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COMMERCIAL APPLICATIONS OF SPINTRONICS TECHNOLOGY

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ABSTRACT

Spintronics or the technology of devices whose properties depend upon the spin of conduction electrons, often requires the fabrication of thin, multilayer structures with layers as thin as 1 nm. The principles of Giant Magnetoresistive (GMR) materials and Magnetic Tunnel Junctions (MTJ) are discussed as well as their application in commercial devices including magnetic sensors, high-speed data couplers, and Magnetic Random Access Memories (MRAM) are discussed.

INTRODUCTION

Spintronics is a new field of research that studies and applies phenomenon that are dependent upon the spin of electrons. Spin-dependent scattering of conduction electrons had been observed for some time, but the advent of improved thin-film vapor deposition systems resulted in the observations in 1988 of large magnetic field dependent changes in resistance of thin-film ferromagnetic/non-magnetic metallic multilayers. The change in resistance was much larger than previously observed changes in resistance due to magnetic field earning the phenomenon the name Giant Magnetoresistance (GMR). This discovery was closely followed in 1994 by the commercial introduction by NVE Corporation of magnetic sensors based on GMR materials. Intense research continues on a wide variety of new materials utilizing the phenomenon of spin-dependent conduction electron scattering as well as research understanding the phenomenon itself. Applications using GMR materials include magnetic field sensors, high-speed data couplers or isolators, and magnetic random access memory (MRAM). This paper first describes the properties of GMR and Magnetic Tunnel Junctions (MTJ) materials. The application of these materials to sensors, data couplers, and MRAM is discussed. It has been argued that the largest application of nanotechnology to date is the use of GMR materials in read heads for high-density magnetic data recording. The use of GMR read heads has allowed hard drives to reach recording densities of 100 GBy/in^2 common today in laptop and desktop computers.

GIANT MAGNETORESISTIVE MATERIALS

Resistance of metals depends on the mean free path of their conduction electrons -- the shorter the mean free path, the higher the resistance. The resistivity of thin films can be considerably larger than the bulk resistivity if the film thickness is less than the mean free path. In ferromagnetic materials conduction electrons can be either spin up if their spin is parallel to the magnetic moment of the ferromagnet or spin down if they are antiparallel. In nonmagnetic conductors there are equal numbers of spin up and spin down electrons in all energy bands. In ferromagnetic metals there is a difference between the number of spin up and spin down electrons in the conduction sub bands of ferromagnetic materials due to the ferromagnetic exchange interaction. Therefore, the probability of an electron being scattered when it passes into a ferromagnetic conductor depends upon the direction of its spin. If a thin nonmagnetic conducting layer separates two thin ferromagnetic layers, we can change the resistance by simply changing whether the moments of the ferromagnetic layers are parallel or antiparallel. In order for spin dependent scattering to be a significant part of the total resistance, the layers must be thinner than the mean free path of electrons in the bulk material. For many ferromagnets the mean free path is tens of nanometers, so the layers themselves must each be typically less than 10 nm (100 Å).

A typical multilayer structure exhibiting GMR characteristics is shown in Figure 1. It consists of alternating thin layers of magnetic and non-magnetic metals. The thickness of the nonmagnetic layers is quite critical. At the proper thickness each magnetic layer is coupled antiparallel to the moments of the magnetic layers on each side – exactly the condition needed for maximum spin dependent scattering. An external field can overcome the coupling that causes this alignment and can align the moments in all the layers parallel reducing the resistance. If the conducting layer is not the proper thickness, the same coupling mechanism can cause ferromagnetic coupling between the magnetic layers resulting in no GMR effect. A plot of resistance vs. applied field for a multilayer GMR material is shown in Figure 2.

