ELSEVIER

Journal of Magnetism and Magnetic Materials 192 (1999) 334–342

Journal of magnetism and magnetic materials

GMR applications

J.M. Daughton*

Nonvolatile Electronics, Inc., 11409 Valley View Road, Eden Prairie, Minnesota, MN 55344, USA

Received 19 August 1998; received in revised form 17 September 1998

Abstract

Giant magneto-resistance (GMR) materials have magneto-transport properties which determine their suitability for applications in magnetic field sensors, read heads, random access memories, and galvanic isolators. Each of these applications for GMR materials is discussed, and desirable materials development are described. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: GMR; Sensors; Read heads; Random access memory; Isolators

1. Introduction

Ten years after the discovery of giant magnetoresistance (GMR), commercialization of the technology is evidenced by product introductions in magnetic field sensors and read heads for hard drives. This comparatively short introduction time was facilitated by the prior existence of similar products using anisotropic magnetoresistance (AMR) materials. While the primary driving force behind the industrial introduction of GMR materials is their high magnetoresistance, other material properties of GMR materials are extremely important to applications. This paper first examines some of these material properties, and then discusses some current and potential applications of GMR materials. Some desirable future advances in GMR materials will be discussed.

2. GMR material properties

Magnetoresistance (the percent change in resistivity with respect to its lowest value under application of a range of magnetic fields) and the magnetic field required to achieve the full range of the material's resistance (saturation field) are two of the most important material properties for GMR material applications. The rate of change of resistance with magnetic field (sensitivity) determines the signal generated by a magnetic field when the field is less than the saturation field.

Table 1 compares some typical magnetoresistance, saturation field, and sensitivity values for a range of GMR materials. A magnetic sandwich [1] is a spin valve [2] without a pinning layer. Granular films [3] are thicker films made of immiscible magnetic and nonmagnetic conductors. Spin dependent tunneling (SDT) structures [4] use a different conduction mechanism from those materials commonly called GMR materials, but for purposes of discussion they are treated as GMR materials in this paper.

---

* Tel.: + 1-612-996-1607; fax: + 1-612-996-1600; e-mail: daughton@nve.com.

PII: S0304-8853(98)00376-X

Table 1
Comparison of typical properties of GMR materials

	% Magneto- resistance	Saturation field (Oe)	Sensitivity (%/Oe)	Comments
AMR	2	5–20	0.4	
Multilayer	10–80	100–2000	0.1	Hysteresis
Granular	8–40	800–8000	0.01	Hysteresis
Spin valve	5–10	5–50	1.0	Thermal?
Sandwich	5–8	10–40	0.5	
CMR	100	1000	0.1	High TCR
Tunneling	10–25	5–25	2.0	High R

Comparison between multilayers and granular structures shows an advantage in GMR and sensitivity for multilayers. It could be postulated that the granular structure is easier to fabricate, but no serious obstacles have been encountered in making multilayers, especially at the so-called 'second peak' thickness for the nonmagnetic conductor in the multi-layer [5]. With computer-controlled sputtering equipment designed for good thickness uniformity, multilayers are relatively easy to manufacture, and hence there is no obvious need for the granular structure at this point in time.

Colossal magnetoresistance (CMR) can give very large changes in resistance with applied magnetic fields [6], but would probably be difficult to apply because of operating temperature (generally well below room temperature), and even more so because of an extremely high temperature coefficient of resistivity (TCR). This latter property would make it difficult to compensate for temperature shifts so as to distinguish between temperature and magnetic field in a practical application. With CMR properties as they now stand, the material would not find widespread use.

The other materials listed in Table 1 are finding use in practical devices. AMR materials (permalloy thin films) have good sensitivity at fields below about 10 Oe, but will yield a smaller signal than spin valve, sandwich, or tunneling materials at fields higher than about 5 Oe. The sensitivity of multilayers is not as high as for the other three, but there are applications which use several hundred Oe field, and in these the other GMR structures and the AMR structure would be saturated, making the multilayer a better choice based on output in higher field applications.

