Sensors and Isolators Using Spin Dependent Transport

by

Jim Daughton, NVE

Abstract - Three product designs using Giant Magnetoresistance (GMR) and Spin Dependent Tunneling (SDT) are described. A cylinder position sensor using GMR multilayers is designed so that the indicated position is relatively independent of temperature and source voltage. Two chips, a sensor chip and a signal conditioning chip, are packaged in miniaturized integrated circuit packages for cylinder position applications. A variation of a spin valve structure is used for a galvanic isolator, where an input current into on an on-chip coil generates a magnetic field sensed by a resistance bridge made of the spin valve material. A high speed version of this isolator could use a pinned-edge GMR sandwich to improve performance, and a potential application of the high speed isolator could facilitate higher system performance. A SDT material is used for a low field sensor, in which a hard layer is pinned using a synthetic anti-ferromagnet to minimize stray fields from the hard layer, and the soft layer is biased, orthogonal to its easy direction and slightly above its anisotropy field, for high easy direction sensitivity to magnetic fields. Although integrated coils were used for biasing, Neel coupling may be used for biasing in the future. 1/f noise in SDT sensors limits their low frequency performance.

I. Introduction

Real product experience with GMR and SDT structures is somewhat limited outside of read heads for hard drives. It is the purpose of this paper to describe three sensor and isolator product design concepts using these materials and to discuss some of the practical problems in making these products producible. The first design is a digital (on/off) magnetic sensor that must turn on at about the same magnetic field over a broad range of supply voltages and temperatures. The second is a galvanic isolator using an on-chip coil and magnetic sensor, where a building-block approach allows a number of products to be fabricated from a relatively small set of functions at the chip level. The last design is a low field SDT sensor, where an orthogonal bias mode of operation is intended to optimize the resolvable magnetic field.

II. Digital Magnetic Field Sensor

GMR sensors have found many applications, including pneumatic cylinder position sensing, currency detection, in-bearing encoders, current and current limit detection, rotational position sensors, noiseless locking mechanisms, vehicle sensors, and crankshaft position sensors. In this section, a digital magnetic field sensor design intended primarily for cylinder position sensing will be discussed.

Cylinder position sensing uses a magnetic sensor outside a cylinder wall to detect the position of a piston which has a permanent magnet attached, as depicted in Fig. 1. The sensor is a digital sensor, i.e. there are two outputs (high voltage or low voltage) which indicate the presence or absence of the piston. The position of the sensor relative to the position of the piston is normally determined by sliding the sensor along a slot in the cylinder housing to a position where the magnetic field turns on at the desired position of the piston, and a set screw is tightened to lock the sensor in place. For accurate position indication, the sensor should turn on at the same piston position over a wide range of temperatures and supply voltages. It will be shown later that a GMR multilayer sensor can meet this requirement very well.

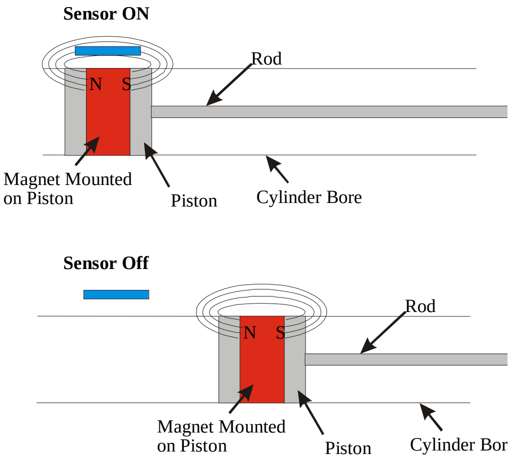

Fig. 1. Cylinder position sensing.

A typical layout of a commercial GMR bridge sensor using 4 approximately equal value resistors (R1,R2,R3,R4) made with GMR multilayers is shown in Fig. 2 [1]. Two legs of the bridge have additional trimming resistors with trim sites which can be zapped with an automated laser trimmer.

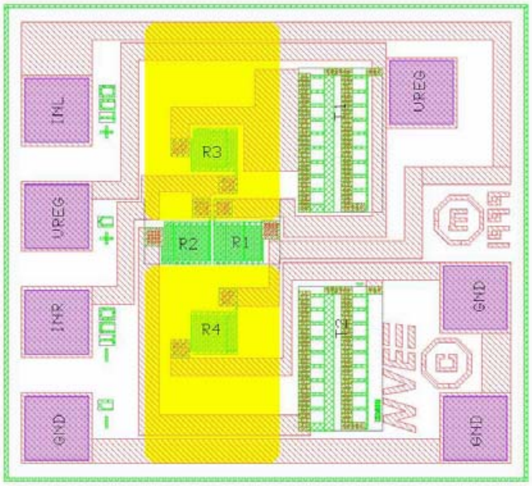

Fig. 2. Layout of Commercial GMR Multilayer Sensor

The signal output from the bridge as a function of applied field is shown in Fig. 3. The signal is symmetric with applied field direction, but in this figure a current source was used for positive fields and a voltage source for the negative fields. Note that the signal voltage is relatively constant over temperature for the current source as compared to the signal using a voltage source. Although there is some hysteresis at low magnetic fields (not apparent in the figure), there is little hysteresis above about 10 Oe. Note that as temperature changes, the output voltage is relatively constant so long as the applied field is less than about 30 Oe. These characteristics suggest

