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An investigation of the switching threshold
of multilayer thin film magneto-resistive memory elements

by

Ruth I. Waite

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INTRODUCTION

Since the development of the electronic computer began, many types of memory have been investigated which can be driven and sensed electronically. With the early vacuum tube computers the requirement that a memory device have two stable states which could be detected by electronic means was sufficient. Size, power consumption and even cost were not major factors under consideration during early work.

With the advent of large-scale integration and the huge advances in semiconductor fabrication techniques which have taken place in the past several decades, however, more constraints are placed on memory systems to keep them competitive. Memory drive signals should be compatible with integrated circuit (IC) voltage and current levels, the fabrication methods should be compatible with IC fabrication, and the memory should be amenable to large batch fabrication. These three constraints serve to lower the cost of the main memory system and the necessary circuits for accessing and decoding the stored information. Additional constraints are applied in the areas of speed and reliability to make a memory scheme commercially viable. These include non-destructive readout (NDRO), random accessibility rather than sequential, non-volatility, and in some applications, radiation hardness. A requirement for minimal area memory elements is also important for the current applications of computers, particularly in the aerospace industry where weight, space, and radiation hardness are a primary consideration.

Magnetic memories are used in applications where radiation hardness is important. Magnetic thin film memories have been an ongoing area of research at Iowa State University for many years. A new thin film multilayer element in which the magneto-resistive effect is used for determining the state of the element has been developed which has very promising characteristics for a random access memory. The multilayer structure, described later, and the use of the magneto-resistive effect are both unique to the memory element under investigation.

One critical characteristic of a memory is the switching threshold. This determines the magnitude of read currents which can be applied without destroying the information contained in the storage element and is used to determine reliable operating levels for the complete memory. A study of the switching threshold of this new magnetic memory structure is the subject of this paper.

Initial tests of the memory element, performed by defining a threshold at which switching occurs in one second, and then reducing the word current to 98±0.5% of that, have shown the switching threshold of these elements to be quite sharp. At this near threshold value the word current was pulsed 10^9 times at a frequency of 2 MHz. The word current was then slowly increased until switching occurred. No output deterioration or change in the threshold was observed as a result of this procedure, indicating a very sharp threshold. Such a sharp threshold in a thin film structure, which are normally plagued by the presence of multiple domains, had not been previously reported. The multilayer structure, though much larger than a single domain particle, appeared to behave effectively as a single domain. A more carefully controlled investigation of the switching threshold was thus warranted. This investigation consisted of a computer controlled experiment in which the word current amplitude was set using a digital/analog converter and the mean time between failures was measured by pulsing the word current and monitoring the output. The threshold was defined as the magnitude of word current at which switching occurs after the application of one pulse. Behavior between 94 and 100% of this newly defined threshold was studied and is reported in this thesis.

LITERATURE REVIEW

Magnetic Computer Memories

As stated earlier, the main requirement for a computer memory device is the ability to store information. This requires two or more distinct states which can be sensed electronically. Magnetic devices are thus a natural choice for computer memories. A brief history of magnetic memories is instructive in some of the problems encountered and will be given in this section.

The earliest type of magnetic random access memory which was widely used was a ferrite core memory [1]. A single memory cell consisted of a toroid made of a ferrite material threaded into a wire mesh. Currents were passed through the wires to provide the necessary fields for switching and for sensing the state of the cell or the information contained in it. Two currents were applied to select a bit and generate a field strong enough to write information into the memory cell. To read a bit, currents of the opposite polarity were applied in the drive lines which would cause a flux change in the magnetic circuit. This flux change in turn caused a voltage across the sensing terminals, the magnitude of which was dependent on the original state of the cell.

Core memories are limited in speed since they are generally limited to a slower wall motion type of switching. It is possible to achieve a faster switching speed in an individual core cell, but the large drive currents necessary make this mode of operation unfeasible in the operation of a large memory [2].

Cores are also quite bulky compared to the amount of memory that can be placed in a small area using modern integrated circuit techniques. Cores were manufactured as small as 0.20-0.34 mm in inner and outer diameter [3]. This is an area of 91,000 μm^2. In modern semiconductor memory, the area required for one bit is on the order of tens of square microns. Speed, area and power requirements have proven to be the main limitations causing a change from core memories to other types of memories.

The speed limitations of core memory were recognized early in the course of memory development. This spurred research into the properties of magnetic thin films as a medium for information storage. Certain magnetic materials can be deposited in the presence of a magnetic field to create uniaxial anisotropy in the material. This creates the necessary condition to have two possible memory states, since the material will be magnetized along this axis with the north pole pointing in one of two directions. The switching in thin films was theoretically predicted to be very fast by coherent rotation of the magnetization.

The basic principles for the use of magnetic thin films for memory cells are quite similar to the principles of operation for a core memory. One memory cell consists of a spot of single layer magnetic material. Two conductors are deposited above the thin film spots orthogonally to each other. Current in both conductors is used to select a bit and to provide high enough field levels to write into a bit. To read the information from a cell, current is applied in one line and the flux change is sensed in the other line.

The limitations encountered in the magnetic thin film spots which kept them from being widely used as a memory technology were due to the large self-demagnetizing fields encountered. In the magnetic core memory the flux path is closed around the toroid. In a flat film, however, there is no such flux closure, resulting in an open flux path and a large self-demagnetizing field. This in turn causes the presence of multiple domains, a factor which can lead to output deterioration by creeping of the domain walls and to slower switching by wall motion at a lower value of applied field. The compromise in flat film size and shape necessary to have a small self-demagnetizing field and a large sense output proved to be the downfall of flat films [2].

Plated wire was a magnetic memory technology which sought to overcome the disadvantage of an open flux path inherent in the flat film memories. A magnetic thin film was deposited on a wire while current was allowed to pass along the wire thus creating an easy axis which wraps around the conductor. In the sensing and writing of the bit, two conductors were again used, similar to the first two schemes described. One of the conductors was the plated wire with the magnetic thin film deposited on it, and the other wrapped around several such plated wires creating a mesh of memory cells [1]. Plated wire memories were widely studied in the late '60s and a summary of developments is given by Mathias and Fedde [4]. Though the problem of the open flux path was solved by this method, creep was still a problem. Two adjacent bits of different polarity have a domain wall between them. Current applied to one bit to write to it or sense it could cause this domain wall to move. This could cause output deterioration of adjacent bits if there were not enough separation between them. Plated wire memories were developed, however, which were used in specialized applications where non-volatility and radiation hardness were important. They have also proven useful in harsh industrial environments [5].

Work on coupled films was begun in the '60s [6,7,8]. The idea here was to have a multilayer structure, using two magnetic layers separated by a conducting layer with the easy axis transverse to the long dimension of the film. This can be pictured as a planar plated wire. The flux closure is not complete as it is for plated wire but the coupling between the two layers reduces the self-demagnetizing field. Ferrite keepers were also used to improve flux closure. The magnetic films in these studies were 2000 Å thick with a separation layer between 0.6 and 8.6 μm in thickness. Some of the processing problems in producing multilayer films are described by Bertelsen [9]. Several multilayer film configurations are described in a review by Bruyère and Massenet [10]. The memory cell operation, using a sense line and a word line and sensing the change in magnetic flux, is similar to the operation of memory cells previously described. A high density experimental multilayer film memory was described by Pohm et al. which showed promising possibilities for magnetic thin film memories [11].

At this time the rapid advances made in bipolar and MOSFET memory fabrication all but halted work on magnetic main memories. Some products were manufactured for specialized applications but the heavy research thrust was in semiconductor memories [3]. Few researchers at that time continued work on flat film magnetic memories due to market considerations.

Magnetic bubble memories, with the easy axis of magnetization perpendicular to the plane of the film were first proposed by Bobeck [12]. Bubble memories are a sequential rather than random access type of memory. These were widely studied in the '70s and were limited by the saturation velocity of the bubbles' movement [13]. The bubbles are moved about in the medium by localized magnetic fields. Detection of the presence or absence of a bubble at a memory location is done using magneto-resistive sensors. Since these are sequential memories, the main competition for bubble memories came from disks. As disks improved in reliability and cost, with the additional advantage of portability from one system to another, the bubble industry nearly died out in the early '80s when three major manufacturers pulled out of the market [14,15].

A recently developed concept is the crosstie random access memory (CRAM) described by Schwee et al. [16]. Using a particular pattern of permalloy, a one or zero is defined as the presence or absence of a crosstie wall at a particular bit location. The magneto-resistive effect is used to sense the bit by allowing current to pass through the permalloy strip. The presence of a one will generate a higher voltage output than will a zero. A change in voltage at the element of 0.8 mV was predicted.

Magneto-resistive Effect

It is well known that moving charges, or currents, generate a magnetic field which wraps around the conductor according to the right hand rule. A magnetic material which has been previously magnetized also has a magnetic moment associated with it due to the direction of magnetization of the material. If this magnetic material is now used as a conductor, the magnetic field caused by the current will induce a force pushing the magnetic moment toward alignment with it. The resistance through the magnetic material takes on different values, depending on the angle between the magnetization of the film and the current through the device. This is called the magneto-resistive effect. In the memory elements being studied this effect is used to determine the orientation of the magnetization in the element, thereby determining the state as 1 or 0.

A summary of investigations on the magneto-resistive effect up to 1975 is given by McGuire and Potter [17]. A thorough analysis of the effect and its causes is also given in this paper. In the same journal Thompson et al. [18] summarizes how the magneto-resistive effect has been applied in many devices, primarily in detection circuits.

Magneto-resistive sensors have the advantage of sensing the change in magnetic flux with an output signal that is not dependent on the speed of the medium. The disadvantage of magneto-resistive sensors is the non-linearity of the output signal without biasing, and a noisy response caused by the presence of multiple domains [19]. Bogue has described a novel application for magneto-resistive sensors in detecting wear to prevent expensive breakdown of industrial machinery [20]. Experimental data of magneto-resistive output of a permalloy sandwich structure with the easy axis along the length of the structure has been reported by Berchier et al. [21]. The center layer in this report was an insulator, silicon monoxide. Use of the magneto-resistive effect for application in a random access memory has been investigated by Schwee et al. [16] and by Pohm et al. [22].

Switching Threshold

If magnetic films are deposited on the substrate in the presence of a magnetic field, this creates a predictable easy axis, which means much smaller fields are required to magnetize the film in the direction of the easy axis. This can be seen in the hysteresis curves of Figure 1. A magnetic field applied in the direction of the easy axis,

H_1, causes the material to be completely magnetized at a relatively low value of magnetic field. As the field is reversed, the material remains magnetized until the coercive force in the opposite direction, H_c, is reached. This gives the open loop appearance of the curve. A larger magnetic field, H_k, is required to completely magnetize the film in the direction of the hard axis, orthogonal to the easy axis. In this direction the film does not stay magnetized as the applied field is removed. Thus the magnetization vector tends to point parallel to the easy axis or anti-parallel to it in the absence of applied fields.

Since the memory elements are fabricated in the presence of a magnetic field creating an easy axis, much smaller fields are required to magnetize the film in the direction of the easy axis than in the transverse direction. In the sample of magnetic material shown in Figure 2 the magnetization vector **M** is first directed to the right. An external field is then applied which tries to force the magnetization in the other direction. This causes the magnetization to be diverted from the direction of the easy axis by an angle θ. As the external field is increased the angle θ also increases. At first, at the lower field levels, the natural tendency of the magnetization is to revert back to its original direction. As θ increases,

