OPTIMIZED, SCALED, TOGGLE, SDT, MEMORY ELEMENTS

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Abstract--Toggle mode, SDT, memory elements with a minimum dimension of 0.09 microns have been analyzed with respect to near optimum parameter choices in a 16 megabit die. The static energy well depth required by an element was found to be 67.9 KT. For the assumed byte wide write cycle, an effective well depth of 48.0 KT must be maintained as the second pulse is applied or the first pulse is removed during ramping of the pulses; also a well depth of 49.6 KT must be maintained during the interval both write pulses are on. These requirements dictate that Hk = 132 Oe, Hcp = 858 Oe, and the drives fields (Ha1,Ha2) = 320 Oe. If Ms = 1000 emu, magnetic layer thickness is 39.5 Angstroms.

Key Words: MRAM, SDT Toggle Mode, Sub Micron Elements

INTRODUCTION

Toggle mode, SDT, memory elements [1] with a minimum dimension of 0.09 microns have been analyzed with respect to near optimum parameter choices. Because of the small element size, a key design criterion was a thermally induced error rate of 10^{-10} per hour for three mechanisms at 77 ^{o}C for an arbitrarily selected but typical 16 megabit die. (The total error rate is substantially less than the semiconductor failure rate for a high quality memory die.) The design criteria also included a 50 nanosecond read time with a read percentage of 67% or more and a 100 nanosecond maximum write time with a write percentage of 33 % or less. (Studies show that read operations occur 3 or 4 times more often than write operations [2]). The quasi static analysis shows that minimum write currents can be achieved for the design error rates if the field coupling the two layers anti-parallel (Hcp), is 6.5 times the material anisotropy constant (Hk), and the field pulses are 1.25 larger than the threshold value for pulses. The static energy well depth required by an element was found to be 67.9 KT. For the assumed byte wide write cycle, an effective well depth of 48.0 KT must be maintained as the second pulse is applied or the first pulse is removed during ramping of the pulses; also a well depth of 49.6 KT must be maintained during the interval both pulses are on.

ANALYSIS

Figure 1 depicts the round, 0.09 micron diameter free layer coupled pair examined. The separation layer is assumed thick enough so that exchange coupling is negligible.

Hk = 132 Oe

Hcp = 861 Oe

Layer Thickness

= 39.5 Angstroms

Ms = 1000 emu

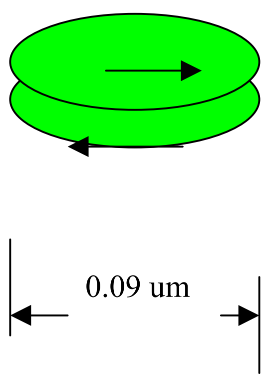

FIGURE 1. TOGGLE ELEMENT

Numerous modes in the free layer pairs are thermally agitated [3]. However, one critical mechanism for thermal error for toggle mode elements occurs when the layer pairs are thermally agitated against the material anisotropy field; all of the elements in the memory die are involved. If the maximum operating temperature is 350 degrees K, the thermal relaxation time (tr) is 10^{-9} seconds, and the chip size is 16 megabits, then the approximate required well depth for the elements in the rest state to meet the error criterion can be computed as indicated below. Note the slight dependence of well depth on chip size.

$$.5 * 10^{+9} * 1.6 * 10^{+7} * 3.6 * 10^{+3} * e^{-(Eb/KT)} = 10^{-10}, \quad Eb = 67.9\ KT \quad (1)$$

error (1/tr) bits sec./hr.

Where K is Boltzmann's constant and T is the absolute temperature.

At 350 ^{o}K , $67.9*KT = 3.28 * 10^{-12}$ ergs

To meet this requirement, the free layer sandwich, assuming a magnetic material with a saturation magnetization (Ms) of 1000 emu, would have a Hk of 132 Oe and a thickness of 39.5 Angstroms. (A Hk of 132 Oe is much larger than that used in materials for disclosed SDT elements.) The coupling field, Hcp, arising from scissoring the magnetization in the two layers is calculated with the elliptical approximation (Hcp = 3.14^2 * Ms*(thickness)/(thickness + diameter)) to be 861 Oe, very slightly larger than the minimum value needed. The coupling field is assumed to derive totally from demagnetizing fields.

In the Motorola toggle mode of writing coupled sandwich elements, two uni-polar fields (Ha1, Ha2) are applied with one pulse following and overlapping the other. The fields that the pulses generate are perpendicular to one another and are at an angle of 45 degrees with respect to the easy axis of the element as shown in Figure 2. The toggling threshold very nearly parallels the axes [1].