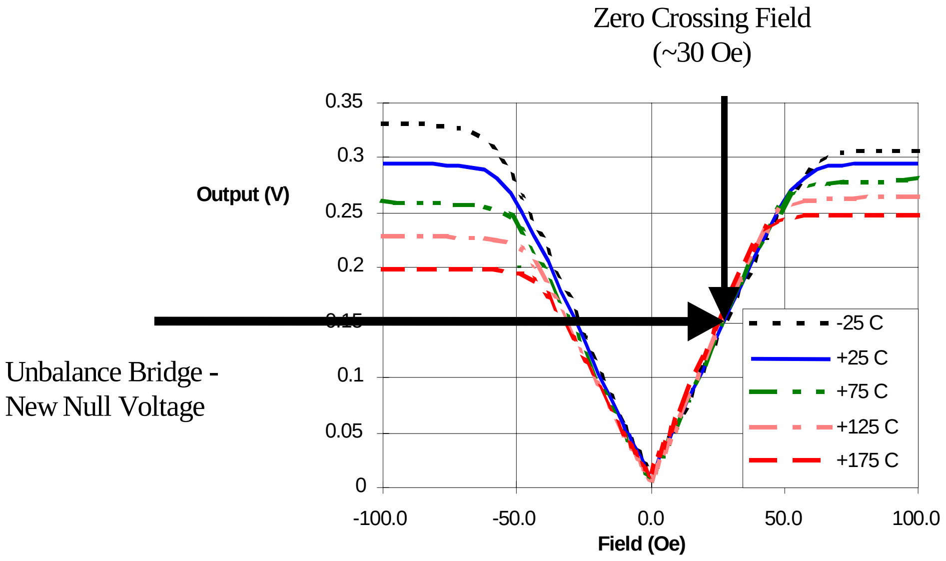

Fig. 3. Bridge sensor output voltage as a function of applied magnetic field. New null voltage and zero crossing field can be attained with laser trimming.

a very stable bridge output in a range of magnetic fields from 10 to 30 Oe. The sensor uses flux concentrators, which can be lengthened or shortened by design, and thus achieve a wide range of field sensitivities.

If the resistors in the GMR bridge are laser trimmed so that the voltage across the bridge is negative with zero magnetic field, then the zero voltage intercept will be at a higher magnitude field. Thus, a GMR bridge can be trimmed so that the bridge output increases through zero voltage at a specified magnetic field. The zero-crossing field of a bridge of this type is relatively precise, i.e. the zero-crossing occurs at about the same magnetic field over a broad temperature range (and supply voltage range as well).

A simple comparitor circuit can be used in combination with the bridge described above. This circuit provides one output voltage level when the bridge signal voltage increases through zero voltage and returns to a different voltage when the bridge output goes negative. The output of the comparitor connected to the bridge thus changes from one level to another at a specified magnetic field. Some hysteresis is built into the electronics to prevent an uncertain output.

The cylinder position sensing system must also be designed in such a way as to account of the strength of the permanent magnet and the thickness of the cylinder wall. The orientation of the permanent magnet also varies from application to application. In cylinder position sensing, space is at a premium, and there is continuous market pressure to reduce the size of the sensors. A very flexible design concept is required to satisfy the diverse requirements for the many cylinder position applications.

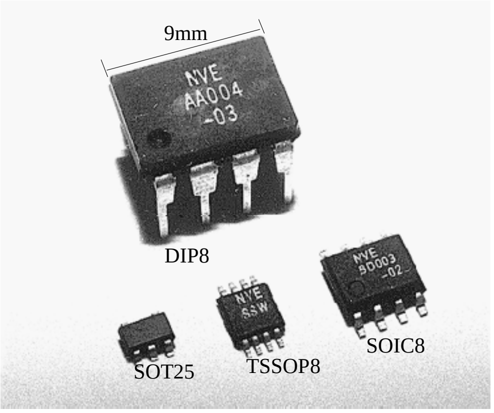

Fig. 4. Integrated circuit packages used for GMR sensors.