There are several important thermal characteristics of magnetoresistive materials. TCR has already been mentioned. (GMR and SDT devices have satisfactory TCRs on the order of 1500 and -700 ppm/°C, respectively). Short term (a few hours) thermal stability is important in fabrication of devices, where modern processes frequently exceed 200°C. Where integrated circuits are combined with the GMR materials, the temperatures can be even higher. Long term (thousands of hours) stability is essential to product reliability. Except for automotive and certain industrial applications, operating temperatures rarely exceed 125°C. The magnetic sandwich is stable to operating temperatures above 200°C. Thermal properties of spin valves have not been as desirable, but have recently improved greatly with the use of iridium manganese [7] and nickel manganese [8] as antiferromagnetic pinning layers, and hence operating temperature is less of a concern for spin valves than it was a few years ago.

Magnetostriction has not been reported as a problem in GMR materials, but there is potential for problems, particularly in devices with small features. Most reported alloys are nominally nonmagnetostrictive in bulk, but magnetostriction in thinner layers may present problems with shifting magnetic properties. This area is worthy of more research than has been reported to date.

The resistance of a device is also an important parameter. In GMR devices the resistance is a function of the length and width of the device, with the sheet resistivity usually in the 2–20 Ω/square range, where its number of squares is its ratio of the length to width. For very small devices which are constrained to be only a few squares (as in memory and read heads), the resistance will be on the order of 10–20 Ω. SDT devices, on the other hand, have a resistance inversely proportional to device area. Typical resistances vary considerably depending on processing parameters, and values ranging from 10^4 to 10^9 Ω μm^2 are common. Even resistances at the lower limits of this range will result in a square micron device with 10^4 Ω resistance, and several orders of magnitude higher are easily attainable.

SDT devices are relatively new, but their intrinsically high sensitivity and high resistance are very promising for some applications. Two potential problems with spin tunneling are: (1) magnetoresistance declines for voltages across the device exceeding approximately 0.1 V, with an irreversible breakdown occurs at about 2 V and (2) uncertainty in the ruggedness of very thin barriers with respect to elevated temperatures. In addition to these problems, their high resistance can result in long RC time constants, particularly where high density requirements dictate small areas.

3. Current and potential applications of GMR materials

There are several current or potential applications for devices based on GMR or SDT materials. Announced products include magnetic field sensors and read heads for hard drives. SDT materials show promise for improved signal/noise ratios, which could extend the use of GMR sensors to much lower magnetic fields. Several companies (including IBM) have announced GMR read head products for hard drives. There are several large development programs in the US and Europe aimed at using GMR or SDT materials for nonvolatile random access memory. A derivative of GMR sensors can make it possible to isolate digital and analog signals in networks to preserve data integrity and to prevent transient damage to components elsewhere in the system. In this section, the status of each application is discussed in turn along with some future projections.

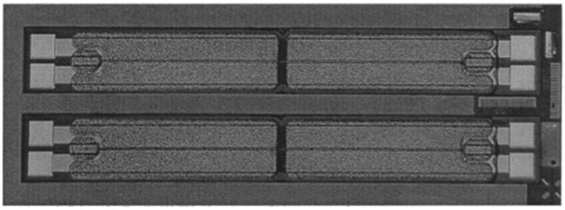

Fig. 1. Top view of two GMR bridge sensor chips.

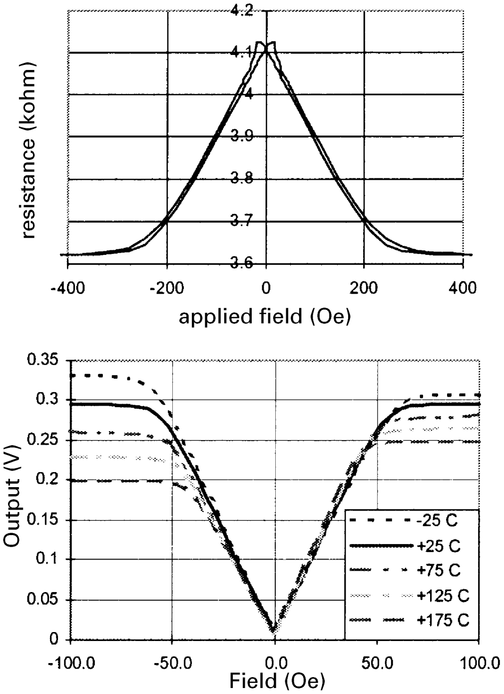

Fig. 2. GMR multilayer resistance (left) and bridge output (right) as a function of applied field.