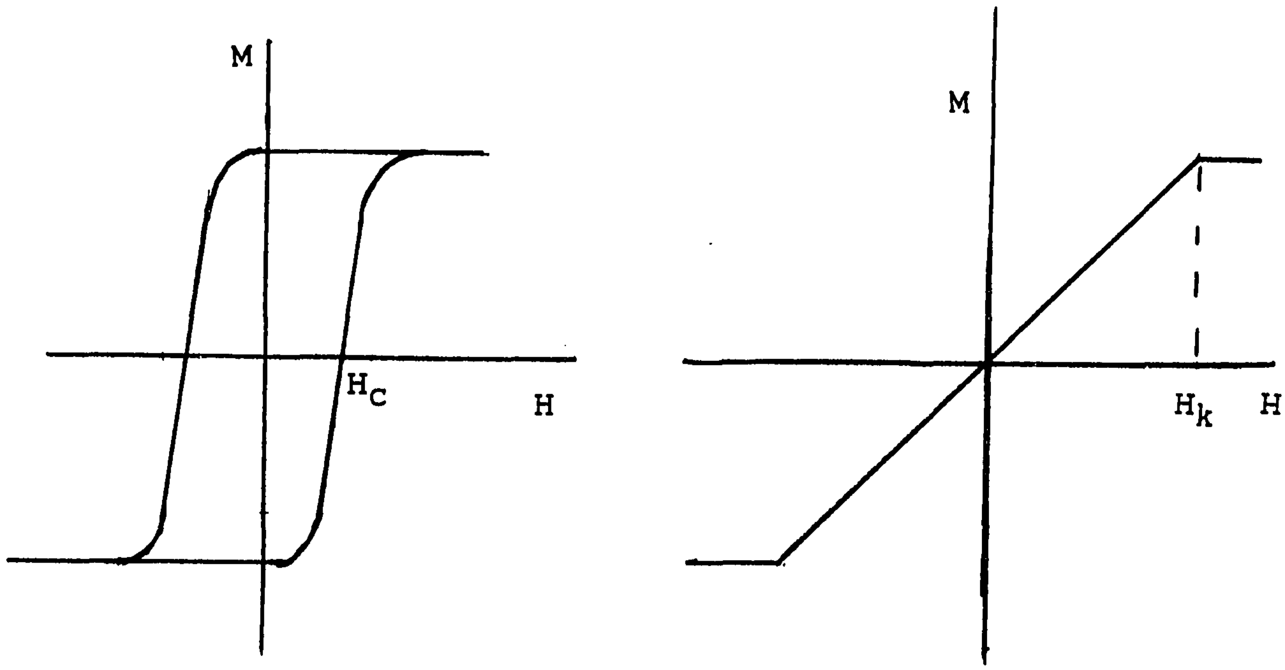

FIGURE 1. Hysteresis curves in the easy and hard directions

however, a point is reached where the magnetization tends to switch to point to the left. This behavior is governed by the minimization of the energy of magnetization. For a thin film the magnetization can be assumed to lie completely in the plane of the film. To a first approximation, the energy of magnetization for this situation is described by

$$E(\theta) = 0.5H_kM\sin^2\theta + H_lM\cos\theta - H_tM\sin\theta \quad (1)$$

Stable configurations of magnetization are those which are local minima of the energy equation. The Stoner-Wohlfarth switching threshold, which takes the anisotropy energy and potential energy due to the applied fields into account, as in equation (1), is shown in Figure 3. This threshold is described parametrically by

$$\frac{H_{lt}}{H_k} = \cos^3\theta_t \qquad \frac{H_{tt}}{H_k} = \sin^3\theta_t$$

This ideal threshold is for a sample with a single magnetic domain present. Two variables can effect a change in this threshold, the presence of multiple domains, and the energy due to thermal agitation.

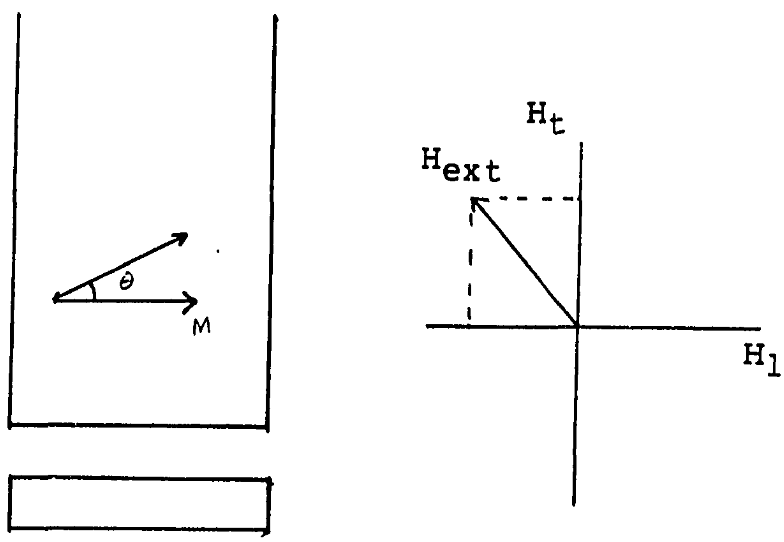

FIGURE 2. Magnetic switching example

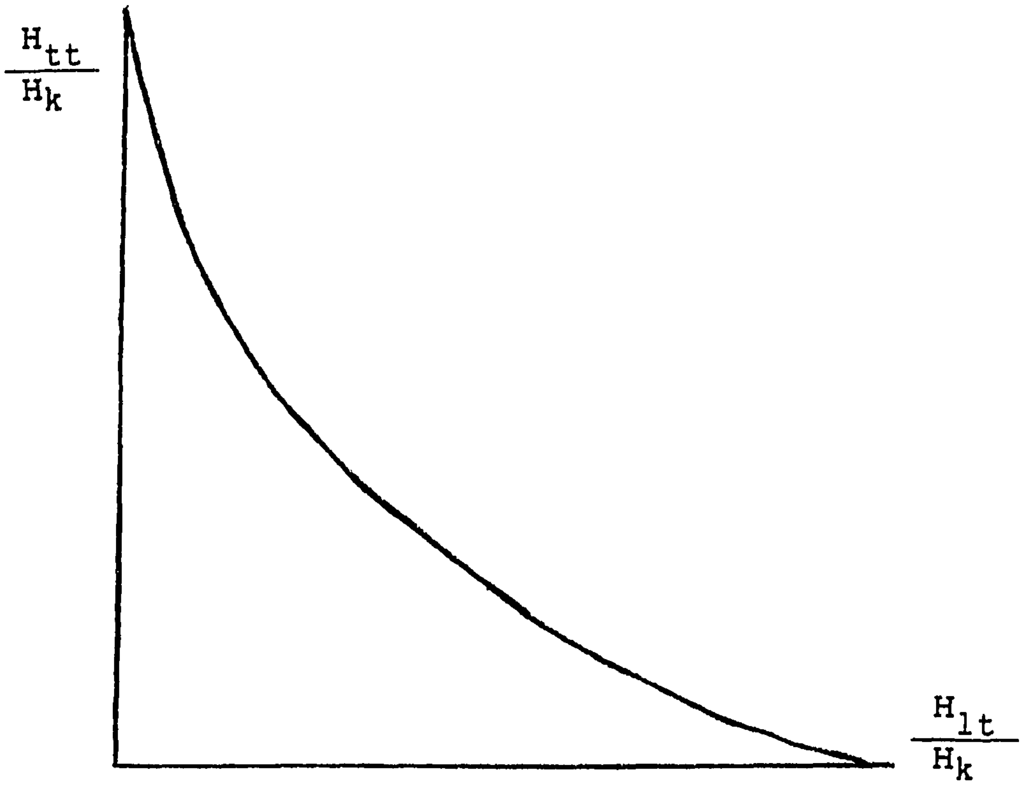

FIGURE 3. Stoner-Wohlfarth switching threshold

Using the energy equation and the threshold values of θ, H_l, and H_t, it is possible to compute the height of the energy barrier which maintains the magnetization in a stable state at given values of applied fields and the threshold angle θ_t. As an example, let H_k = 18 Oe and M = 893 ergs/Oe cm^3, typical values for the materials under consideration. If H_{lt}/H_k = 0.5 then θ_t = 37.5°. If the easy axis field is held at the threshold value, and the hard axis field is near the threshold the additional energy required to switch the magnetization can be computed. The results of such a computation are shown in Table 1. At 99% of the threshold this energy well depth corresponds to 5.5kT at 300 K for a volume of 1.6 x 10^{-13} cm^3. A plot of this same computation is shown in Figure 4. The magnetization is in a stable state at a local minimum of the energy curve. As the switching threshold is approached and the energy barrier decreases, the energy due to thermal fluctuations is great enough to cause spontaneous switching.

TABLE 1. Height of Energy Barrier

H_t/H_k	E_{min}	E_{max} energy is in Joules	E(well)
0.96	$0.8678287 \times 10^{-16}$	$0.8696577 \times 10^{-16}$	$0.1829062 \times 10^{-18}$
0.97	0.8655349	0.8667202	$0.1185317 \times 10^{-18}$
0.98	0.8631828	0.8638274	$0.6445391 \times 10^{-19}$
0.99	0.8607604	0.8609876	$0.2271107 \times 10^{-19}$

The Stoner-Wohlfarth switching threshold was modified by Comstock, Yoo, and Pohm [23] taking exchange energy and self-demagnetizing also into account for the specific device structure being tested in this experiment. The threshold obtained is shown in Figure 5. Experimental points measured for such a device are also shown.

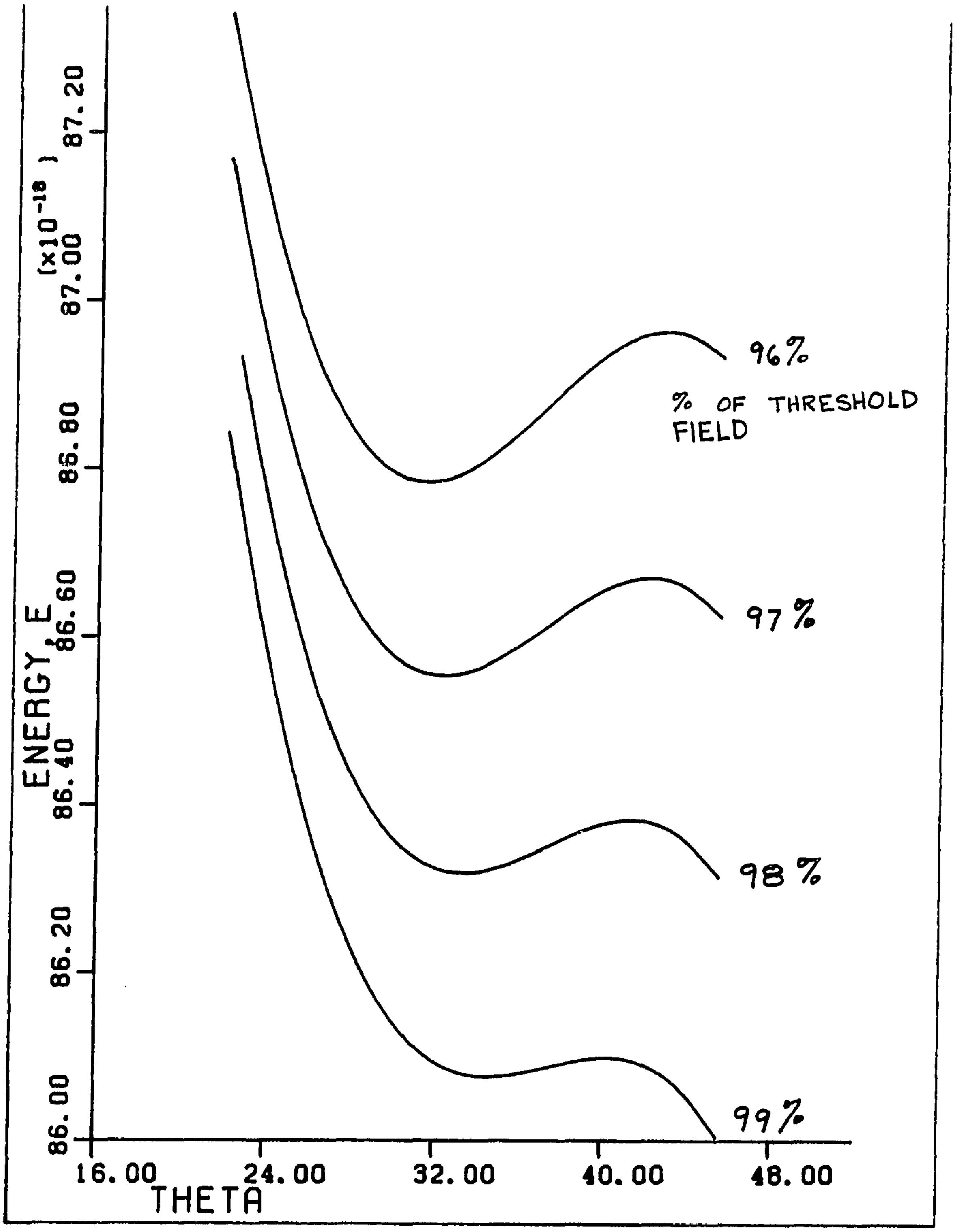

FIGURE 4. Plot of energy barrier computations using the Stoner-Wohlfarth threshold

