4 \pi \text{ gmr } i (r/c)^{1/2}/(1 + r/R) \quad (9$$

We leave R fixed and adjust r (by varying the number of turns) to maximize H with respect to r. The result gives

$$0 = ½ - (r/R)/(1 + r/R)$$

which is satisfied for

$$r=R \quad (10$$

General Formula

If one starts with expression 4b and substitutes equations 5 and 10 one finds

$$H = 4 \pi \text{ gmr } \beta T_g W_g/[2W_c] \quad (11$$

One can find an expression for W_g/W_c by substituting equations 6 and 8 into equation 10:

$$W_g/W_c = (1/2)[\rho_g T_c /(\rho_c T_g)]^{1/2} \quad (12)$$

Substitution of 12 into 11 yields

$$H=\beta \pi \text{ gmr } T_g^{1/2} T_c^{1/2} [\rho_g /\rho_c]^{1/2} > Hc \quad (13$$

Substitution of typical values (gmr = 0.05, T_g = 20 nm, T_c = 900 nm, $\rho_g /\rho_c = 4$) yields H = 8.5 Oe, which is greater than the typical values of Hc of one or two Oe. The amplification is H/Hc, or between four and eight depending on whether Hc is 2 Oe or 1 Oe.

Branching Logic and Fanout

It is highly desirable to have one transpinnor drive a number of other identical transpinnors. How many other transpinnors can be switched if the current amplification is four? The answer is the square of the amplification. If the amplification is four, than 16 transpinnors can be switched by one transpinnor. Connect the 16 transpinnors to be switched in a 4x4 series-parallel arrangement, i.e. in a square four resistors on a side. The total resistance is the same as that of one resistor, so the total current output is the same as if only one transpinnor were being switched, and the total current is also the same. However the current is being put through four parallel rows, so each row gets one fourth of the total output.

5. MEMORY APPLICATIONS

An immediate application of transpinnors is for a nonvolatile NDRO SpinRAM (all-metal) chip. Transpinnors are radiation hard and ideally suited for nonvolatile memory applications. Another advantage is that the number of mask levels and fabrication steps is far less than for a magnetic RAM in which the selection electronics and the sense amplifiers are made of semiconductors. The all-metal design uses transpinnors instead of transistors to perform the logic functions. The design for a 1 Mbit SpinRAM includes roughly 2000 OR gates for word and digit selection and 64 differential sense amplifiers with multiple OR inputs. The design allows 64 bits to be written at once and 64 bits to be read out at once. The memory is coincident current, NDRO and nonvolatile. The layout for a 1 Mbit chip is given in figure 6.

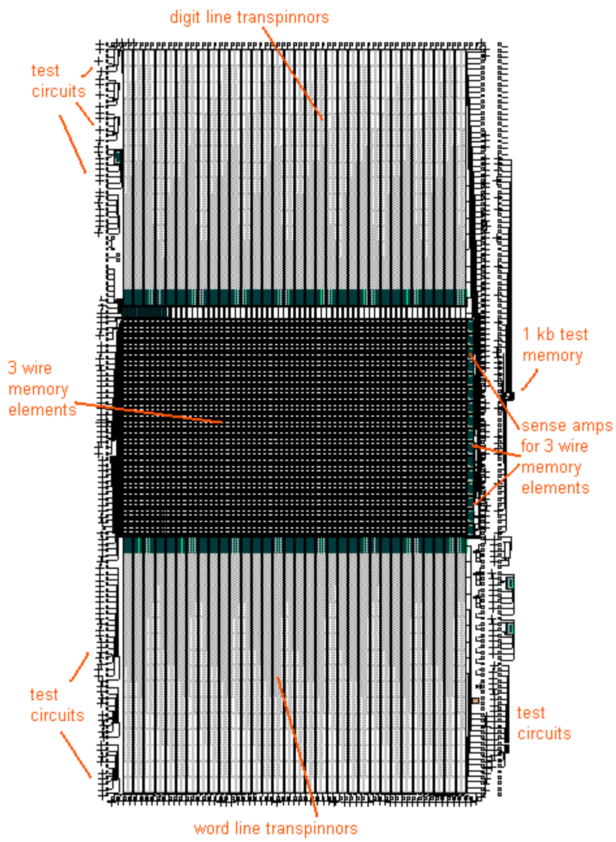

Figure 6: Layout of full megabit chip. Sense-digit selection transpinnors at top, word-selection transpinnors at bottom, memory array and sense amps in between. The chip size is 1cm x 2 cm. Pads and test circuits are around the periphery.

6. TRANSFORMERS

Transpinnors can be used as transformers. Like conventional transformers, the input is electrically isolated from the output, i.e. the resistance between input and output is infinite. Unlike conventional transformers, the transpinnor response goes down to D.C.

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