Fig. 4 is a picture of a series of integrated circuit packages that have been used for GMR sensors. The smaller packages, TSSOP8 and SOT25, are the most desirable for many cylinder position applications. Because of the small GMR chip sizes and advances in inter-chip bonding, both the GMR bridge and the signal conditioning chip can be connected inside the TSSOP8 package, as indicated in the assembly diagram shown in Fig. 5. Both chips can also be packaged in the SOT25 package by stacking the chips one on top of the other, and wire-bonding between them (between top and bottom chips).

One of the advantages of the two chip approach is the flexibility which it provides in satisfying the broad range of requirements for cylinder position sensing. As mentioned earlier, a range of magnetic field sensitivities can be attained through trimming. The sensor chip can be rotated to change the directions of sensitivity of the sensor. Several different signal conditioning circuits can be designed on one chip, and alternative circuit functions can be obtained by wire bonding to different output pads on the chip. With two different IC designs (eight wiring options), two sensor directions, 4 magnetic field ranges, two package designs, there is potential to make 128 different product configurations -- and have adequate applications flexibility.

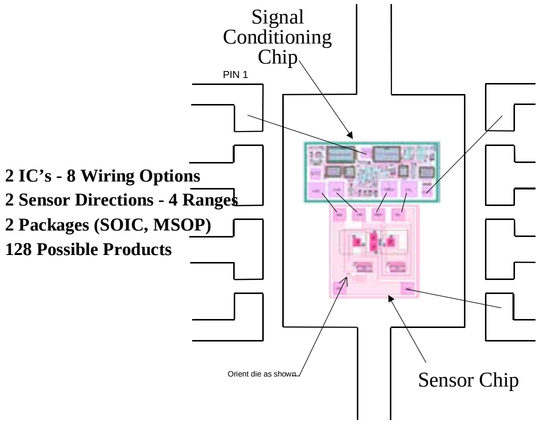

Fig. 5. Two chip sensor configuration for the MSOP package.

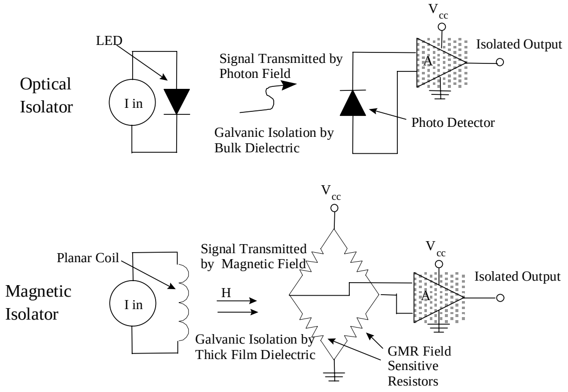

Fig. 6. Opto-isolator and IsoLoop isolator functions.

III. GMR Isolator (IsoLoop)

Galvanic isolation provides a means of seamlessly passing signaling information while isolating ground potential differences and common mode transient events. Besides being a good design practice, isolation components are often mandated in industry standard specifications for applications such as data bus communications where two separate systems interface through common copper connections. Other examples include modems, local area and industrial network interfaces, telephones, switched mode power supplies, printers, and fax machines. Fig. 6 illustrates the isolation functions using optical isolation (opto-isolator) and magnetic isolation (IsoLoop) [2].

As reported elsewhere, our company has developed this new kind of isolator which uses the combination of integrated on-chip coils and GMR sensing [2,3,4]. Fig. 6 illustrates the physical orientation of the integrated planar windings and the GMR sensor. A polymer dielectric barrier provides up to 6000 V isolation from the coil to the GMR sensor. A magnetic shield provides the dual function of reducing the effects of external magnetic fields and doubling the field applied due to currents in the on-chip coil. GMR sensors are configured as a bridge, with opposing directions of magnetic fields applied to two pairs of magnetoresistors in order to obtain a significant bridge output signal when current is applied through the coil.

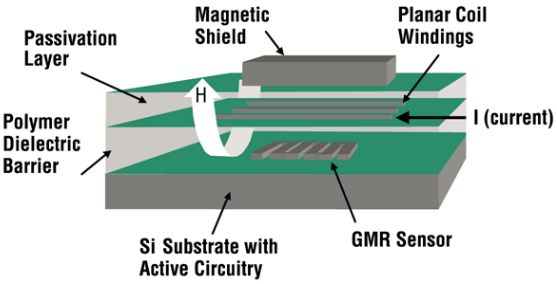

Fig. 7. Cross-section illustration of the GMR isolator concept.