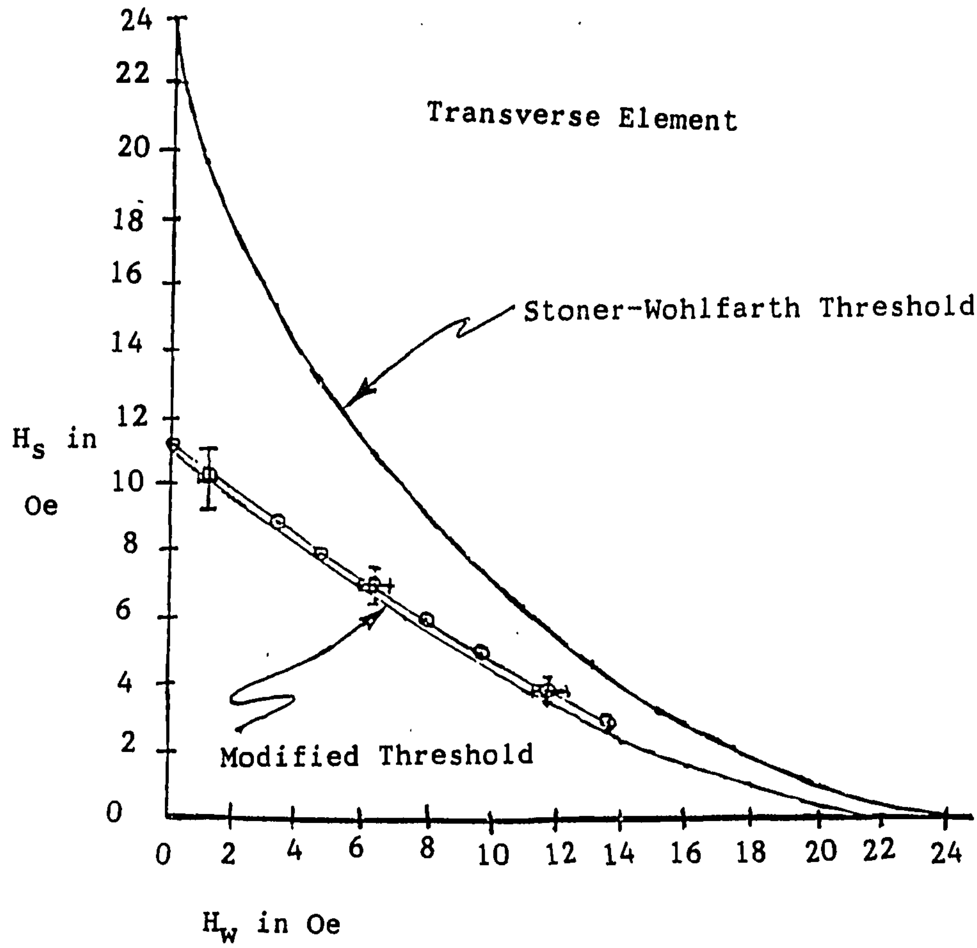

FIGURE 5. Modified Stoner-Wohlfarth threshold

The effect of thermal fluctuations on the magnetization reversal threshold has been previously investigated in two broad contexts. The first is that of spontaneous magnetization and magnetization reversal in very fine single domain particles. The second is in the investigation of magnetic aftereffect or magnetic viscosity. The idea that the energy due to thermal fluctuations could be sufficient to cause magnetization reversal was formulated in the early

1950s by Néel [24]. C. P. Bean [25] did experimental work on small single domain particles which demonstrated a phenomenon he called super-paramagnetism. For very small particles the energy barrier was so small that the magnetization responded to any applied field and was not stable. Bean and Livingston [26] estimated the size for a transition to stable behavior as that corresponding to a relaxation time of 100 seconds. This occurs when the energy barrier is about 25 kT. Bean and Jacobs [27] showed that this property could be used to measure particle sizes. They also showed that the reversal process can be thermally activated in larger particles if a reversal field is applied which is large enough to reduce the energy barrier to 25kT.

Street and Woolley [28,29] found the probability of overcoming a potential barrier E by thermal agitation to be $P = Ce^{-E/kT}$. Stacey [30] showed the factor C to be

$$\frac{\pi^2 kT}{6h\sqrt{3}}$$

where k is the Boltzmann constant, T is the temperature in Kelvin, and h is Planck's constant. Aharoni [31] estimated the energy barrier to spontaneous magnetization reversal and domain wall nucleation in a spherical particle which was too large to show super-paramagnetism. He concluded that thermal effects can be neglected except when the applied field approaches the nucleation field for magnetization reversal, thereby reducing the effective energy barrier.

The studies mentioned thus far have all dealt with small single domain particles. In bulk materials thermal effects on switching are studied under the broad context of magnetic viscosity which refers to the time delay required when a reversing field is applied to a saturated sample for the magnetization to reverse. Recent work by Gaunt [32] and by Ram, Ng, and Gaunt [33] has found the coefficient of magnetic viscosity to depend on two possible mechanisms, that of strong pinning of domain walls and weak pinning of domain walls. In thin films the presence of multiple domains and large demagnetizing fields has in general hindered efforts to study thermal effects on the magnetization reversal threshold.

Creep and Wall Motion Thresholds

The instability due to thermal fluctuations is usually not the primary factor in determining the realizable switching threshold. Most samples of magnetic materials have some domains which are not aligned with the easy axis, especially near the edges of a sample. If multiple domains already exist, a smaller applied field is necessary to cause them to grow than that required to switch the magnetization direction by coherent rotation. This is switching by wall motion and is a slower switching mode, as demonstrated by Olson and Pohm [34].

Another variation in the attainable switching threshold is the creep threshold, also caused by the presence of multiple domains. An AC field or pulsed field can cause switching or output deterioration a small amount at a time by deforming a wall into another stable configuration on each application of the pulse. A mechanical analogy of the creep phenomenon has been given by Kayser et al. [35]. This also causes the actual switching threshold to be less abrupt than that described by the ideal switching threshold curve, and for most thin film configurations comes into effect long before thermal effects on the switching threshold can be observed.

MATERIALS AND PROCEDURE

The experimental apparatus consisted of the memory element itself, the computer interface and the memory element drive and detection circuits. The purpose of this section is to describe the experimental apparatus and the experimental procedure.

Memory Element

Device structure

Each memory element, capable of storing one bit, consists of a sandwich of a magnetic alloy, 150 Å thick (65% Ni, 15% Fe, 20% Co), separated by a very thin layer of a non-magnetic conductor such as tantalum. The layer of tantalum, about 50 Å thick, serves to decouple the two magnetic layers so that the magnetization vector **M** is not constrained to lie in the same direction throughout the element. Connections are made to allow a sense current to flow the length of the element. The easy axis of magnetization, created by fabricating the device in the presence of a magnetic field, is orthogonal to the direction of current flow. Covering the magneto-resistive elements is an insulating material. Above this layer is a conductor called the word strap which carries current orthogonally to the sense current. These currents act as the sources of magnetic fields in the easy axis direction, H_s, and in the direction of the hard axis, H_w. The layout of several elements in the configuration to be tested is shown in Figure 6. An individual element is selected by selecting the appropriate inputs for sense current, I_s, and for word current, I_w. The anisotropy field H_k of the elements had a nominal value of 18±3 Oe. The resistivity of the material was 10 Ω per square with an individual element having a resistance of 100±10 Ω. The magneto-resistive coefficient ΔR/R was 2.4±0.3%.

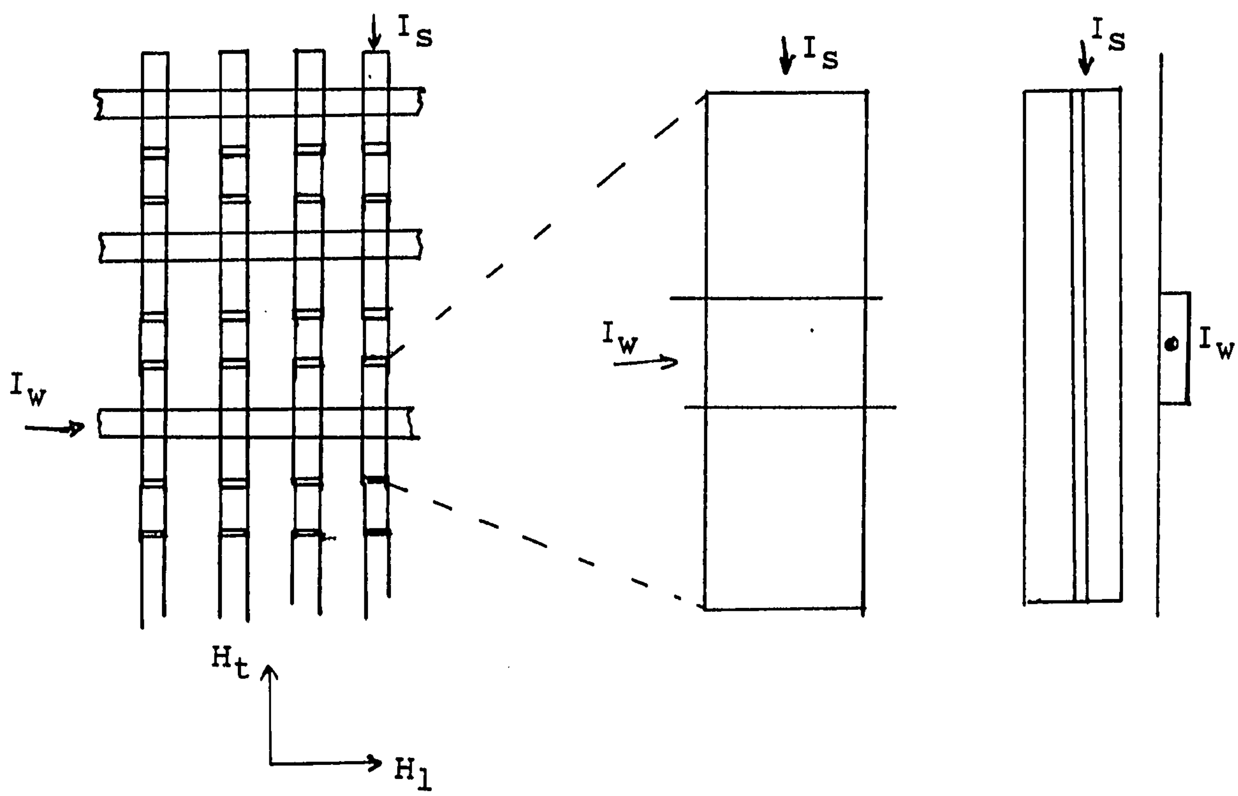

FIGURE 6. Layout of several memory elements

Operation of memory devices

The memory device operation will now be described. The sense current described above generates a magnetic field which wraps around the conductor according to the right hand rule. In order to describe the device operation, assume that the element is magnetized as shown in Figure 7. The field which wraps around the conductor has caused the magnetic moment to be directed to the left in the upper magnetic layer, and to the right in the lower magnetic layer. As stated before, the central layer is a non-magnetic material. A current directed into the paper would generate a magnetic field wrapping around in the opposite direction. The two possible directions of magnetization are the two states necessary to store information.

In order to detect the direction of magnetization the magneto-resistive effect is used. A sense current is allowed to flow through the element. This current generates a magnetic field which wraps around the conductor either in the direction of magnetization, or in the direction opposite to it. If the field opposes the magnetization, the resistance through the device will be higher than if it does not. This effect can be magnified by applying a transverse field generated by the word current I_W, as shown in Figure 8. As long as the combination of the two fields is kept

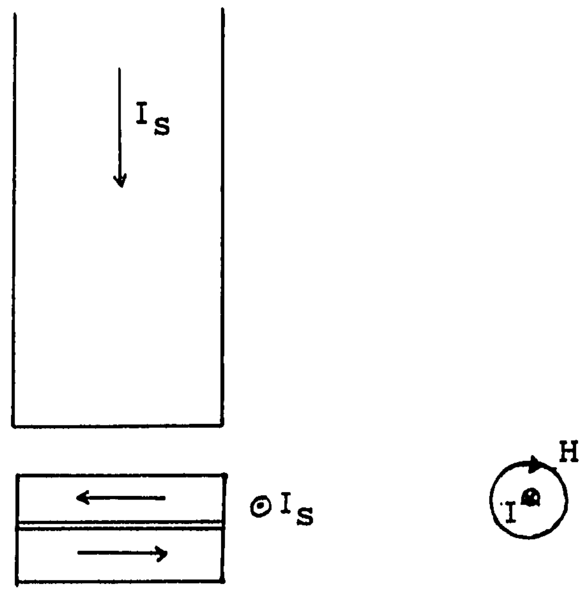

FIGURE 7. Device magnetization

below the switching threshold, the magnetization will remain in the same direction, giving non-destructive readout (NDRO). The change in resistance as the two fields are applied is also shown in Figure 8. The sense current remains constant. The output voltage, V_O, is the voltage drop across the memory element and follows Ohm's law: $V_O = I_S R$. As can be seen, the resistance for one direction of magnetization is higher than for the other. This effect is increased as the field in the direction of the hard axis is increased, until the switching threshold is reached in curve I and a switch to curve II occurs, corresponding to a switch in magnetization direction.