Sensors – The first commercial GMR sensors, which were introduced in 1995, use multilayer GMR materials [9]. The use of shields and flux concentrators allow the sensors to operate at fields of 10–100 Oe using GMR materials with saturation fields of 200–300 Oe. Fig. 1 is a picture of two bridge sensor chips prior to chip packaging. Fig. 2 shows a GMR multilayer's response to magnetic field along with the resulting output of a Wheatstone bridge using a current source or voltage source to drive the bridge, with operating temperature as a parameter. With a current source, the bridge output decreases with temperature at the rate of about 4% per 100°C, whereas the output declines at the rate of about 30% per 100°C with

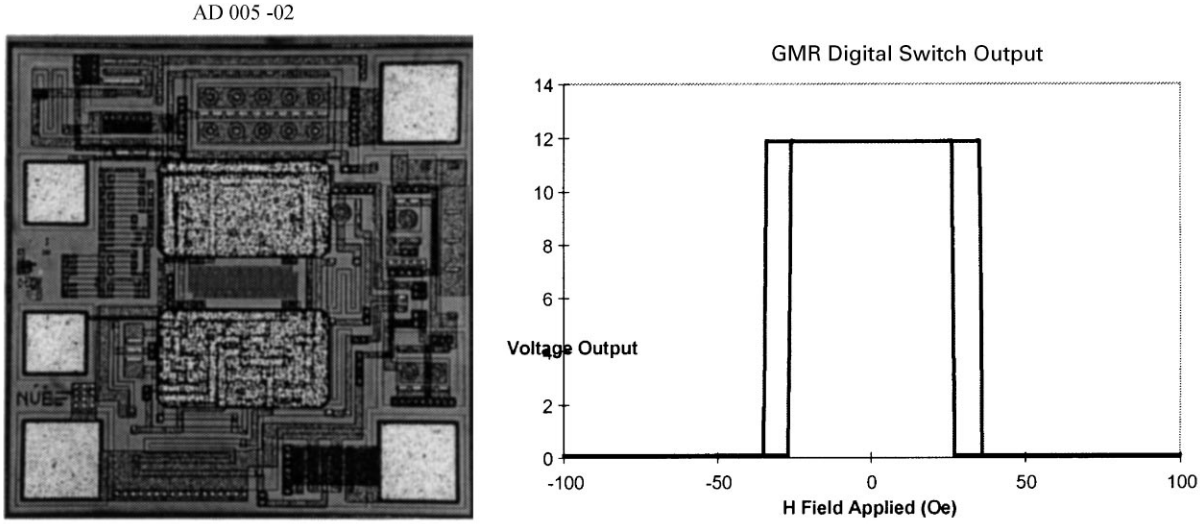

Fig. 3. Digital GMR sensor and output characteristics.

a voltage source. The difference is due to the background resistance, which increases at the rate of about 20% per 100°C, whereas the GMR values decline at only 4% per 100°C. Fig. 3 shows a digital magnetic field sensor which includes a bridge and integrated electronics, also shows the output of that chip with applied field. The hysteresis of the output is mostly due to designed-in hysteresis in the on-chip electronics. A new GMR magnetic field sensor for angular position sensing was introduced in 1997 [10].

The two largest categories of applications for magnetoresistive sensors are: (1) sensing the position or speed of a ferrous body by using an auxiliary permanent magnet, which magnetizes the body to be sensed and (2) sensing the position or speed of a ferrous body using the earth's magnetic field to magnetize the body. A third large potential applications area is current sensing, which will be discussed later in the paper.

In the first category it is necessary that the field from the body be higher than the earth's magnetic field so that the earth's magnetic field doesn't create a large error. A magnetic field on the order of 10 Oe should be sufficient. In fields higher than about 100 Oe, a Hall sensor is generally adequate and inexpensive. Thus, practical applications for GMR sensors of the type discussed here are for fields in the 10–100 Oe range. Two areas for improving GMR materials for these applications are: (1) Elimination of virtually all hysteresis over the field operating range and (2) Self biasing GMR materials which give a bipolar (positive for positive fields and negative for negative fields) change in resistance under applied fields.

For sensors which detect perturbations of the earth's magnetic field, or the earth's field itself (compasses), sensitivity (signal/field) and noise are the most critical parameters. Spin dependent tunneling materials have the potential to be very important to low magnetic field sensor applications (below 10^{-3} Oe). Tunneling devices can have 20–25% equivalent magnetoresistance [11,12], and if properly biased, can give a linear output with respect to applied field with little hysteresis [13]. Although thorough noise measurements in SDT materials has not been published, there are indications that noise in SDT materials is lower than for equivalent GMR materials. The combination of lower noise and higher sensitivity indicate a potential for SDT sensors to reach low field sensitivities not yet achieved by existing magnetoresistive technologies.