A key to the successful design of an IsoLoop is the cross-section of the shield-coil-dielectric, which must provide the magnetic field and the stand-off voltage between the input circuit (coil) and the output circuit (GMR sensor). The cross-section is rather thick, with the dielectric being on the order of 10 microns thick and the permalloy shield being on the order of 8 microns thick. Development of a mechanically stable structure not subject to premature electrical leakage and breakdown was the most challenging task in the development of prototype products. Once that was developed, using a variation of a spin-valve [5] to make a 4 element bridge was straightforward. A comparitor similar in function to the one used in the digital magnetic sensor is used to provide an output signal from the receiver chip.

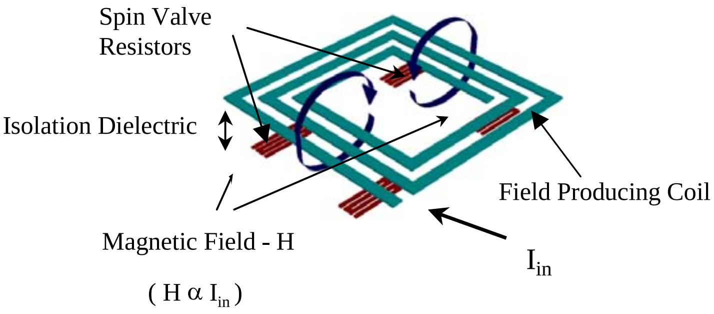

Fig. 8. Field drive for IsoLoop bridge resistors

First IsoLoop products also use a second chip, a transmitter. The transmitter takes an input pulse and "differentiates" it to make positive and negative current spikes. It is these spikes which drive the spin valve into two different remanent states, giving two distinct outputs from the receiver chip. For a single channel part, there are thus two chips, a transmitter and a receiver, in one integrated circuit package. A "building block" approach allows the fabrication of a number of integrated isolator products using standard receiver and transmitter chips in common with a few interface chips for standard communications protocols. Some of these integrated products are illustrated in Fig. 9.

One of the key advantages of the IsoLoop is its ease of integration with on-chip electronics. Multi-channel isolators, potentially integrated with other communications electronics, are relatively easily designed and fabricated. Implemented using today's opto-isolator technology, this part requires 4 separate packages. NVE builds an RS 485 product with IsoLoop technology using 3 small chips in a single SOIC integrated circuit package, and should be possible to implement this function with two chips in the future.

Today's IsoLoop prototype products can run at 100 MHz (200 M baud) as compared to about 20 M baud for the fastest commercial opto-isolators, and with additional development, the GMR isolator could be made to operate at much higher speeds. The improved performance of this new component depends on several factors. The first is to insure high-speed switching of the magnetic material using “rotational switching". Rotational switching of magnetization in soft ferromagnets can occur in 0.2 ns if the angles of rotation are limited to a few tens of degrees. Other factors are parasitic inductance and capacitance in packaging the chip, which in large part depend on the size and lead lengths of the package and the kind of integrated circuits used. Current designs minimize power consumption by generating current spikes from pulses on the input side of the isolator, and then turning the input current off until the next input transition occurs. A high speed approach would be a direct drive, i.e. the drive current would be a replica of the input current rather than current spikes.

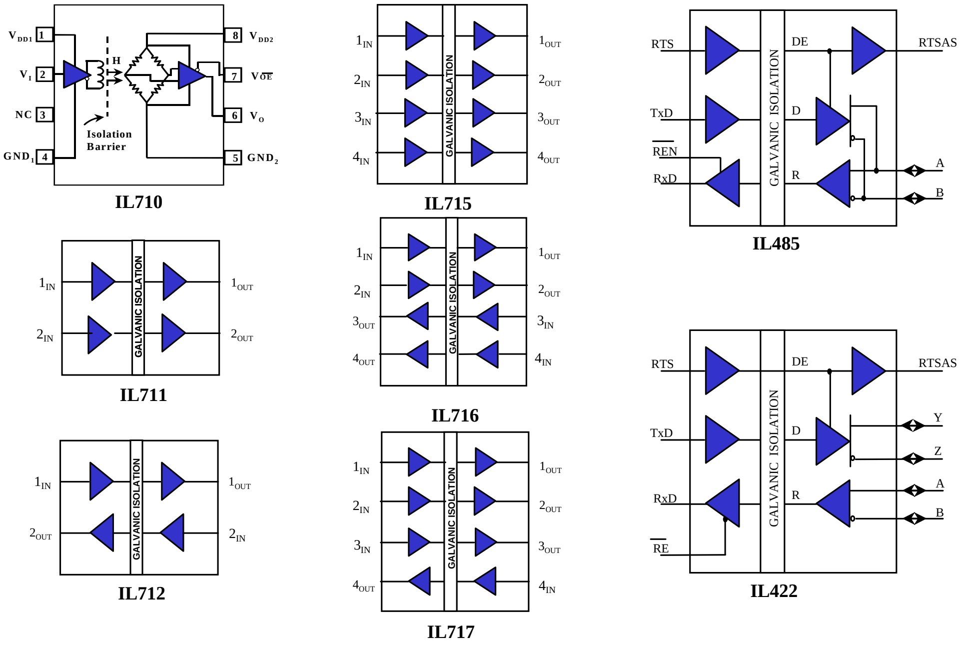

Fig. 9. Integrated IsoLoop products using standard transmitter and receiver chips.