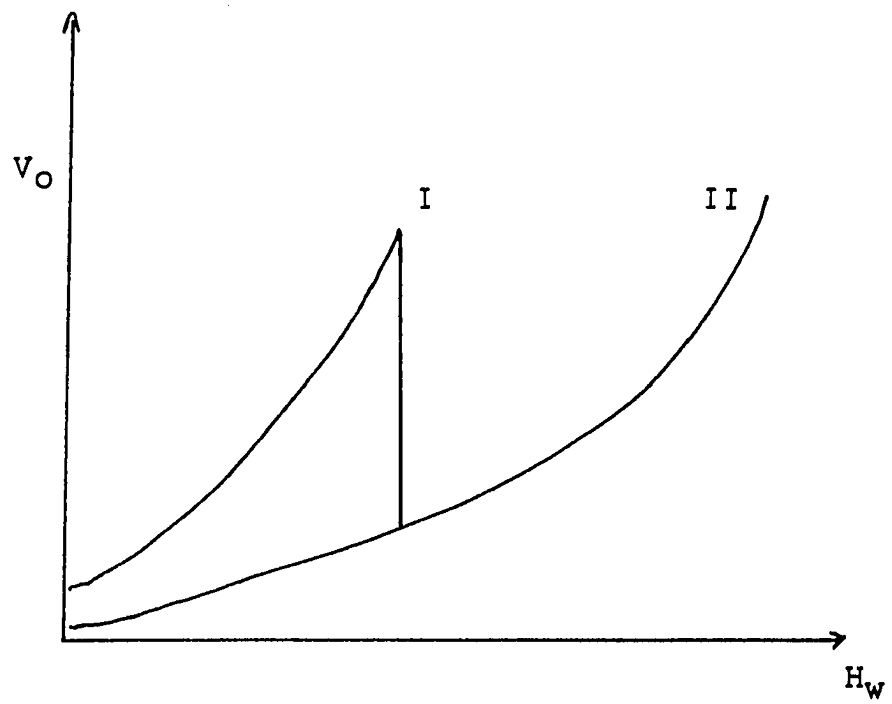

FIGURE 8. Effect of applying the word current, I_w

Computer Interface

The controller to run the experiment was made to interface with the S100 bus on the Zenith Z-100 personal computer. A block diagram of the controller is shown in Figure 9. The controller is an input/output device and uses five I/O addresses. The controller is used to set the amplitude of the word current using a D/A converter, to set the direction of the sense current for writing or for reading, to enable or disable a clock pulse which allows the word current to flow through the element, and to count the number of times the word current is pulsed with non-destructive readout.

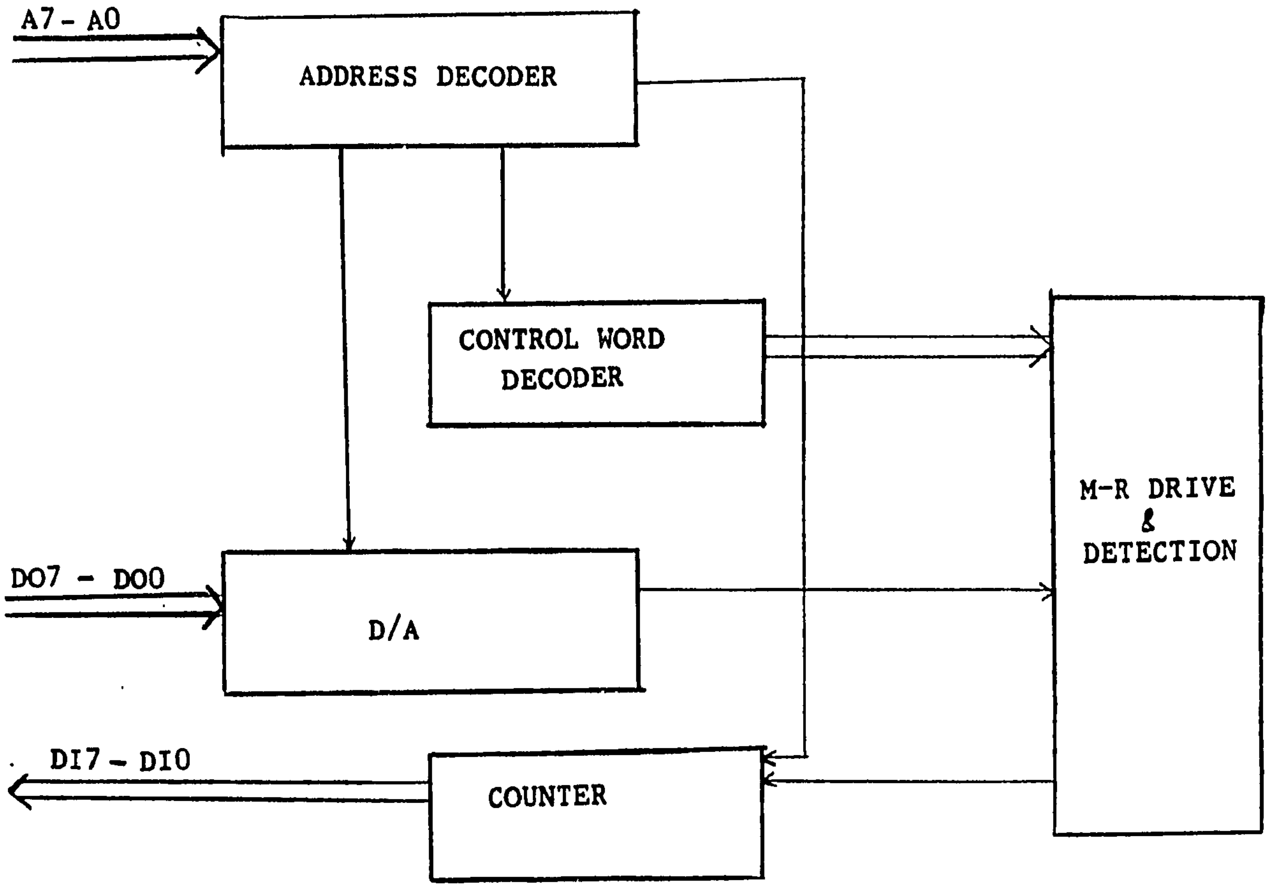

FIGURE 9. Block diagram of the controller

The upper four bits of the eight bit address are set using the DIP switches on the board for ease of interfacing to different systems. The addresses to access the various functions are given in Table 2. The control word configuration is shown in Table 3. The control code necessary to perform the desired functions is also shown. It should be noted that the bit for enabling the clock uses negative logic, so that bit must be set if the clock is to remain disabled. A schematic diagram of the computer interface board is shown in Figures 10, 11, 12, 13 and a parts list is given in Table 4.

TABLE 2. Function addresses

Address(hex)	Input/Output	Function
80	Output	D/A converter; least significant eight bits
81	Output	D/A converter; most significant two bits
82	Output	control word
83	Input	least significant byte of counter
84	Input	most significant byte of counter

Switching and Detection Circuits

The voltage and clock signals from the interface board were connected to a small board, shown in Figure 14, with the appropriate switching and detection circuitry via a ribbon cable. A parts list for this circuit is given in Table 5. The voltage output from the D/A converter was fed through a current amplifier with a voltage gain of unity in

TABLE 3. Control word configuration

Bit	Value when asserted	Function
0	1	Clear counter
1		Not used
2	1	Set I_s direction to read
3	1	Set I_s direction to write
4	1	Disable clock
5	0	Enable clock
6		Not used
7		Not used

order to supply an adequate word current for the test. The maximum word current available was 25 mA.

The 2 MHz clock pulse served to turn the transistor Q1 on and off. With the transistor saturated most of the current went through the transistor to ground and very little passed through the memory element. With the transistor in the cutoff region, however, the current was allowed to flow through the element. Low pass filtering followed the transistor switch to avoid overshoot.

An SR latch was used to set the direction of the sense current for reading or writing. For writing into the