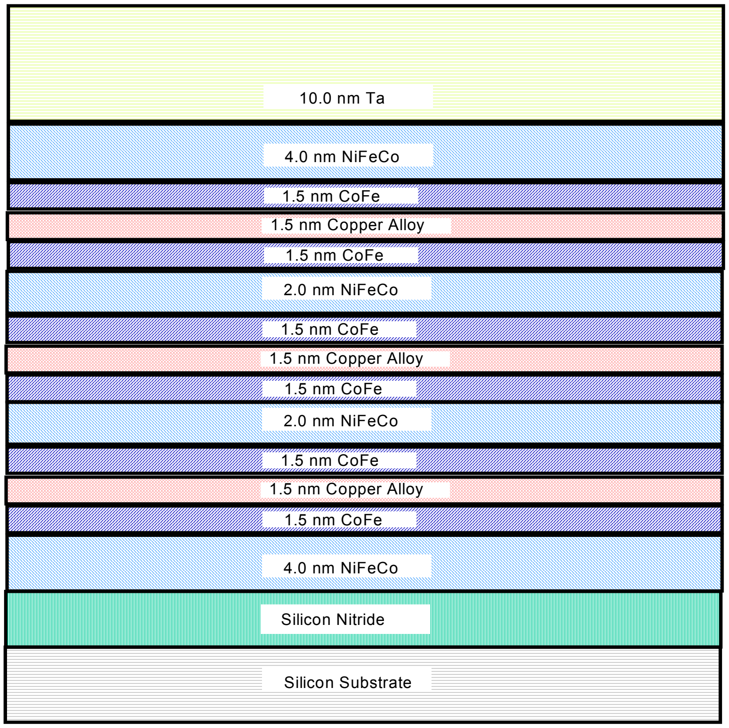


Figure 1. Layer structure of a typical commercial GMR multilayer.

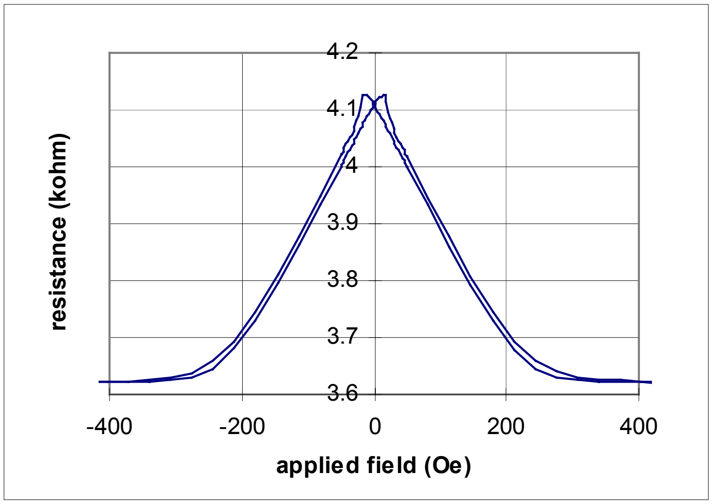


Figure 2. Resistance *vs*. applied field for a 2 μm wide stripe of antiferromagnetically coupled multilayer GMR material. GMR = 14 %.

MAGNETIC TUNNEL JUNCTION MATERIALS

Magnetic Tunnel Junctions (MTJ) also known as Spin Dependent Tunneling (SDT) structures also can exhibit a large change in resistance with magnetic field. In contrast to GMR structures, MTJ structures utilize a thin insulating layer to separate two magnetic layers. This insulating layer is as thin as 1 nm (10 Å). The conduction between the conducting magnetic layers is by quantum tunneling. The size of the tunneling current between the two magnetic layers is affected by the angle between the magnetization vectors in the two layers. Changes of resistance with magnetic field of 10 to 70 % and even higher have been observed in MTJ structures. The field required for maximum change in resistance depends upon the composition of the magnetic layers and the method of achieving antiparallel alignment. Values of saturation field range from 0.1 to 10 kA/m (1.25 to 125 Oe) offering at the low end, the possibility of extremely sensitive magnetic sensors. Actual prototype sensors with a 1.5 nm Al_2O_3 barrier thickness have demonstrated up to 40 % GMR and sensitivities of 30 mV/V/G (3 µV/nT @ 10 V).

A diagram of the layers in a pair of low-power shape-biased SDT junctions is shown in Figure 3. Junctions in sensors are usually designed in series connected pairs so that contact can be made to the top layer of the junction by subsequent metal layers. The magnetization in the lowest CoFe layer is pinned as part of a multilayer structure consisting of a CrPtMn antiferromagnetic and the antiferromagnetically coupled CoFe/Ru/CoFe sandwich. The NiFeCo free layer on the bottom responds to the applied field. The shape factor biases the free layer along its long dimension eliminating the necessity of orthogonal field coils. The measured field is applied parallel to the axis of the antiferromagnetic structure. Depending upon the direction of the field, the resistance increases as the moments become more anti-parallel or decreases as they become more parallel. The response of an MTJ is shown in Figure 4.