A GMR structure which could be especially suitable for a fast isolator is the pinned-edge sandwich structure. This structure is similar to the spin valve structure, but without a pinning layer. The edges are treated in processing so that the magnetizations at the edges of the stripe are pinned along the stripe, with about 100-300 Oe required to reverse the edge magnetizations. Operating characteristics (major and minor loops) of two micron stripes with pinned and unpinned edges are shown in Fig. 10. With the proper line width (about one micron), the magnetoresistance of the stripe can be "biased" into a linear resistance vs field operating point. An isolator made with this material could be used in the rotational mode for operation in the one GHz range. A similar structure was described by A. Pohm [6] for use in a read head.

Development of a high speed IsoLoop would enable system grounds to be partitioned into functional blocks, and bus connections between functional blocks would be made through these isolators, giving clean input signals to each of the functional blocks with a minimum of delay. Faster rise times, higher currents, and lower supply voltages are making the problems of ground noise in systems more important [7]. The insertion of these isolators could greatly reduce the efforts of ground noises, and thus allow the systems to run faster.

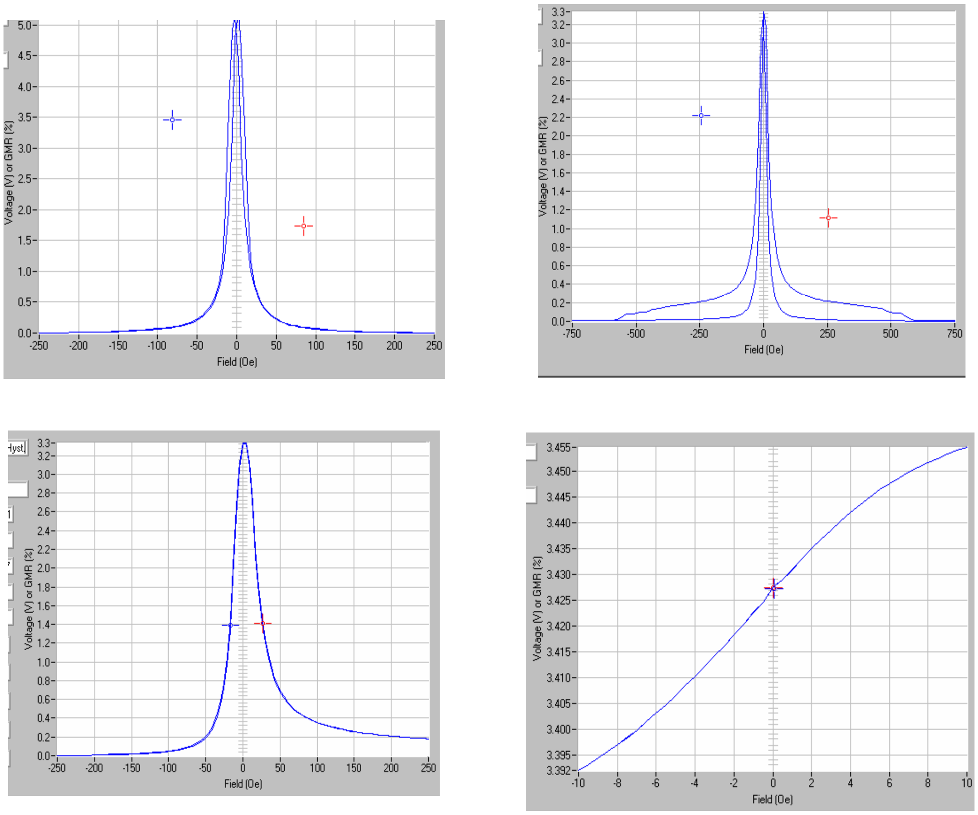

Fig. 10. Resistance field characteristics for GMR sandwiches.

Two micron stripe without edge pinning (upper left). Two micron stripe with edge pinning (upper right). Two micron stripe with edge pinning - minor loop (lower left). 0.6 micron stripe with hard edges - minor loop (lower right).