Read Heads – New GMR read head products have been introduced by IBM and others. Although little product description is available, it is

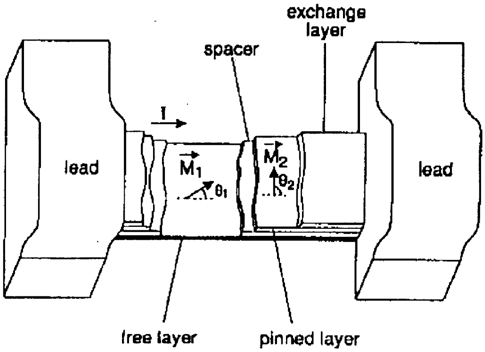

Fig. 4. Spin valve read head sensor (from Ref. [14]).

believed that spin valve material is etched into a narrow stripe, and the magnetization of the pinned layer is oriented across the stripe [14]. Fig. 4 shows how the spin valve stripe is then oriented with respect to the media in order to detect stored data.

In the last several years, substantially improved materials antiferromagnetic material (for example, iridium manganese [7] and nickel manganese [8]) has improved stand-off field and operating and processing temperature tolerance of the spin valves used. Further improvement through the addition of a thin ruthenium film and another ferromagnetic layer has demonstrated still better temperature and field characteristics [15].

With shrinking geometries forced on the read head designer by industry demands for higher density, demagnetizing effects in very narrow horizontal sensor stripes will become a major challenge. For example, a 100 Å thick permalloy stripe 0.25 μm wide has a self demagnetizing field of approximately 200 Oe in the center of the stripe. At the edges of the stripe, demagnetizing effects tend to 'pin' the magnetization along the edge, thus making magnetization near the edges of the stripe very insensitive to magnetic fields. Exchange coupling of magnetization near the edge region tends to reduce sensitivity of materials short distances away from the edge, an effect which gets worse with shrinking geometries. These demagnetizing effects limit the sensitivity to the fields supplied by the media, and although clever techniques can ameliorate the demagnetizing effects, they become more difficult to implement as linewidths keep shrinking.

One way to reduce demagnetizing effects in the horizontal stripe would be to make the magnetic films (and the nonmagnetic interlayer) thinner while retaining high GMR. This would have the benefit of increasing resistance and improving signal level (provided current densities can be higher).

Another way would be to reduce the magnetization of the magnetic layers. This raises fundamental issues about the relationship between magnetization and GMR. Intuitively, one would suspect that magnetic moment and GMR are linked by some necessary relationship through spin-polarized electrons (conduction and bound), but this has not been demonstrated.

Still another useful development would be spin valves with high field sensitivity, but with lower exchange coupling. Once again, this raises a question about the fundamental relationship between GMR and exchange constant. Can high GMR coexist with low ferromagnetic exchange? One might think that lower exchange would imply a low ordering temperature. This problem has been overcome in recording media by doping grain boundaries so as to reduce exchange coupling between grains without affecting the material properties within the grains. Could something similar be done with spin valve structures?

Because the magnetic field from the media decreases very rapidly with vertical distance perpendicular to the stripe, it is important that the spin valve be sensitive to fields very near the outside surface of the head. The rapid decrease is due both to the nature of the field from the media, and to magnetic shields, lying on either side of the stripe, which prevent 'reading' data from nearby bits. Shield materials are thick and have high permeability, thus creating a low reluctance path to shunt off the signal flux.

One potential method of lowering the effect of demagnetizing fields is the use of vertical stripes as suggested by Pohm [16]. Demagnetizing problems are also reduced, but not eliminated. An optimum GMR material for this configuration would be to maximize magnetic moment so as to provide as low a reluctance path as possible for the media signal flux to follow the sensor. If this solution were to be implemented, finding techniques to stabilize the