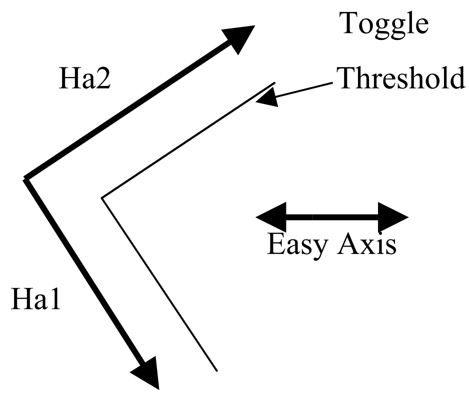

FIGURE 2. TOGGLE MODE PULSE FIELDS

Figure 3 shows the assumed timing for the pulses during the 50 nanosecond write operation when the elements are toggled. Rise times are assumed to be 1.5 to 2 nanoseconds. Small angle resonant frequency for a coupled pair is the order of 5 GHz so the toggling behavior can be considered quasi static [4].

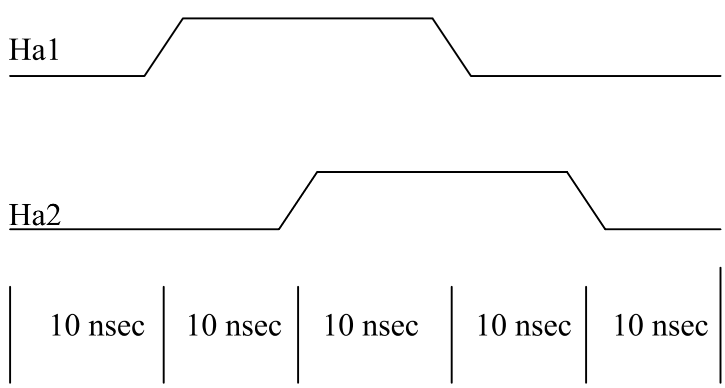

FIGURE 3. SWITCHING PULSE TIMING

In terms of the anisotropy field Hk and the much larger anti-parallel coupling field Hcp, the individual pulse fields must have an amplitude of at least the value given by the following equation to initiate toggling: Ha1, Ha2 = (Hk*(Hcp+Hk)/2)^.5 (2).

Quasi statically, as the second pulse increases in amplitude before the threshold is reached, the average direction of the magnetization in each layer rotates back toward the easy axis. If the pulse amplitudes are just below the required threshold, the final net field is along the easy axis. Consequently, the magnetization directions have returned to the easy axis and there is a 50% chance the pair will be thermally agitated to rotate in either direction. Thus if the total field just exceeds the threshold, there is a large probability the rotation will be in the wrong direction. To prevent this, the pulses must be larger than the minimum value. Assuming that fifty percent of the time for byte wide writing the bits are toggled and that the critical interval for pair rotation causing an error is 1 nanosecond, an effective well depth of 48.0 KT must be maintained during the rise of the second pulse or the fall of the first. For the 10 nanosecond interval that both pulses are applied, a well depth of 49.6 KT must be maintained to prevent layer direction reversal by scissoring to reverse positions. This dictates that Hcp = 6.5 Hk. Computation of the required well depths is similar to that of equation (1) but with a reduced number of elements and reduced trials per second being the only difference as indicated in equation (3) and (4) below.

$$.5 * 2 * 4 * .5 * 10^{+7} * 3.6 * 10^{+3} * e^{-(Eb/KT)} = 10^{-10}, \quad Eb = 48.0\ KT \quad (3)$$

$$.5 * 10 * 4 * .5 * 10^{+7} * 3.6 * 10^{+3} * e^{-(Eb/KT)} = 10^{-10}, \quad Eb = 49.6\ KT \quad (4)$$

The energy well depths for thermally induced errors were numerically evaluated by computing the equilibrium positions and energy of the magnetic layers and then computing the configuration and energy of the magnetic layers when the toggling barrier is just exceeded. Assuming a magnetic material with Ms = 1000 emu, and a layer thickness of 39.5 Angstroms, calculations show that the approximate minimum field values which will meet the three well depth requirements for the 0.09 micron diameter sample are: Hk = 132 Oe, Hcp = 6.5*Hk = 858 Oe, and Ha1 = Ha2 = 1.25*(Hk*(Hk +Hcp)/2)^.5 = 320 Oe. If materials with a lower Hk value are assumed, the thickness of the magnetic layer must be increased to meet the energy well requirement and this consequently would increase the value of Hcp above the optimum value.

The computation procedure used is indicated in the following discussion. Let the volume of a layer be indicated by (V), the clockwise rotation of the magnetization of layer 1 from the easy axis by (an1), counter clockwise rotation of layer 2 by (an2) and let a component of Ha1 and Ha2 be parallel to the rest direction of layer 1. The energy (E) of the system is given by equation (5) below. The coupled torque equations (6A,B) also were obtained from the derivatives of the energy equation.