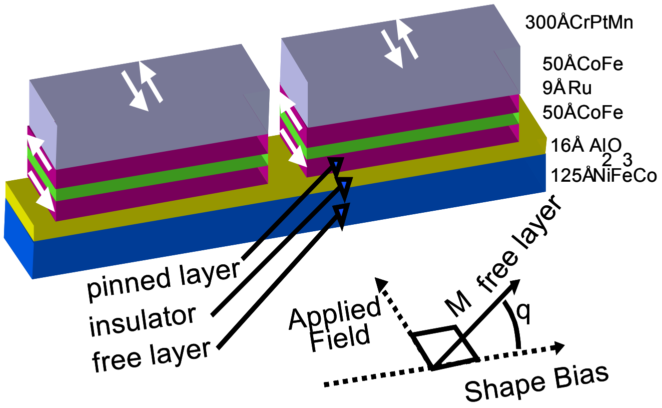


Figure 3. The layers and structure of a pair of SDT junctions. The magnetization in the lowest CoFe layer is pinned as part of the structure consisting of a CrPtMn antiferromagnetic and the antiferromagnetically coupled CoFe/Ru/CoFe sandwich. The NiFeCo free layer on the bottom responds to the applied field. The shape factor biases the free layer along its long dimension.

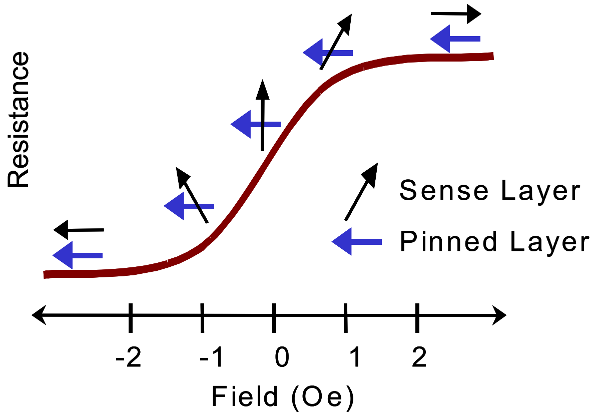


Figure 4. Resistance of a SDT junction as a function of applied field. The relative directions of the pinned and sense or free layers are shown.

MAGNETIC SENSORS

Most sensor applications are power limited; therefore, high sensor resistance is desirable. GMR materials are thin film and have relatively high resistance of 12 and 16 ohms per square. A serpentine 10 kΩ resistor can easily be fit into a square 100 μm space using photolithographically patterned GMR stripes with a 2 μm linewidth. A Wheatstone bridge sensor can be made from four such resistors. Small magnetic shields of permalloy electroplated over two of the four equal resistors in a Wheatstone bridge protect these resistors from the applied field and allow them to act as reference resistances. They have the same temperature coefficient as the active resistors since they are fabricated from the same material. The two other GMR resistors are both exposed to the external field. The bridge output is twice the output from a bridge with only one active resistor. Additional permalloy structures plated onto the substrate act as flux concentrators and increase the field at the sensor resistors. The active resistors are placed in the gap between two flux concentrators as is shown in Figure 5.

The small size and low power of GMR sensors allow them to be fabricated into on-chip arrays of sensors to detect very small magnetic fields with very high spatial resolution. Previously, solid-state magnetic sensors such as Hall-effect and Anisotropic Magnetoresisitive (AMR) sensors were not able to be applied in these applications either due to size, power or sensitivity issues. With the advent of the more sensitive Giant Magnetoresistive (GMR) and Spin-Dependent Tunneling (SDT) sensors, it has become possible to manufacture such arrays. These devices can be used to measure very small magnetic fields, or changes in magnetic fields, associated with magnetic biosensors, non-destructive test/inspection/evaluation, position, document validation including currency and credit cards, and magnetic imaging. Arrays of sensors are necessary for these applications either to provide a large number of independent, analytical sites in a small area as in biosensors or to allow high spatial resolution as in magnetic imaging and sensors for eddy-current detection of hidden flaws. By fabricating sensors directly on a silicon substrate, the signal conditioning and logic capability of integrated circuits can be used to optimize system performance when compared to a collection of sensors supplying raw signals to a processor. This integrated technique reduces the effect of noise and simplifies the sensor/signal-processing interface.