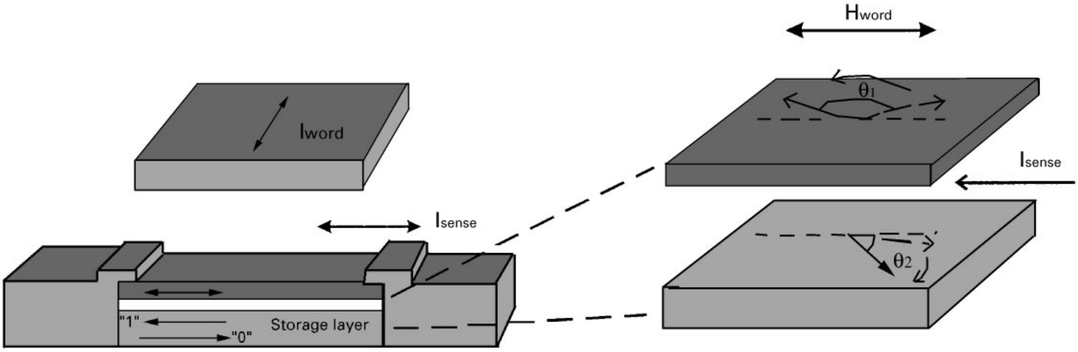

Fig. 5. Pseudo-spin valve concept.

edges of the vertical stripe through process or design techniques would also be a challenge.

MRAM – Spin valve [17], tunneling [18,19], and pseudo-spin valve [20,21] structures have all been proposed for high density nonvolatile random access memory. The use of GMR materials to replace anisotropic magnetoresistive (AMR) materials shows promise to ameliorate one of the most difficult problems which has faced MRAM technology – that of a small signal size, leading to relatively long read access times for memory applications.

Honeywell was the first to demonstrate an operating memory chip using GMR materials [22] using sense linewidths of approximately 2 μm. Submicron GMR memory cells required an improved mode of operation, and one of the more promising proposals is the pseudo-spin valve. Fig. 5 shows the cell concept where two magnetic films are separated by a thin conducting layer. These layers are etched into stripes sufficiently narrow to constrain the magnetizations in the stripes to lay along the long axis of the stripe. A conductor layer etched into a strip line is place over the stripe to apply a magnetic field when a current is passed through it. One of the magnetic films switches at a lower magnetic field than the other. This is accomplished either by the two films having different thicknesses or composition. Data is stored in the magnetization layer requiring the larger magnetic field for reversal. The softer film can switch back and forth without the storage film switching. The magnetoresistive property is used to read out data by observing whether the resistance increases or decreases when a magnetic field is swept from a negative to a positive value as shown in Fig. 6 (from 1 to 2). Most of the available range of resistance is observed, and a stored '1' and a stored '0' have opposite signs.

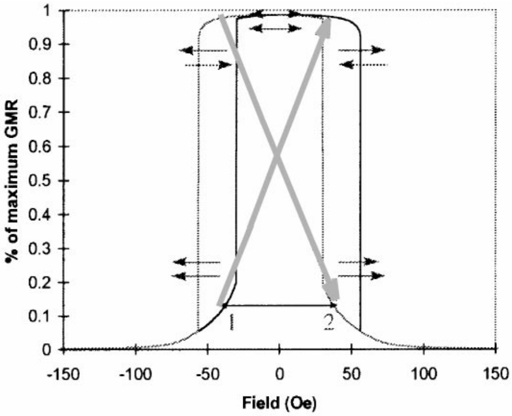

Fig. 6. Pseudo-spin valve read method.

Stable MRAM cells with sense linewidths of less than 0.5 μm [20,21] have been demonstrated, but not without careful end-shaping to avoid magnetic anomalies. It is interesting to recall the commonly held view of only a few years ago, that if magnetic thin films were etched into geometries less than a wall width in diameter, then the magnetization would be 'single domain'. However, both experimental data from several sources and calculations [17] by Zhu et al. indicate that not to be the case. Magnetic anomalies occur at a very small

($\sim$0.2 μm) length scale. Methods of preventing these anomalies, or perhaps living with them, or even using them for memory applications will be interesting research topics for the next several years.

Some of the GMR materials improvements suggested for read heads would not apply to MRAM, because unlike read heads, data storage stability is essential to MRAM. The energy well created by the magnetic moment and the coherence of the magnetization (exchange) demand maintaining both magnetization and exchange at relatively high values.