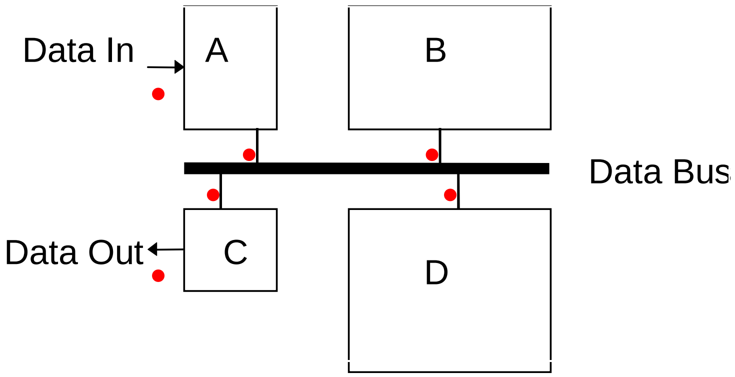

Fig. 11. System configurations with isolators shown as ●.

A block diagram illustrating the system level concept is shown below in Fig.11. There is a trend in electronics to derive the voltages for blocks from a primary power source, thus isolating the power between blocks. The design approach eliminates commons grounds between the blocks by using high performance GMR isolators (shown with a ●) for all signal paths in and out of the circuit blocks. This concept could work for a broad range of packaging concepts such as hybrid structures, mother-daughter boards, and chip-on board. The isolators would be packaged in miniaturized packages consistent with the systems packaging technology.

The expected payoff would be a significant increase in permissible operating speed and data reliability between communicating systems of all types. Reliable system data rates of 2 G baud and delays of less than 0.5 ns could be possible with the proposed technology using existing low cost copper physical layer media without resorting to costly optical interconnect.

III. SDT Low Field Sensor

There are both military and commercial applications for magnetic field sensors which can detect magnetic fields at or below the micro-Gauss range. By virtue of their sensitivity, spin dependent tunneling (SDT) devices have the potential to satisfy these applications needs [8]. Potential applications include perimeter or intrusion detection, vehicle detection, and nondestructive evaluation. Currently, the market is served by SQUID and flux gate sensors, but the SDT sensor could potentially be superior in size, power and cost.

A magnetoresistance of 30% or higher with a saturation field of less than 10 Oe has been achieved by a number of workers, and a number of others at this symposium will discuss these structures. The most common form of data presented on SDT is a square loop of tunneling resistance as a function of field. It is probably not practical to use the steep slope of this square loop as a low field sensor because the operating point would not be stable relative to the magnitude of the low field to be measured. A linear mode of operation can be obtained through biasing the soft layer in a pinned SDT device.

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A low dispersion (uniform easy direction and uniform anisotropy) film is very sensitive to magnetic fields in the easy direction when a hard direction bias field of approximately the anisotropy field is applied. Under that bias condition, the anisotropy is approximately nulled out for low fields in the easy direction. Further, when the bias field is slightly larger than the anisotropy field, the film is essentially saturated, and noise associated with domain walls can be largely eliminated. The biasing gives the situation which is shown in Fig. 12.

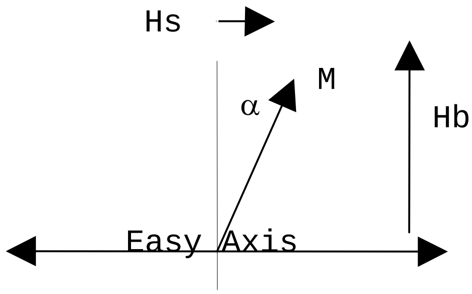


Fig. 12. Biasing a uniaxial anisotropic film with Hb ~ Hk makes the magnetoresistance of a SDT device very sensitive to applied fields (Hs).

The bias Hb is intended to be slightly higher than Hk, and if the torque equation is written in terms of α, the angle the magnetization makes wrt the bias field, then

$$Hs*\mathrm{Cos}\alpha - Hb*\mathrm{Sin}\alpha + Hk*\mathrm{Sin}\alpha\mathrm{Cos}\alpha = 0$$

Now let $Hb = Hk(1 + \delta)$, and let $Hs/Hk = hs$. Then,

$$hs*\mathrm{Cos}\ \alpha - \mathrm{Sin}\alpha[1 + \delta - \mathrm{Cos}\ \alpha], \text{ or}$$

$$hs = \mathrm{Sin}\alpha[1 + \delta - \mathrm{Cos}\ \alpha]/\mathrm{Cos}\ \alpha$$

Let α and δ be small, then

$$hs = \alpha\delta, \quad \text{or } \alpha = hs/\delta$$

Now since the effective resistance varies as $\mathrm{Sin}\alpha$,

$$(\Delta R/R) = (JMR/2)\mathrm{Sin}\alpha \sim (JMR/2)\alpha = (JMR/2)hs/\delta$$

This is the ideal expression for the operation of the sensor. For example, if Hk = 18 Oe, JMR = 30%, and $\delta = 0.1$, then the ratio $(\Delta R/R)/Hs$ would be about 0.08/Oe, a respectable sensitivity. This mathematical model would suggest that an infinite sensitivity as δ approaches zero. Dispersion of the magnetic film anisotropy and non-homogeneous biasing fields limit the achievable sensitivity. A plot of resistance as a function of applied field with a hard direction bias is shown in Fig. 13. The offset of the curve from zero field is due to exchange coupling between the soft and pinned layers.