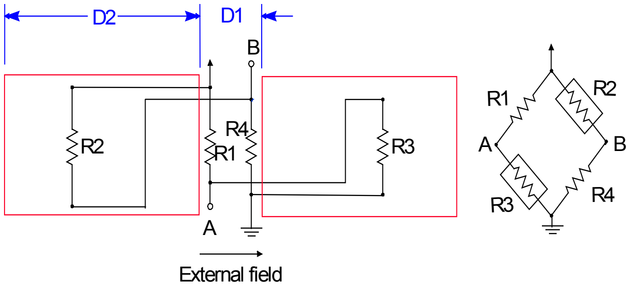


Figure 5. GMR resistors in a Wheatstone bridge sensor. Flux concentrators shown: D1 is the length of the gap between the flux concentrators and D2 the length of one flux concentrator.

Figure 6 shows a portion of an array of 16 GMR half-bridge elements with 5 μm spacing. The elements are 1.5 μm wide by 6 μm high with a similar size element above the center tap. The bottoms of the stripes are connected to a common ground connection and the tops of the half bridges are connected to a current supply. The center taps are connected to 16 separate pads on the die. A bias strap passes over the lower elements to provide a magnetic field to bias the elements away from zero. Due to demagnetization factors, the GMR elements are sensitive only to the component of magnetic field along the stripe of GMR material. This directional sensitivity is very useful in designing vector magnetometers to measure the three components of the magnetic field. It is also useful in eddy-current testing to decrease the background from the excitation coil.

Wider spacing between the elements can be achieved while retaining the directional sensitivity of narrow stripes by using serpentine resistors as the lower elements. For arrays with large numbers of sensors, the chip area required for connections to the outside world becomes excessive. One method of reducing the number of pads is to connect the sensor elements together in a matrix. A 4.5 mm by 2 mm chip has been made with 128 single elements each 32 μm wide for a total width of 4.1 mm. The elements are arranged into two groups of 8 sets of 8 elements connected to 16 leads. Each set of 8 elements has a common ground pad. The other 8 pads are each connected to eight elements -- one in each set of eight. On-chip multiplexing of sensors reduces the number of connections to the chip. The multiplexing can be accomplished by using on-chip FETs to select the device. The patterning of GMR materials on semiconductor underlayers is also important in digital couplers and MRAM applications.

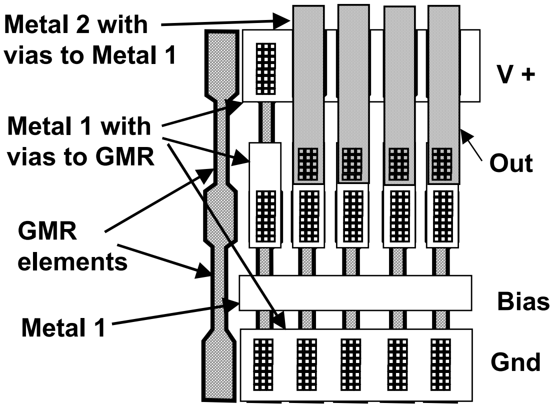


Figure 6. Part of a 16-element array of GMR half-bridge sensors with 5 μm spacing. The first three elements have portions removed to show the three layers and their interconnections.

SPINTRONIC COUPLERS

Using the same sputtering technology, it is possible to build a thin film on-chip coil. A current in this coil, when combined with an on-chip GMR magnetic sensor separated by an insulating layer, can couple a signal across the insulator achieving galvanic isolation. Like the sensor, these components can be combined with other semiconductor functions to produce a very high-speed digital isolator.