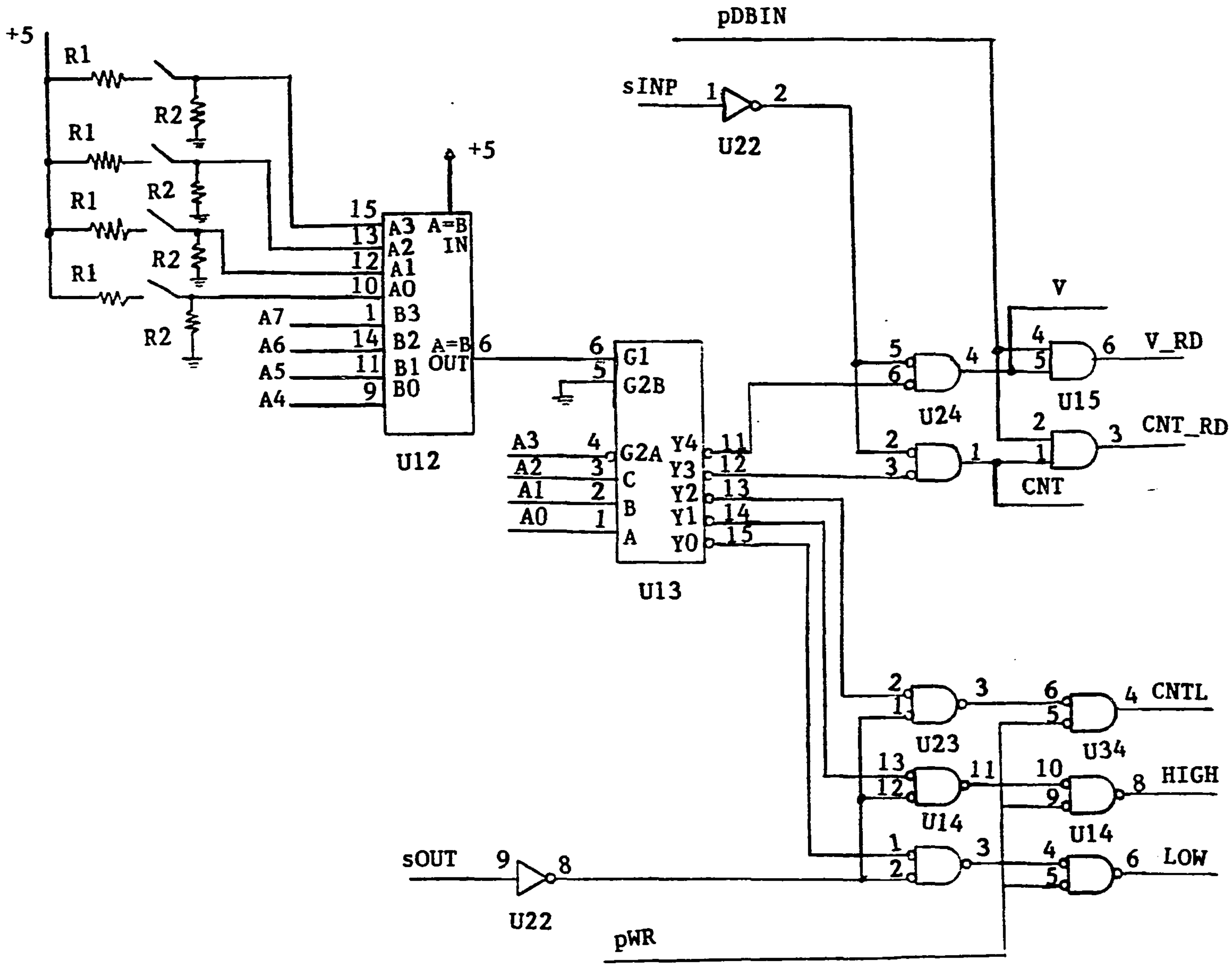

FIGURE 10. Schematic for the address decoder

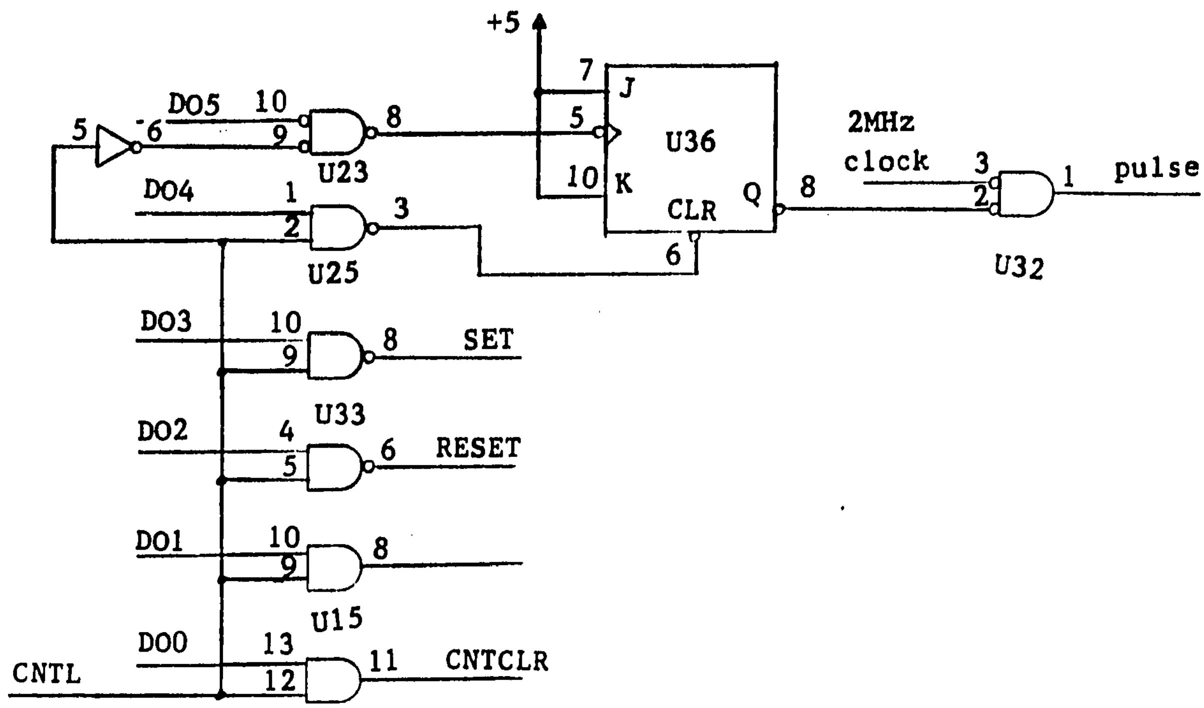

FIGURE 11. Schematic for the control word decoder

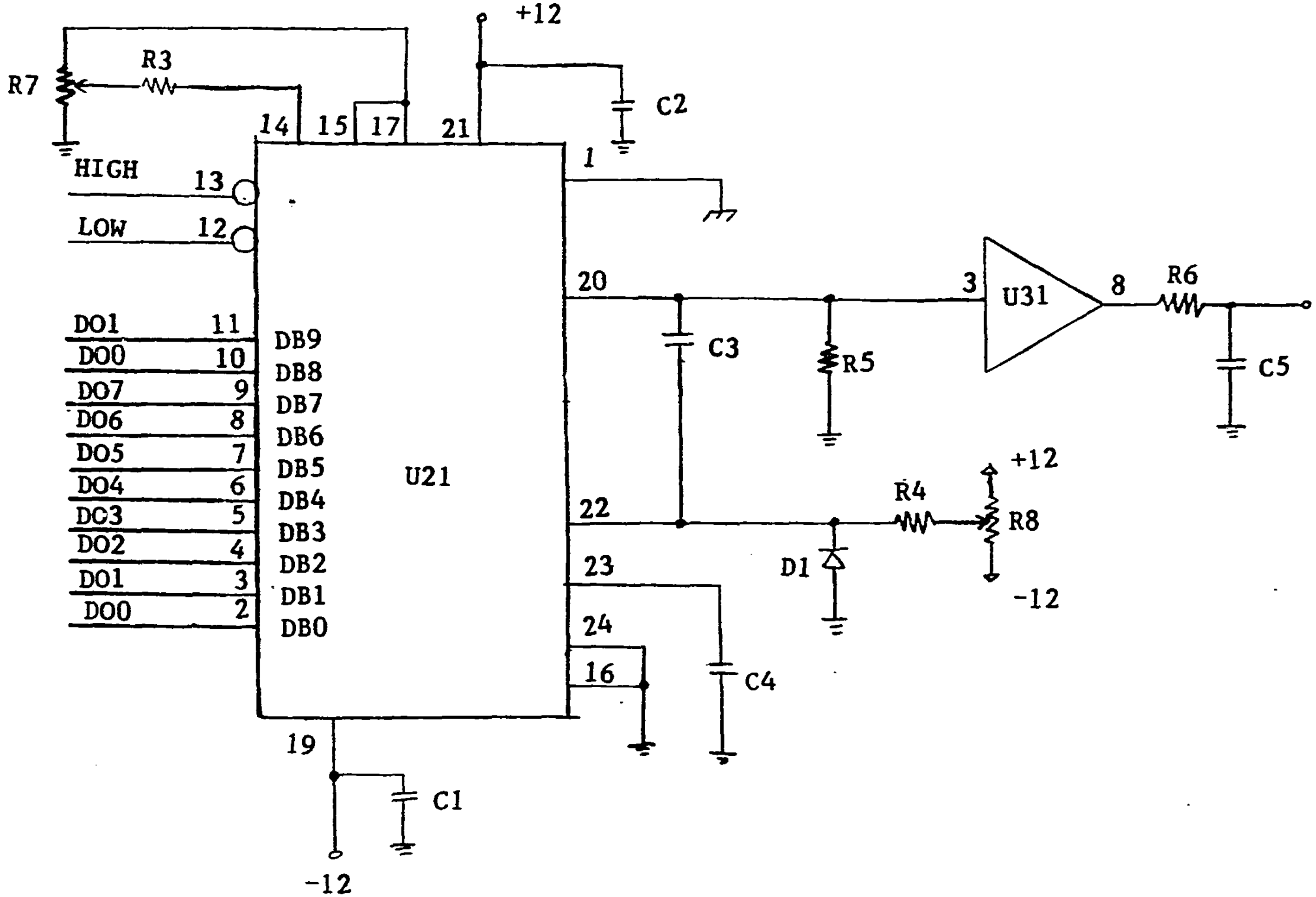

FIGURE 12. Schematic for the D/A converter

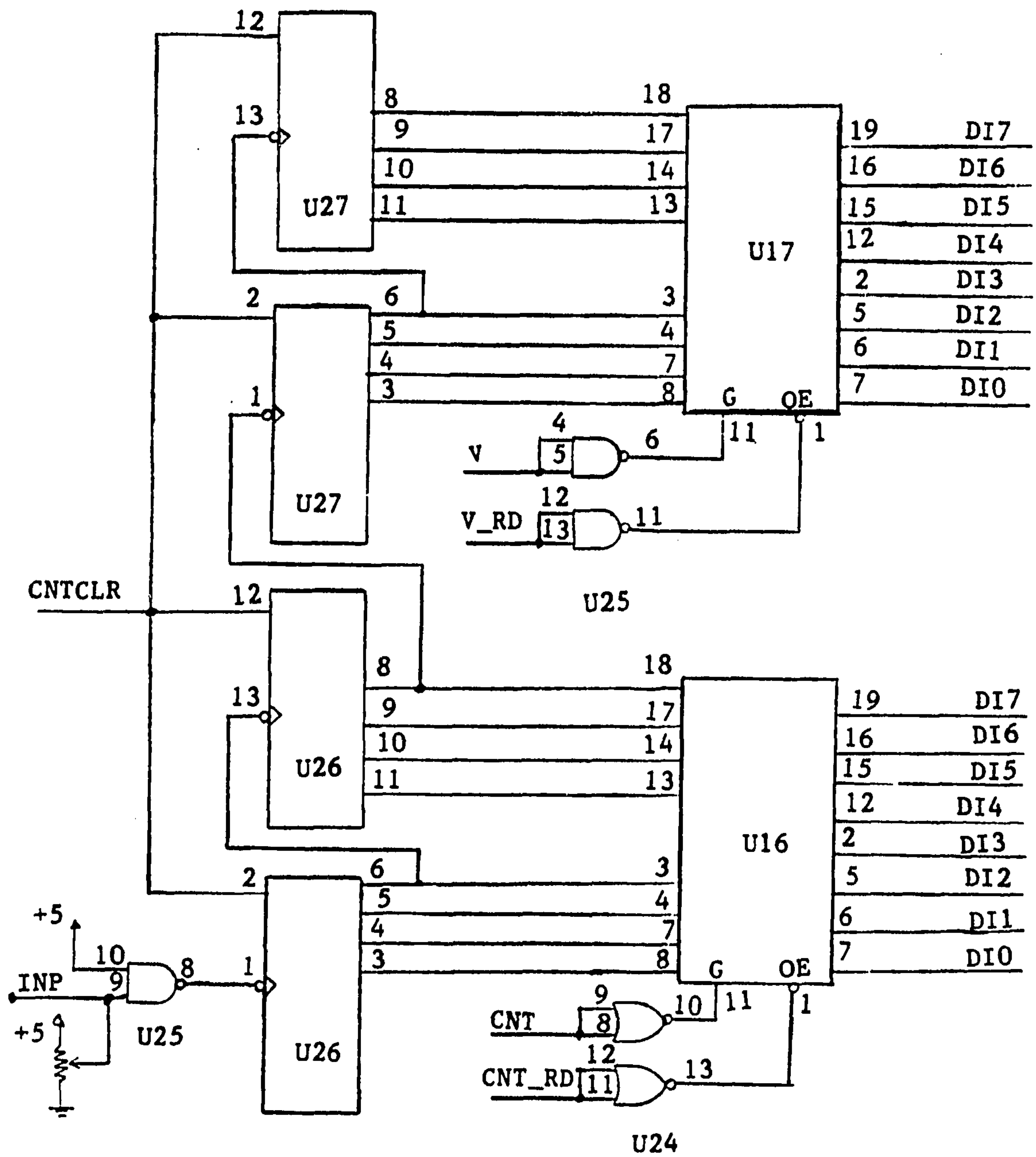

FIGURE 13. Schematic for the counter circuit

TABLE 4. Parts list for the Computer Interface

PART NUMBER	DESCRIPTION	FUNCTION
U11	DIP switches	address selection
U12	74LS85	4 bit comparator
U13	74LS138	3 to 8 decoder
U14	74LS32	2 input OR gate
U15	74LS08	2 input AND gate
U16, U17	74LS373	8 bit latch with tri-state outputs
U21	NE5020	10 bit D/A converter
U22	74LS04	inverter
U23	74LS32	2 input OR gate
U24	74LS02	2 input NOR gate
U25	74LS00	2 input NAND gate
U26,U27	74LS393	dual 4 bit binary counter
U31	LH0002C	current amplifier
U32	74128	2 input NOR line driver
U33	74S140	4 input NAND line driver
U34	74LS02	2 input NOR gate
U35		not used
U36	74LS73	JK flip-flop
R1	100 Ω	
R2	750 Ω	
R3	80 kΩ	
R4	1 MΩ	
R5	4.7 kΩ	
R6	100 Ω	
R7	10 kΩ 10 T	potentiometer
R8	20 kΩ 10 T	potentiometer
C1	0.1 μF	
C2	0.47 μF	
C3	30 pF	
C4	100 pF	
C5	500 pF	

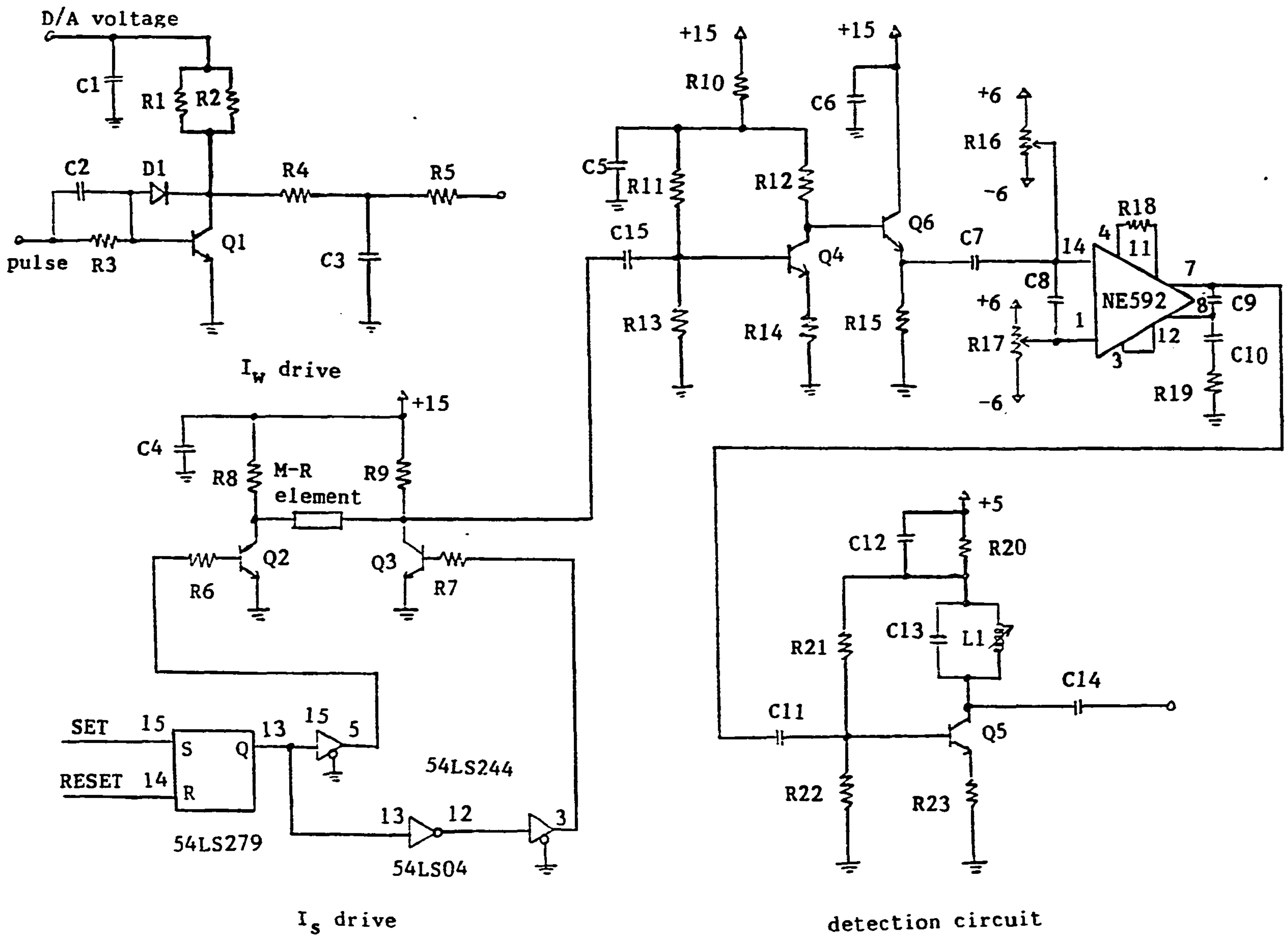

FIGURE 14. M-R drive and detection circuits

TABLE 5. Parts list for M-R drive and detection

Resistors		Capacitors	
R1, R2	470 Ω	C1	2.2 μF
R3	600 Ω	C2	47 pF
R4	47 Ω	C3	220 pF
R5	150 Ω	C4	15 μF
R6, R7	5.6 kΩ	C5	100 μF
R8	2.2 kΩ	C6	15 μF
R9	3 kΩ	C7	.001 μF
R10	100 Ω	C8	10 pF
R11	2.2 MΩ	C9	160 pF
R12	15 kΩ	C10	0.1 μF
R13	1.0 MΩ	C11	.0047 μF
R14, R15	1.5 kΩ	C12	100 pF
R16	20 kΩ 10T	C13	.001 μF
R17	10 kΩ 10T	C14	.0047 μF
R18	100 Ω		
R19	1 kΩ	Transistors	
R20	1.5 kΩ		
R21	68 kΩ	Q1-Q5	2N4259
R22	47 kΩ	Q6	2N2222
R23	100 Ω		
Germanium diode			
Variable inductor			