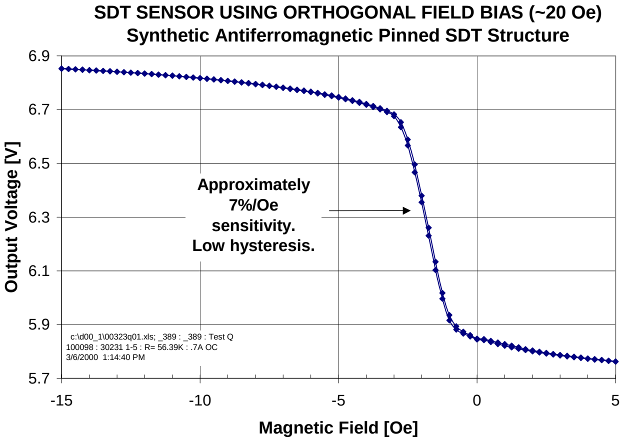


Fig. 13. Resistance-field plot for a biased SDT resistor indicating a 7%/Oe sensitivity.

One design challenge is operation at a reasonable voltage level (5-10 Volts) in order to get high output voltage. Because the best operating voltage for an SDT device is about 100 mV, it is necessary to connect in series a number (N) of these devices. The noise should increase with the square root of N, while the signal increases directly proportional to N, and the signal-to-noise ratio will improve as the square root of N. With 16 devices in series, the operating voltage can be brought up to 1.6 V, and with a JMR of 30%, the maximum voltage swing across a SDT device would be 480 mV.

The essence of the unit SDT cells is a pair of hard magnetic contact areas (pinned in the easy direction of the soft layer) and a single soft layer (which is biased in the hard direction). There are two junctions in series, with soft layer acting also as a series connection between the junctions, as shown in Fig. 14. In actual bridges which we fabricated, there are approximately 50 junctions per resistor leg.

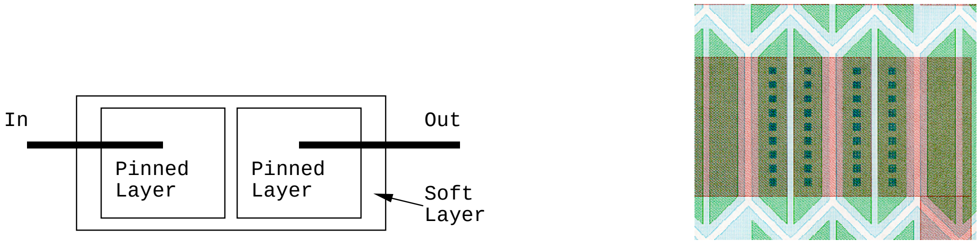


Fig. 14. Diagram showing connection of two SDT junctions through a soft layer (left) and layout of some of the elements of a SDT bridge resistor.

A number of SDT bridge sensors with integrated coils have been fabricated over the past two years. Fig. 15 displays the sensors in various stages of completion. During this time the designs have evolved and improved with respect to sensitivity. Flux concentrators of a similar design to those used in the commercial GMR sensors provide improved sensitivity. Use of synthetic antiferromagnet reduces stray fields and improves sensitivity. Current feedback through an integrated coil applies a bucking field in the applied field direction, which improves the linearity and dynamic range of the sensor.

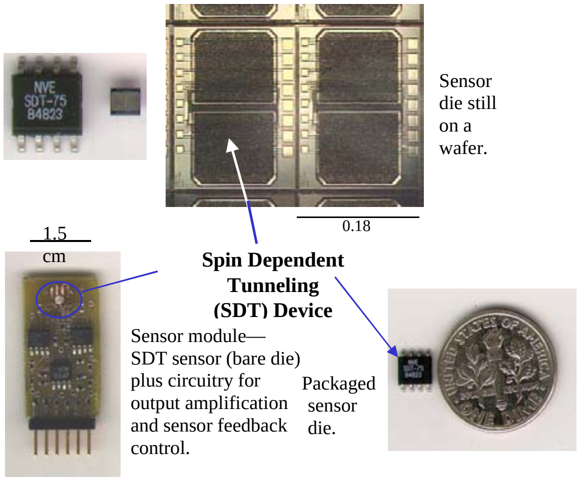


Fig. 15. SDT sensors in various stages of assembly.