In a spintronic coupler, four GMR resistors form a Wheatstone bridge (see Figure 7). A thin polymer dielectric barrier layer provides several thousand volts of isolation from the input coil. A magnetic field proportional to the input current signal is generated beneath the coil winding. The resulting magnetic field flips the spin of electrons in the GMR resistors, changing their resistance. A magnetic shield protects the sensor from external fields.

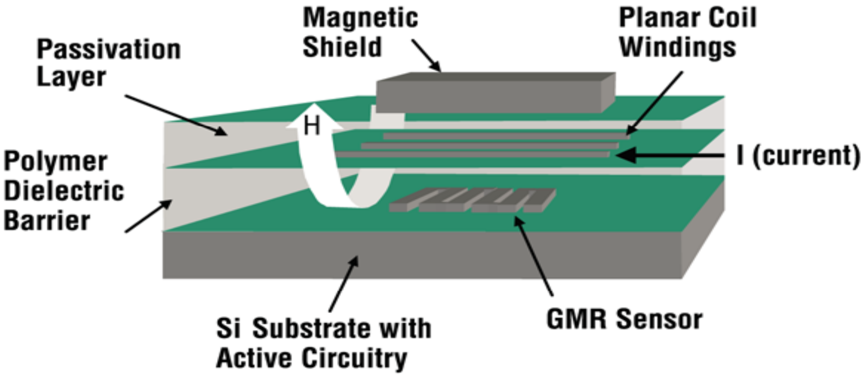


Figure 7. Schematic diagram of a spintronic coupler.

The GMR bridge output is fed to a comparator, which drives either a CMOS output stage or an open drain transistor output. The bridge configuration helps cancel ambient magnetic fields, and the devices also contain an integrated magnetic shield to eliminate interference from external magnetic fields. Ground potential variations are common to both sides of the input coil, so they do not generate an input coil current. Thus ground potential variations are rejected yielding a very high common-mode rejection ratio (CMRR) and true galvanic isolation.

The GMR resistors are sensitive to magnetic fields in the plane of the substrate. This leads to a more compact integration scheme than would be possible with a Hall sensor, for example, which measures fields perpendicular to the substrate. And because of the high sensitivity of GMR, the propagation delay of spintronic couplers is shorter and more stable than a simple MEMs-based pick-up coil.

Advantages of Spintronic Coupling

Spintronic coupling advantages compared to conventional opto-couplers include high speed, small footprint, excellent noise immunity, and unlimited life.

High Speed—Spintronic couplers are at least twice as fast as the fastest opto-couplers and have correspondingly faster rise, fall, and propagation times. Faster rise and fall times also reduce power consumption in the device and system by minimizing time in active regions.

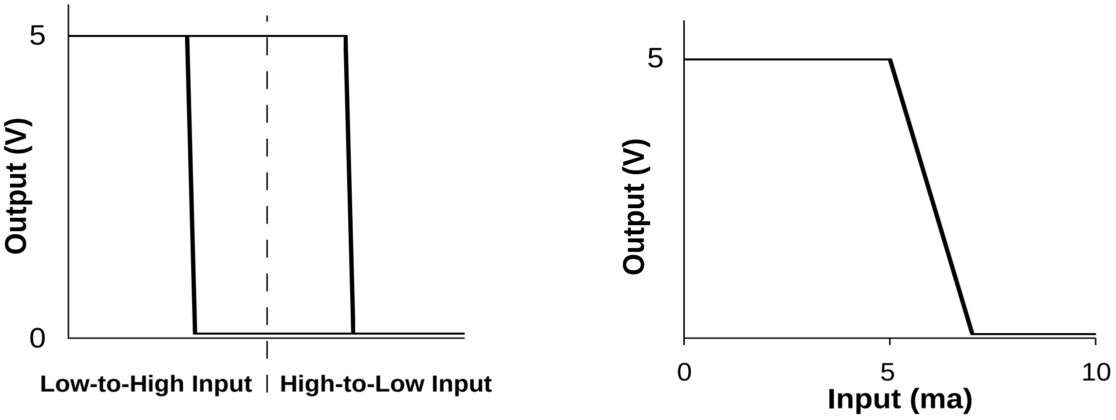
High Channel Density—Unlike opto-couplers, which are discrete devices, and transformers, which are inherently bulky, spintronic couplers are truly monolithic and can be fabricated in less than 1 mm^2 of die area per channel. Their size allows multi-channel devices in an 8-pin MSOP packages. Less board real estate means lower costs and more room for other functions. Furthermore, because of their small die size, spintronic couplers cost no more than high-performance opto-couplers.