element, the sense current was 4.7 mA, the D/A was set at the full scale output and the clock was pulsed to enable the word current. For sensing, the sense current was 4.0 mA in the opposite direction and the word current was varied using the D/A output. The test was performed at a fixed setting of sense current. Only the word current was varied.

The output of the element was amplified and filtered to get a difference in the amplitude of the signal for the two states of 1 V. This was capacitively coupled into the input of a TTL NAND gate which was biased to generate an output before switching and no output after switching. This signal was fed into a 16 bit counter. The 16 bit counter, counting at a frequency of 2 MHz, allows a time delay of 32 ms between readings from the counter to avoid overflow and a misleading value of the count.

Experimental Procedure

Using a program which merely writes a one into a bit, reverses the sense current for sensing and pulses the word current at a single value, a nominal threshold was found. An oscilloscope was used to observe the output before and after switching. A nominal threshold was found at which switching occurred within a few seconds. This was done for each bit, at each test temperature individually.

For the computer controlled test, this threshold was used to determine a good D/A output at which to begin the experiment. The test was begun about 50 steps higher than the nominal threshold. At a given value of word current, determined by the D/A output, the counter counted the number of times the word current was pulsed until switching occurred. The counter output was read every 3 to 4 ms, well within the 32 ms maximum allowable interval. If the same value was read from the counter twice, the total count was tallied and recorded. The same procedure was repeated fifteen times at each current level in order to reduce the probable error. The current was then decremented one step and the procedure repeated. The step size was determined by the D/A output and ranged from 0.11% to 0.16% of the threshold, depending on where the threshold fell within the range of the D/A output.

This procedure was repeated until the word current was decremented far enough that switching did not occur for ten minutes or more. The test was then begun again at the initial value and the data recorded in a separate file. The entire test described thus far was performed repeatedly on one memory cell since the variation from cell to cell is far greater than the variation seen by reducing the word current 0.1%. The same test was then performed on a different memory cell.

The procedure was done at an elevated temperature by placing the memory element in a convection oven. The apparatus was allowed to come to thermal equilibrium before the test was begun. The maximum temperature variation through the test was 2°C. An independent measure of the variation of H_k and of skew of the tested bits with temperature was also done. Sense current was also measured independently as a function of temperature. The test was also repeated at a cold temperature by using dry ice in an insulated container. At room temperature, the thermal noise due to the drive circuits was in the nanoampere range. The step size was 19 μA, which far outweighs any noise effects due to the drive circuits.

RESULTS AND DISCUSSION

The rate at which the coupled magnetization can be thermally agitated over the threshold is of the general form:

$$r = \frac{B}{\tau}\exp[-E_w/kT]$$

where τ is the relaxation time, E_w is the energy well depth, kT is the Boltzmann energy and B is a constant of proportionality. The number of word pulses applied, n, before switching occurs is a measure of the time in which the element remained in the initial state. On the average, this will be proportional to 1/r so that

$$\ln(n) = \frac{E_w}{kT} + \text{constant}$$

The depth of the energy well is dependent on the anisotropy constant H_k, the magnetization M, the applied fields, H_s and H_w, and the effective activation volume, V. At a constant temperature H_k, M, and V are constant and the energy well depth is a function of applied field alone.

The experiment was performed at a constant value of sense field. The word field was reduced from the threshold value by a small percentage. Using the model developed by Comstock et al. [23], the depth of the energy well can be estimated and is found to be an approximately linear function of the reduction in the word field [36]. The natural log of the count should thus be linearly related to the applied word field. This was indeed the case with a high degree of correlation. This exponential relationship also indicates that the threshold under investigation is that for rotational switching, since for wall motion type switching, the change in wall position per cycle is linearly related to the applied field.

For bit A, the results of the tests performed at room temperature, at an elevated temperature, and at a cold temperature are shown in Figures 15, 16, 17. The natural log of the count is shown as a function of the applied word field, which is normalized to the threshold field. The threshold was defined for this analysis as the point at which switching occurs after the application of one pulse. Each point on the room temperature plot represents an average of 210 samples at each level. The high and low temperature test points are an average of 45 and 30 samples at each point. At the higher and lower temperatures fewer samples were averaged together to minimize the possibility of temperature fluctuation effects throughout the test being measured, rather than the threshold characteristics at a given temperature. A summary of the data obtained for bit A at these temperatures is given in Table 6. Corresponding plots for bit B are shown in Figures 18, 19, 20. The points on these plots represent averages of 180, 60, and 30 samples at each point, for room, high, and low temperatures respectively. A summary of the data obtained for bit B at these temperatures is given in Table 7.

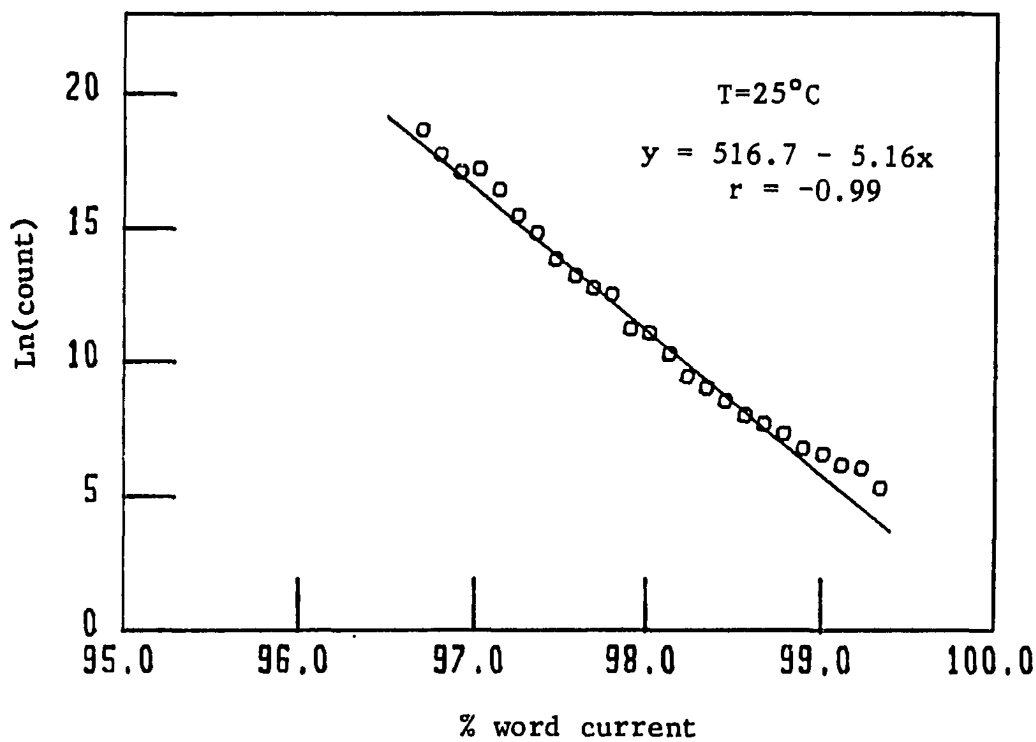

FIGURE 15. Bit A, room temperature measurements

The data summaries show the temperatures at which the measurements were taken, the slope of the line which best fits the data for each temperature, the correlation of the

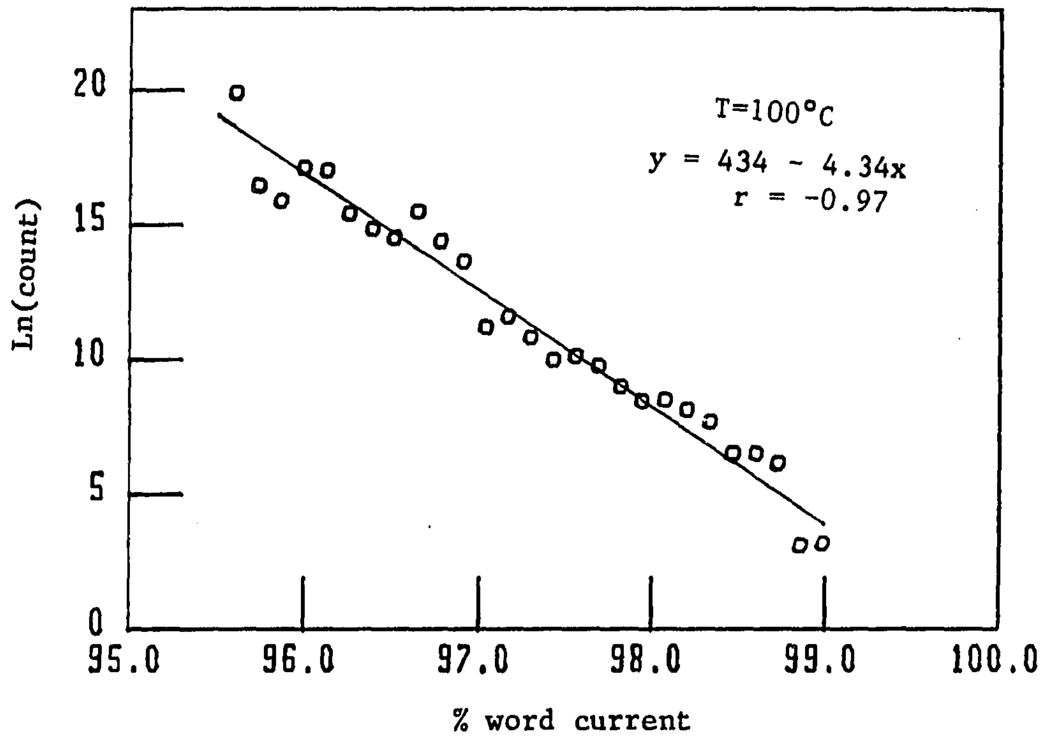

FIGURE 16. Bit A, high temperature measurements

data to the linear regression fit, and the value of H_k. To determine H_k, the sense current and word current for switching were measured, and the easy axis and hard axis fields involved were estimated. If the easy axis points in the expected direction, the easy axis and hard axis fields, H_e and H_h, are equivalent to the fields due to the sense and word currents, H_s and H_w respectively. Thus we have:

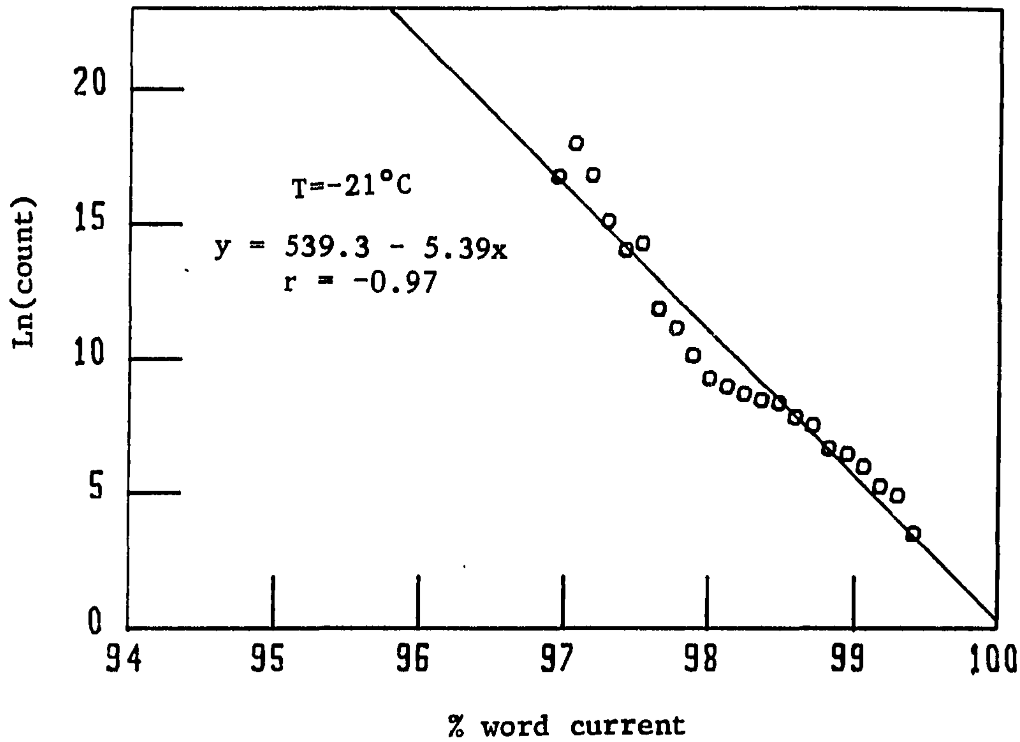

FIGURE 17. Bit A, low temperature measurements

TABLE 6. Summary of bit A characteristics

skew angle, δ = 25.8°

TEMPERATURE, C	SLOPE	CORRELATION	H_k, Oe
25	-5.2	-0.99	15.94
100	-4.3	-0.97	14.89
-21	-5.4	-0.97	16.62

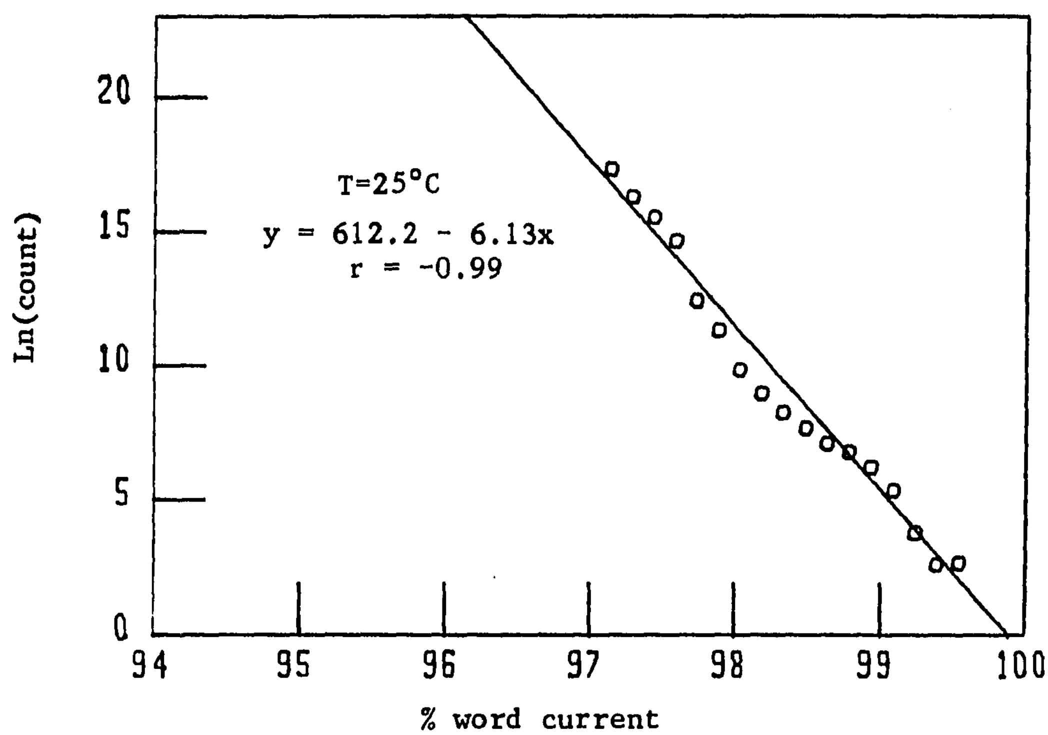

FIGURE 18. Bit B, room temperature measurements

$$H_e = \frac{I_s(4\pi \times 10^{-3})}{2(2W_s)} = H_s$$

$$H_h = \frac{I_w(4\pi \times 10^{-3})}{2W_w} = H_w$$

The anisotropy field H_k can be estimated using a tangent line to the threshold curve as follows:

$$0.45H_k = H_e + 0.65H_h$$

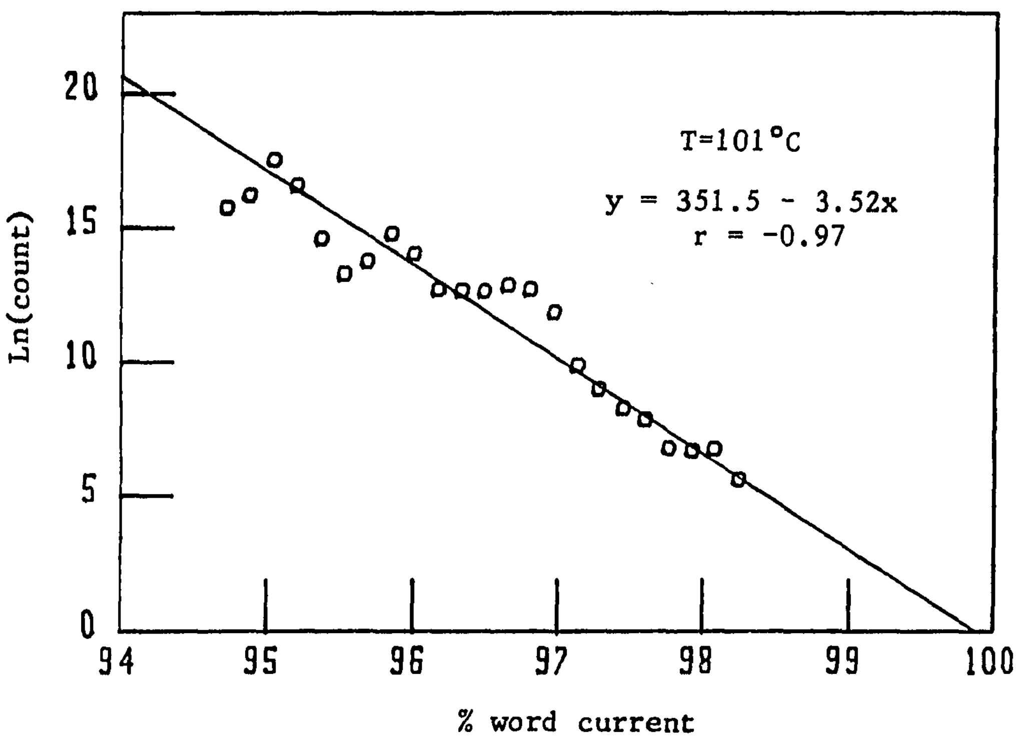

FIGURE 19. Bit B, high temperature measurements

where H_S is the field due to the sense current, H_W is the field due to the word current, I_S is the sense current, I_W is the word current, W_S is the element width, and W_W is the effective word line width. The factor $4\pi \times 10^{-3}$ converts the units to Oe. If the easy axis is skewed, however, the field due to the sense current and that due to word current both have components along the easy and hard axis directions. Thus if δ is the skew angle:

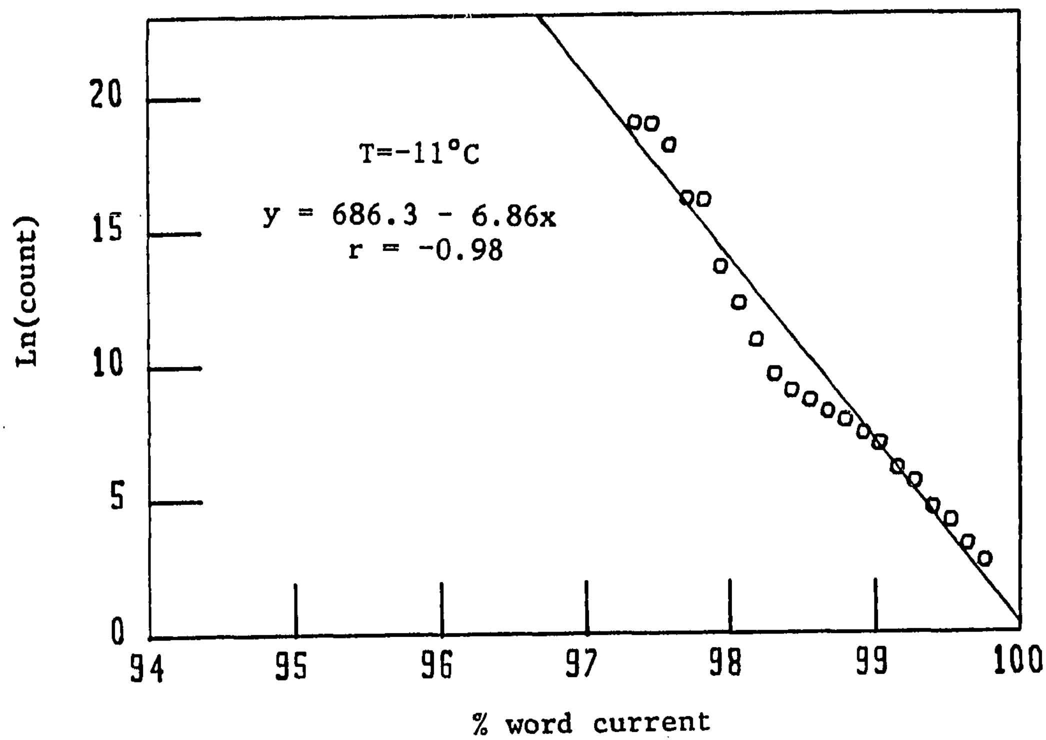

FIGURE 20. Bit B, low temperature measurements

TABLE 7. Summary of bit B characteristics

skew angle, δ = 28.5°

TEMPERATURE, C	SLOPE	CORRELATION	H_k, Oe
25	-6.1	-0.99	14.84
101	-3.5	-0.97	14.64
-11	-6.8	-0.98	14.94

$$H_e = H_s\cos\delta + H_w\sin\delta$$

$$H_h = -H_s\sin\delta + H_w\cos\delta$$

$$0.455H_k = H_s(\cos\delta - 0.68\sin\delta) + H_w(\sin\delta + 0.68\cos\delta)$$

By measuring H_s and H_w required for switching at two points, the difference can be taken and the angle δ can be determined.

$$\tan\delta = \frac{(H_{s1} - H_{s2}) + .68(H_{w2} - H_{w1})}{0.68(H_{s2} - H_{s1}) + (H_{w1} - H_{w2})}$$

Since the contribution of H_s and H_w to the easy and hard axis fields can then be found, H_k can be approximated by:

$$H_k = \frac{1}{0.455}[(H_s\cos\delta - 0.68\sin\delta) + H_w(0.68\cos\delta + \sin\delta)]$$

The skew angle determined in this way for bit A was 25.8°. For bit B the skew angle was 28.5°. A plot of the computed H_k value vs. temperature is shown in Figure 21. A similar plot for bit B is given in Figure 22.