The biggest challenge in achieving high sensitivity at low frequencies is 1/f noise. This noise in our standard SDT sensor elements has a magnitude of 10^{-7}rmsV/VrtHz at one Hz, and appears to be relatively independent of magnetic state, i.e. the noise does not change noticeably after clamping the magnetization with a large magnetic field. The noise is proportional to current through the element. Figure 16 shows a scatter plot of 1/f noise for a number of wafers and measurements over a wafer. The noise figure is normalized to a standard device area. There are obviously large variations in noise, and methods for reducing the noise are being investigated.

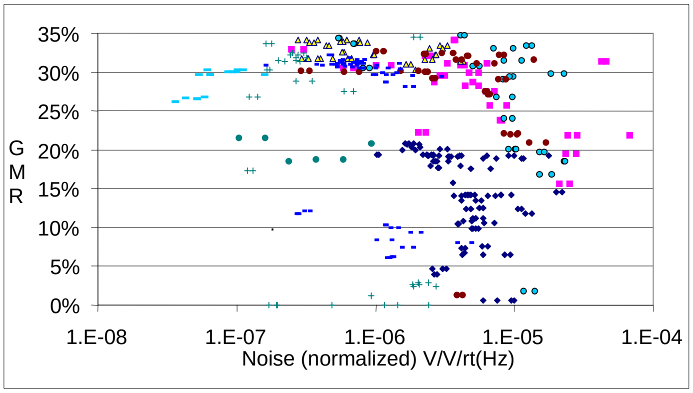
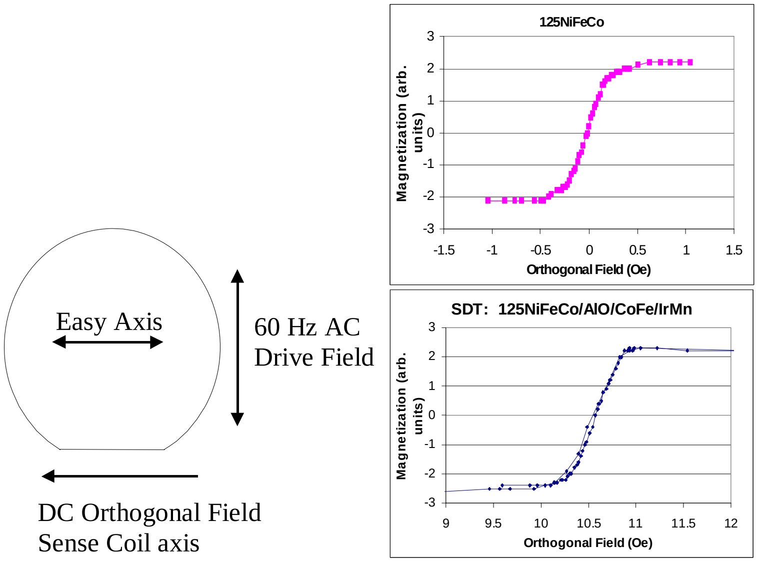


Fig. 16. 1/f noise in a number of SDT process runs.

Another area of desired improvement is the elimination of the bias coil that applies the hard direction bias. The use of coupling due to roughness of a pinned layer in contact with the soft layer could be promising. We measured the "dispersion" of a SDT material on a 4 inch wafer, where non-uniformity of the coupling field from the hard layer could be detected. A normal dispersion test applies a large ac field in the hard direction, and detects flux in the easy direction. With the application of a small easy direction field, the magnetization should rotate in the half-plane defined by the easy direction field. The strength of the easy direction field needed to get most of the magnetization to stay in that half plane is a measure of the "angular dispersion" of the film. A pinning layer effectively adds a bias field on the soft layer in the direction the hard magnetic layer is pinned. The data in Fig. 17 show that the pinning field from the hard layer is amazingly uniform over a four inch wafer, about 10.6 Oe with less than a 0.6 Oe variation.

IV. Acknowledgements

The work discussed in this paper was performed by the employees of NVE, nearly all of whom have played some part in developing the ideas and in obtaining the results highlighted in this paper. The work was largely financed through contracts with DARPA, the United States Navy, the United States Army, the Department of Commerce, and the National Science Foundation.



NiFeCo Film
H_k = 18 Oe
Dispersion (90%) =0.9º

NiFeCo Film in SDT stack
H_k = 18 Oe
Dispersion (90%) =0.9º
Coupling Field =10.6Oe
Coupling Variation < 0.6Oe

Fig. 17. Method of measuring angular dispersion and data on an isolated soft film and data on a soft film in proximity to a pinned layer.

V. References

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