Excellent Noise immunity—Spintronic couplers provide transient immunity up to 25 kV/µs, compared to 10 kV/µs for opto-couplers. This is especially important in harsh industrial and process control environments.

Unlimited Life—Opto-couplers, like incandescent light bulbs degrade over time and have limited life. Spintronic couplers have no such wear-out mechanism; they last indefinitely with no performance degradation over time.

Advancements in Spintronic Couplers

The first spintronic couplers used latching GMR and a separate die was used to drive the coil. This type of device is fast and the devices latch in a particular state and remain in that state if the drive is removed (see Figure 8a). Using more advanced spintronics materials, the new current-mode couplers are failsafe, meaning the output returns to a known state when the input signal is removed, much like venerable opto-couplers (see Figure 8b).



Figures 8a and 8b: Digital and current-mode coupler transfer functions.

Like opto-couplers, the new devices have a current-mode input as the signal is applied directly to the coil. The devices can be driven with any input voltage up to 400 volts through a current-limiting resistor. And unlike opto-couplers which typically require at least two volts to turn on the light-emitting diode, the coil-drive input can be driven with just millivolts and typically requires less drive current.

Since the input is applied directly to the coil no driver electronics is needed, and the isolation function can be contained in a single die, making the new products true monolithic couplers. The single-die design has also made possible what are billed as the world's smallest packaged couplers, with 3 mm by 3 mm MSOP-8s housing two-channel devices.

Integrated Isolated Network Transceivers

Spintronic couplers can be combined with conventional integrated circuits to create single-package isolated transceivers. Spintronically-coupled RS 485, RS 422, and Profibus isolated transceivers are available in 16-pin SOIC packages. With the speed of spintronic couplers, these devices support data rates as high as 35 megabaud—the fastest single-package isolated transceivers.

MAGNETIC RANDOM ACCESS MEMORY

Magnetic Random Access Memory is potentially an *ideal* memory because it has the properties of nonvolatility, high speed, unlimited write endurance and low cost. These memories use the hysteresis of magnetic materials for storing data and some form of magnetoresistance for reading out the data. Because of the difficulty of separately connecting a large array of memory cells with complex integrated support circuits, the memory cells and support circuits are connected together on chip.

Work on MRAM started devices based on Anisotropic Magnetoresistance (AMR). The change in resistance of AMR materials, about 2 per cent, offered severe challenges in making high-density MRAM. The difference between reading a 1 and a 0 was about 1 mV in practical devices. The interest was mainly for military applications and small capacity nonvolatile memories and 16 kbit integrated MRAM chips were developed by Honeywell and qualified for military applications in the mid 1990s.

The discovery of GMR with its much higher change in resistance, revitalized the interest in MRAM and offered the promise of higher density MRAM devices. A scaling indicates that a factor of 3 in magnetoresistance improves the read time by a factor of 9. A selected bit could be written by a combination of fields from currents in a matrix of word lines and sense current lines. This writing scheme is shown in Figure 9. Reading out the state of the bit is done by sensing the differential resistance of the cell when a sense current is passed through it.