The slope of the line obtained as the applied transverse field approaches the threshold is inversely related to the temperature. The energy well depth is proportional to the anisotropy field H_k, the magnetization M, the effective activation volume V, and the difference between the threshold and the applied field.

$$E_w = BVH_kM(H_{wt} - H_w)$$

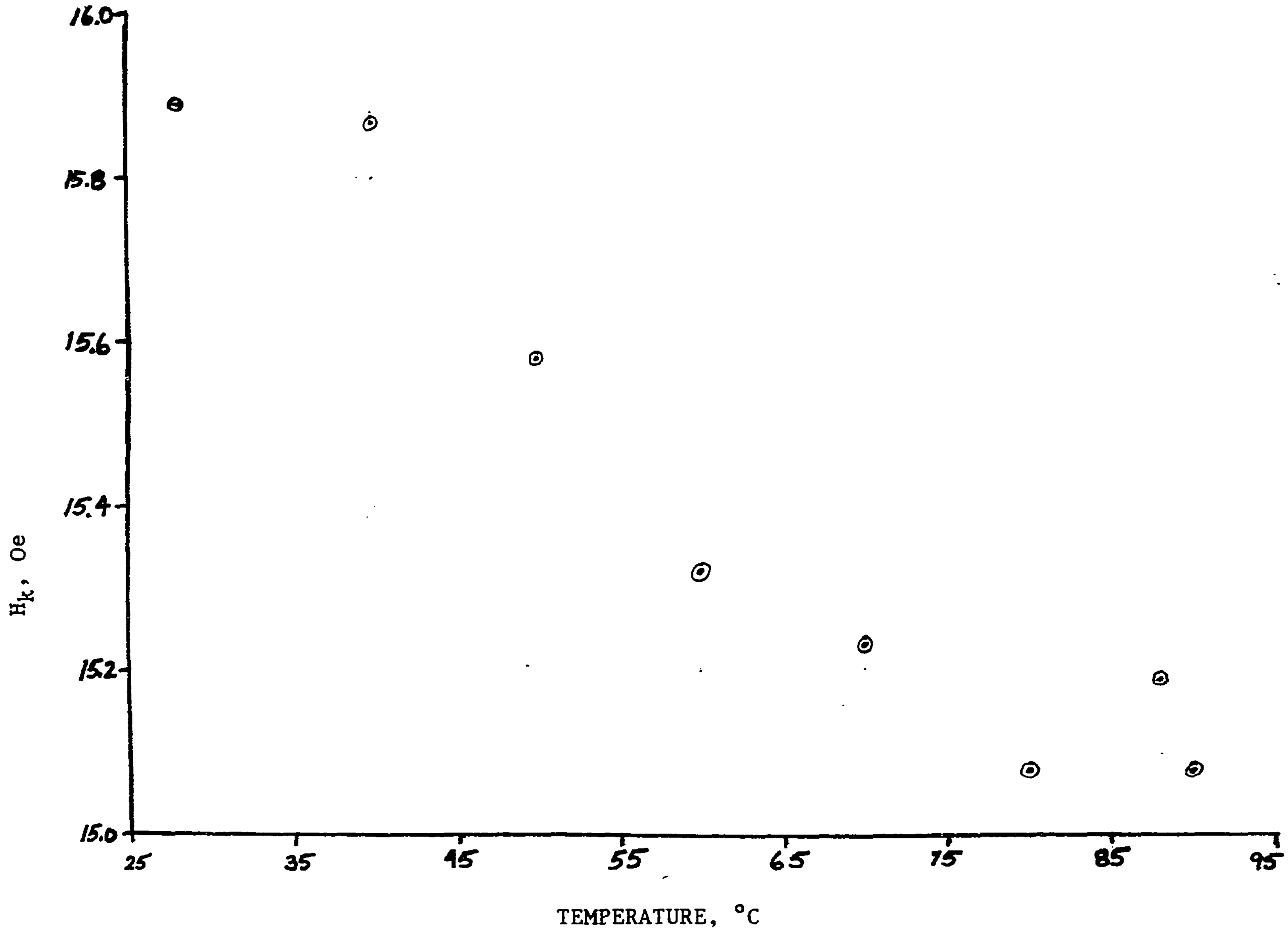

FIGURE 21. Change in H_k with temperature, bit A

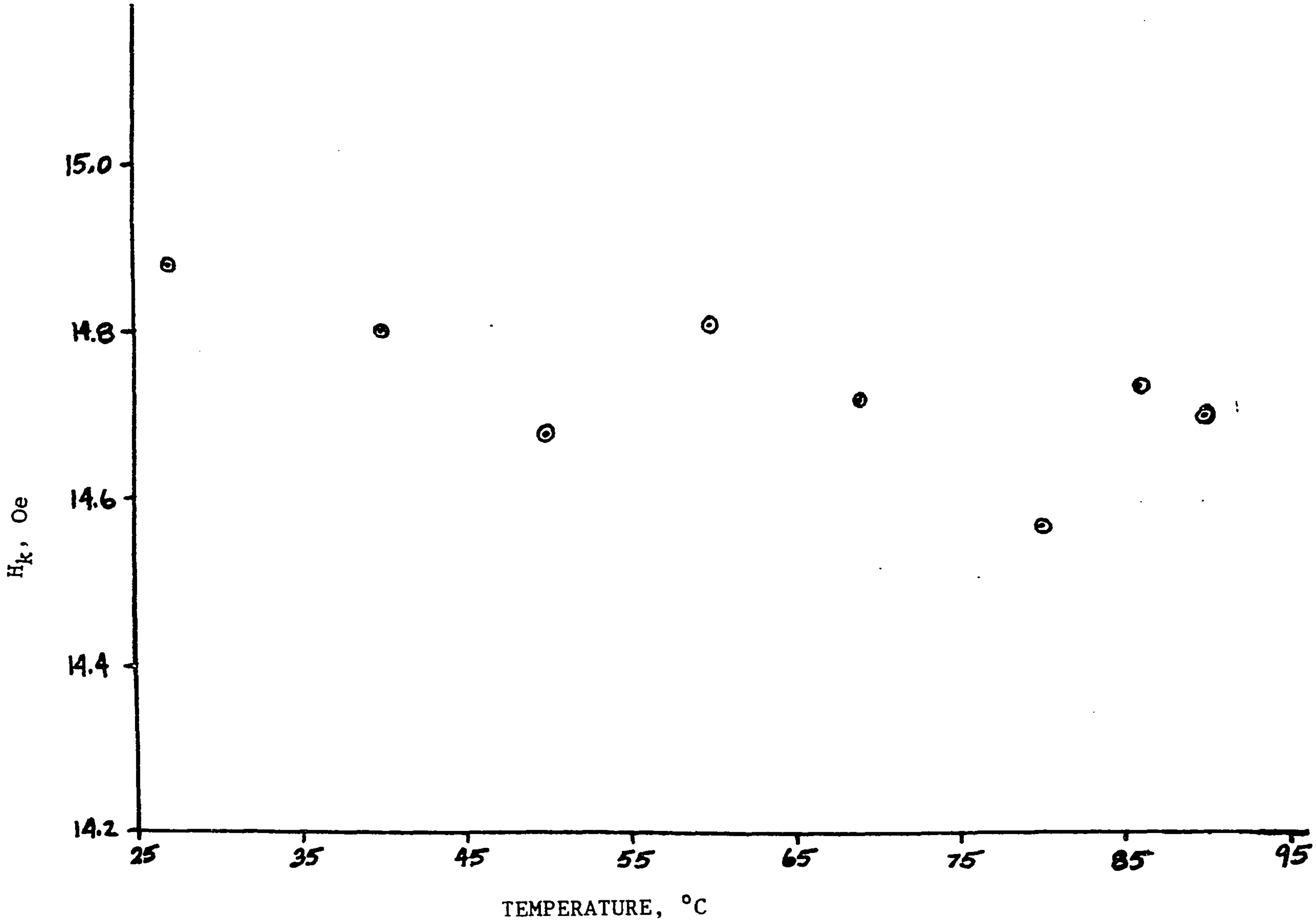

FIGURE 22. Change in H_k with temperature, bit B

where B is a constant of proportionality, H_{wt} is the threshold word field, and H_w is the applied word field. For measurements performed at different temperatures the slope of the lines as the word field is increased should be related as:

$$\frac{slope_1}{slope_2} = \frac{T_2 H_{k1} V_1 M_1}{T_1 H_{k2} V_2 M_2}$$

M_1 and M_2, the magnetization at each temperature varies only negligibly over the temperature range involved. The change in H_k with temperature has been previously shown. The activation volume, which is not equivalent to the total volume of the element, is not known and its behavior with temperature is not known. For the known factors involved, the effect of higher thermal energy with higher temperature outweighs the effect due to small changes in H_k and M. A summary of the effects of higher and lower temperatures is given for bits A and B in Tables 8 and 9.

For both bits the ratio of the slopes is quite close to the inverse ratio of the temperatures in one direction of temperature change but not in the other. For bit A, the relationship between the high temperature test and the room temperature test is quite close to the inverse ratio of the two temperatures. Similarly, the same thing occurs for bit B at the colder temperature. A possible explanation for this could be a difference in the effective activation

TABLE 8. Relationship between temperatures, bit A

	SLOPE RATIO	TEMP RATIO $\frac{T_1}{T_2}$	$\frac{T_1 H_{k2}}{T_2 H_{k1}}$
$\frac{\text{HIGH}}{\text{ROOM}}$	0.827	0.799	0.746
$\frac{\text{ROOM}}{\text{LOW}}$	0.963	0.846	0.811
$\frac{\text{HIGH}}{\text{LOW}}$	0.796	0.676	0.605

TABLE 9. Relationship between temperatures, bit B

	SLOPE RATIO	TEMP RATIO $\frac{T_1}{T_2}$	$\frac{T_1 H_{k2}}{T_2 H_{k1}}$
$\frac{\text{HIGH}}{\text{ROOM}}$	0.571	0.798	0.786
$\frac{\text{ROOM}}{\text{LOW}}$	0.894	0.879	0.873
$\frac{\text{HIGH}}{\text{LOW}}$	0.510	0.702	0.688

volume at the different temperatures. Since this is dependent on the density and location of pinning sites in the material it could not be expected to have any simple linear relationship to the temperature. Other sources of error include the uncertainty in the width of the sense line, the effective width of the word line, the value of H_k and the small change in H_e as H_w is changed due to the skew of the easy axis.

Another way to look at the data, which is particularly important for storage devices, is an analysis of the mean time to failure, or the probability of a bit switching to an incorrect state. For operation at room temperature, if a mean time between failures (MTBF) of 10,000 hours is required, $n = 72 \times 10^{12}$. For bit A at room temperature, this occurs at 94.0% of the threshold word field. By using the reliability function

$$P_0 = e^{-t/MTBF}$$

if it is necessary to be 99.9% confident that no failures will occur after 10,000 hours, the following allowable operation level is obtained:

$$0.999 = e^{-72x10^{12}/MTBF}$$

$$MTBF = n = 72 \times 10^{15}$$

Thus the word current can be operated at 92.6% of its threshold value or less under these stringent requirements.

This is consistent with results obtained in earlier tests of the switching threshold. In earlier tests, a threshold was defined as the point at which switching occurred within about a second. The word current was reduced to 98±0.5% of that and was pulsed 10^9 times at 2 MHz in which time no switching occurred. The point defined as the threshold for that experiment corresponds to 97.3% of the threshold defined as the point at which switching occurs in one pulse. Reducing the word field by 2% corresponds to a word field of about 95.3% in the current experiment.

$$\ln(n) = 516.72 - 5.16(95.3) = 24.69$$

$$n = 53 \times 10^9$$

$$\text{MTBF} = 442 \text{ min}$$

The experiment lasted less than 10 minutes. The probability of failure within that time would be $1-P_0 = 2.2\%$. This is consistent with the fact that no failure was seen in that experiment.

Even at high temperatures the switching threshold was quite sharp. For a MTBF of 10,000 hours for bit B at 100° C, the word current needs to be reduced from its threshold value by only 9.2%. For the more stringent requirement, 99.9% confidence of no failure in 10,000 hours, the word current needs to be reduced by only 11.2%.

Since the elements studied can operate quite reliably at current levels up to 90% of the switching threshold the size limitations placed on the memory cells will be due to the variations in processing which cause variations from one memory chip to another, thus causing variation in the switching thresholds, and due to the limits of the sensing circuits. For example, if $\Delta R/R = 2\%$, the sense current is set at 4 mA, and the minimum sense output is 1 mV, the minimum resistance of an individual element is then $R = 14\ \Omega$. If the resistivity is 10 ohms per square a resistance of 14 ohms radically alters the shape of the element and invalidates the model used.

SUMMARY

The switching behavior of the multilayer magneto-resistive elements was tested at the sense current level selected for the nominal operating level. Two elements were thoroughly tested at room temperature, at 100°C, and at a cold temperature by pulsing the word current at a value near the switching threshold. The word current was reduced in steps to determine a relationship between the applied word field and the mean time between failures. In all cases, with a high degree of correlation, the relationship between the applied word field and the mean time between failures was an exponential one, indicating that the rotational threshold was under investigation. As expected, the rapidity at which a reliable operating level was approached decreased with increasing temperature. The amount it decreased, however, was not fully explained by the changes in temperature and in H_k alone. The reliable operating level was stated in terms of a percentage of the switching threshold. The absolute threshold itself also changed but this phenomenon was not investigated. All results were normalized to a percentage of the switching threshold at the temperature at which the measurements were taken. Even at higher temperatures the elements could be operated quite reliably at word current levels up to 88.8% of the threshold level. Results in the investigation were also shown to be consistent with results obtained in previous tests of the same type of memory elements.

CONCLUSION

The requirements for a viable random access memory technology have changed greatly since the early days of computer development. The multilayer magneto-resistive memory element under investigation in this thesis overcomes many of the problems experienced with earlier magnetic thin film memories. By means of the tight flux coupling between the two magnetic layers, the element does not have the problems associated with the presence of multiple domains. The investigation of the switching threshold gives evidence that the element behaves effectively as a single magnetic domain. The sharp switching threshold, small area requirements, and low drive currents all show great promise for the use of the multilayer element as a nondestructive readout random access memory.

In order to fully understand the switching behavior of the multilayer element much work remains to be done. The threshold behavior should be investigated over a range of sense current, and the change in the effective activation volume should be examined both theoretically and experimentally. The change in the absolute threshold with temperature and the effect which a skewed easy axis has on the threshold should also be studied.

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