E = Hcp*Ms*V*(sin(an1/2 + an2/2)^2 + 0.5*Hk*Ms*V*(sin(an1))^2

+ 0.5*Hk*Ms*V*(sin(an2))^2 + Ha1*Ms*V*(cos(an2+.785) – cos(.785 – an1))

+ Ha2*Ms*V*(cos(.785 – an2) – cos(an1 + .785)) (5)

Tq1 = 0 = -.5*Hk*Ms*V*sin(2*an1) - .5*Hcp*Ms*V*sin(an1 +an2)

+ Ha1*Ms*V*sin(.785 – an1) – Ha2*Ms*V*sin(.785 + an1) (6A)

Tq2 = 0 = -.5*Hk*Ms*V*sin(2*an2) - .5*Hcp*Ms*V*sin(an1 + an2)

+ Ha1*Ms*V*sin(.785 + an2) – Ha2*Ms*V*sin(.785 – an2) (6B)

By use of the torque equations, the equilibrium directions of the magnetizations were determined by iteration as the appropriate write pulses were stair-stepped on or off. The toggle threshold was reached if an1 increased beyond 1.57 radians as Ha1 was removed. To determine well depth under a variety of drive field conditions, energy calculations were repeated with an1 fixed at 0.02 radian intervals and with an2 at equilibrium.

The simulation shows that as the second 320 Oe toggle field is ramped on for the indicated parameters, the well depth diminishes from 85.1 KT to 46.2 KT as the toggle threshold is approached and then increases again to 87.7 KT. An exponential weighting of the well depth over the assumed linear two nanosecond rise time is approximately equivalent to a constant 48 KT well depth for a nanosecond interval.

Pulse fields of 320 Oe are large by conventional memory standards. Figure 4 below shows a cell geometry [1] with clad copper drive lines, 200 Angstrom overlap, and 300 Angstrom insulation that can provide the required write fields at acceptable current density levels.

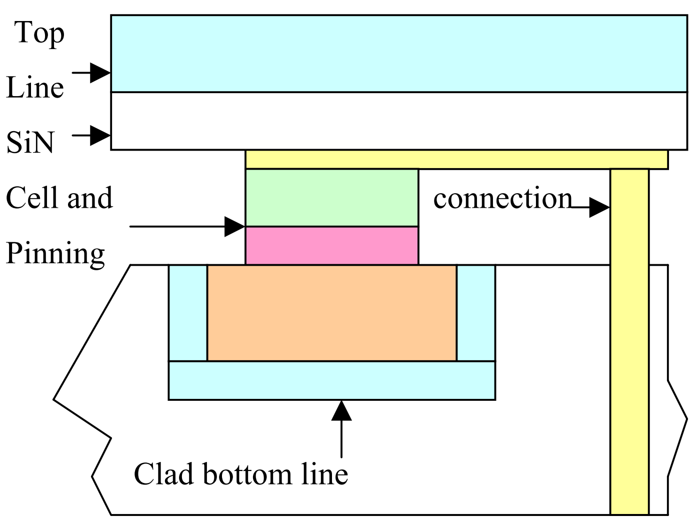

FIGURE 4. CELL GEOMETRY

To achieve the 320 Oe design fields, the top conductor requires a current of about 5.6 mA and the bottom conductor requires a current of about 4.9 mA. Each line is capable of spanning five hundred or a thousand elements.

SUMMARY

An analysis was performed on round, SDT, toggle mode, memory elements with a diameter of 0.09 microns in a 16 megabit memory. The quasi static analysis showed that minimum write currents can be achieved for the design error rate of $3*10^{-10}$/hr if the field coupling the two layers anti-parallel, Hcp, is 6.5 times the material anisotropy constant Hk, and that the write pulses are 1.25 larger than the threshold value for the pulses. The static energy well depth required by an element was found to be 67.9 KT. For the assumed byte wide write cycle, an effective well depth of 48.0 KT must be maintained as the second pulse is applied or as the first is removed as they are ramped up or down; also a well depth of 49.6 KT must be maintained during the interval both pulses are on. The approximate minimum field values which will meet these three requirements for the 0.09 micron diameter sample are: Hk = 132 Oe, Hcp = 6.5*Hk = 858 Oe, and Ha1 = Ha2 = 1.25*(Hk*(Hk +Hcp)/2)^.5 = 320 Oe. A coupled storage pair with 39.5 Angstrom magnetic layers with Ms = 1000 and Hk = 132 Oe meets the stated requirements.

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