Galvanic Isolators – In the discussion of GMR magnetic field sensors, an important application category of magnetic sensors was deferred. Current sensing is a primary application area for magnetic sensors. Magnetoresistive sensors have an intrinsic advantage over Hall sensors in that they are sensitive to in-plane fields. This makes it possible to integrate a coil on chip to generate a field from a current. Hall effect sensors generally use a ferromagnetic or ferrite toriod with a flux gap to generate a field to which they are sensitive. An on-chip coil on Hall sensors could also be used, but the field efficiency (field per unit current) would be relatively low compared to the in-plane field produced by under planar windings, and the field sensitivity of Hall sensors is much lower. As a consequence, the GMR sensor with an integrated coil requires at least an order of magnitude lower current for the same output as a Hall sensor with an integrated coil.

An interesting extension of the GMR sensor technology is the GMR isolator [23]. Fig. 7 illustrates the concept, where an on-chip coil driven by an external current creates a magnetic field sensed by an on-chip GMR sensor. The coil circuit and the sensor circuit are separated by a few microns of high dielectric strength. Thus, data can be passed through this device by driving the coil and sensing magnetic field, and the coil circuit and sensing circuits don't have a direct connection path to each other, i.e. they are isolated. Isolation voltages are typically 1000–3000 Volts. Fig. 8 shows how this concept compares to the presently utilized opto-isolators. In opto-isolators, a current input to an LED causes light to be emitted across an insulating barrier, and the light activates a semiconductor device. In a GMR isolator, a current in a coil produces a magnetic field which extends across an insulating barrier, and the magnetic field is sensed by a GMR sensor.

The GMR isolator has been reduced to practice in several forms. Fig. 9 shows a photomicrograph

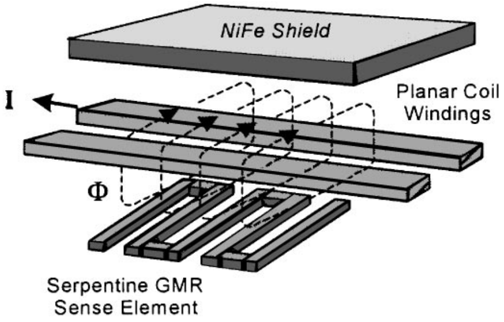

Fig. 7. Isoloop concept for GMR isolator.

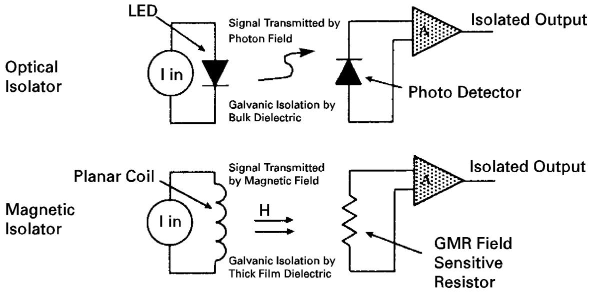

Fig. 8. Comparison of opto-isolator and GMR isolator.

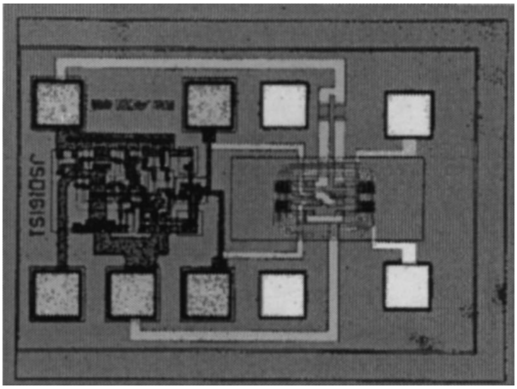

Fig. 9. Photomicrograph of GMR isolator.

Table 2
Some potential improvements to GMR materials

Application	GMR materials	Desired developments
General	All	Temperature stability High Sensitivity
	Tunneling	Higher conductance Higher roll-off voltage
Field Sensors,	Multilayer	Low hysteresis
Isolators	Sandwich, SV Tunneling	Bipolar response
Read heads		
Horizontal	Spin valve	Thinner films Lower moment Lower exchange
Vertical	Sandwich	Higher moment Edge property control
MRAM	Sandwich, SV Tunneling	No magnetic anomalies

of an integrated isolator. A linear bipolar integrated circuit acts as the substrate for the GMR sensors and integrated coil. This GMR isolator measures about 1 mm on a side and operates at 50 Mbaud. Much faster GMR isolators are in evaluation. The inherent advantages of this technology are small size, integration with silicon circuits, and high speed potential (>1 GBaud). First prototype products are planned for this year.