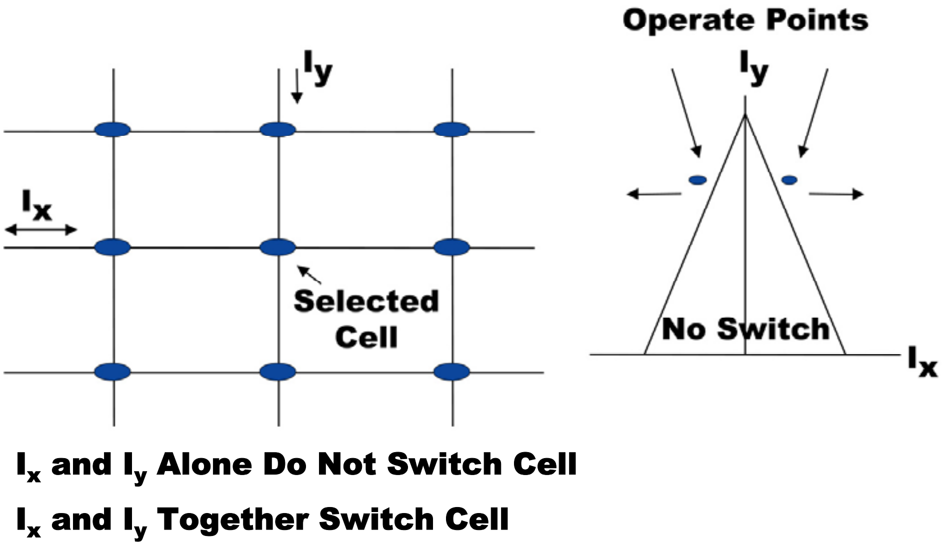


Figure 9. Write criteria or 2-D array of magnetic memory cells.

Magnetic tunnel junctions with their very high magnetoresistance have opened the possibility of higher signals and faster read times for MRAM. The important characteristics of MTJs are their large magnetoresistance values, their high resistance, and their low operating voltage. The magnetoresistance decreases if the voltage across the junction is over a few tenths of a volt, and catastrophic breakdown occurring at 1 to 2 volts. Read and write circuits must be separate. One method used to select the cell to be read is to incorporate an isolation transistor in each cell. This scheme is shown in Figure 10.

Several companies are currently working on programs to bring commercial MRAM to the market. Freescale Semiconductor (Motorola) sampled MRAM in 2003 with limited availability of 4 MB in 2004. Cypress Semiconductor has projected samples by year's end 2004. Other companies with MRAM programs include. IBM, ST Microelectronics, Philips, Infineon, Toshiba, NEC, Taiwan Semiconductor and Samsung. There is little question that MRAM will be available. The question remains as to how much they will displace conventional semiconductor memory.

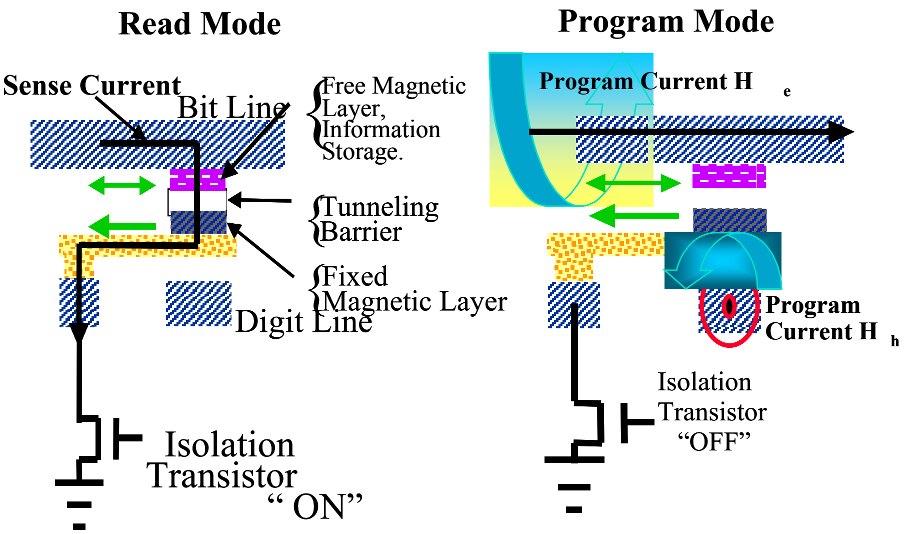


Figure 10. Example of an MTJ memory cell structure using isolation transistor.

CONCLUSIONS

Spintronics is a technology with a fast track from the discovery of GMR and MTJ materials to the incorporation of these materials in commercial devices. Spintronics read heads dominate the hard-disk market. Magnetic sensors based on spintronics are making inroads in markets where some combination of high resolution, high sensitivity, small size, and low power are required. Digital data couplers and displacing opto isolators in many applications and are making inroads into new markets heretofore unavailable. MRAM devices are on the horizon and offer the promise of laptop computers that do not need to boot up and cell phones with increased battery time and increased capabilities.

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