The most desired materials for the isolator are similar to those for magnetic field sensing. High GMR with low saturation fields are important. Because direction of current in an on-chip coil must be sensed, it is also important that the material have a bipolar response.

4. Desirable developments

Besides the never-ending quest for high magneto-resistance ratios and lower saturation fields, there are several developments which would aid in the commercialization of GMR materials which may not be obvious to researchers concentrating on GMR material development. These were discussed along with GMR materials and their applications, and are summarized in Table 2.

Materials which have little or no hysteresis would be very valuable for magnetic field sensors. Tolerance for very high temperatures of approximately 400°C for an hour would enhance the integrability of GMR materials with integrated circuits. In the case of SDT devices, lower resistances are required for low field sensors and memory. A specific resistivity of $1000\ \Omega\ \mu\mathrm{m}^2$ would be very desirable. Finally, if a very high on/off resistance ratio (>10) can be attained under room temperature conditions through the application of a magnetic field, GMR devices could have potential for functions which now use transistors.

Ten years after the discovery of GMR materials, products using GMR materials are being produced. Wider applications of these materials would benefit from continued advances in understanding and development of GMR materials.

References

[1] J. Daughton, P. Bade, M. Jenson, M. Rahmati, IEEE Trans. Magn. 28 (1992) 2488.

[2] B. Dieny, V. Speriosu, S. Metin, S. Parkin, B. Guerney, P. Baumgart, D. Wilhoit, J. Appl. Phys. 69 (1991) 4774.

[3] A. Berkowitz, J. Mitchell, M. Carey, A. Young, S. Zhang, F. Spada, F. Parker, A. Hutten, G. Thomas, J. Appl. Phys. 73 (1993) 5320.

[4] J.S. Moodera, L.R. Kinder, T.M. Wong, R. Meservey, Phys. Rev. Lett. 74 (1995) 3273.

[5] S. Parkin, A. Li, D. Smith, App. Phys. Lett. 58 (1991) 2710.

[6] L. Chen, T. Tiefel, S. Jin, T. Palstra, R. Ramesh, C. Kwon, IEEE Trans. Magn. 32 (1996) 4692.

[7] H. Yoda, H. Iwasaki, T. Kobayashi, A. Tsutai, M. Sahashi, IEEE Trans. Magn. 32 (1996) 3363.

[8] S. Mao, N. Amin, E. Murdock, J. Appl. Phys. 83 (1998) 6807.

[9] J. Daughton, J. Brown, E. Chen, R. Beech, A. Pohm, W. Kude, IEEE Trans. Magn. 30 (1994) 4608.

[10] Siemens Product Information 03.98, Ordering Number B143-H7098-G1-X-7600.

[11] R. Jansen, J.S. Moodera, J. Appl. Phys. 83 (1998) 6682.

[12] Y. Lu, X. Li, G. Xiao, R. Altman, W. Gallagher, A. Marley, K. Roche, S. Parkin, J. Appl. Phys. 83 (1998) 6515.

[13] M. Tondra, J. Daughton, D. Wang, R. Beech, A. Fink, J. Taylor, J. Appl. Phys. 83 (1998) 6688.

[14] C. Tsang, R. Fontana, T. Lin, D. Heim, V. Speriosu, B. Gurney, M. Williams, IEEE Trans. Magn. 30 (1994) 3801.

[15] J. Leal, M. Kryder, J. Appl. Phys. 83 (1998) 3720.

[16] A. Pohm, J. Anderson, R. Beech, J. Daughton, IEEE Trans. Magn. 34 (1998) 1486.

[17] Y. Zheng, J. Zhu, IEEE Trans. Magn. 34 (1998) 1063.

[18] J. Daughton, J. Appl. Phys. 81 (1997) 3758.

[19] W. Gallagher, S. Parkin, Y. Lu, X. Bain, A. Marley, K. Roche, R. Altman, S. Rishton, C. Jahnes, T. Shaw, G. Xiao, J. Appl. Phys. 81 (1997) 3741.

[20] B. Everitt, A. Pohm, R. Beech, J. Daughton, IEEE Trans. Magn. 34 (1998) 1060.

[21] J. Shi, T. Zhu, M. Durlam, E. Chen, S. Tehrani, Y. Zheng, J. Zhu, IEEE Trans. Magn. 34 (1988) 997.

[22] G. Granley, Honeywell, Private communications.

[23] T. Hermann, W. Black, S. Hui, IEEE Trans. Magn. 33 (1997) 4029.