ELSEVIER

Sensors and Actuators 76 (1999) 167–171

SENSORS ACTUATORS A PHYSICAL

www.elsevier.nl/locate/sna

Giant magnetoresistance Co/Cu multilayer sensors for use in magnetic field mapping

C. Christides [a,b,*], S. Stavroyiannis [b], G. Kallias [b], A.G. Nassiopoulou [c], D. Niarchos [b]

[a] Department of Engineering Sciences, School of Engineering, University of Patras, 26110 Patras, Greece
[b] Institute of Materials Science, National Centre for Scientific Research NCSR 'DEMOKRITOS', 153 10 Aghia Paraskevi, Attica, Greece
[c] Institute of Microelectronics, NCSR 'DEMOKRITOS', 153 10 Aghia Paraskevi, Attica, Greece

Accepted 27 November 1998

Abstract

Low hysteresis, giant magnetoresistance (GMR) sputtered Co/Cu multilayers were employed in a 2×4 array of sensing elements. Patterning was performed by optical lithography, using the lift-off technique. To assess the applicability of this sensor, magnetic field mapping of a ring-magnet was performed with a computer controlled scanning system and the results were compared with those obtained from a Hall-sensor.

Keywords: Magnetic field sensors; Giant magnetoresistance; Metallic multilayers

1. Introduction

The giant magnetoresistance (GMR) effect is of interest for applications in magnetoresistive recording read-heads or sensors and has stimulated much of the activity in this field. GMR arises in a variety of magnetic systems including multilayers, spin valves and granular materials [1]. Recent practical developments have favored the spin-valve or the GMR-multilayer design for building ultrahigh density (~ 10 Gbit/in.^{2}) magnetic heads [2] and magnetic field bridge-sensors [3]. The GMR-ratio $\Delta R_{max}/R_o$, (ΔR_{max} and R_o are the maximum resistance change and the minimum resistance, respectively), the switching field range and the magnetic coercivity are the only relevant parameters for the evaluation of GMR sensor elements in DC magnetic field measurements. As compared to sensors based on the anisotropic magnetoresistance (AMR) effect, GMR devices offer superior signal amplitude and very high linear resolution without shields [2,3]. However, fabrication of the spin-valve devices requires a novel approach in setting the directions of the antiferromagnetic exchange layers that bias the sensor. So, mass production of GMR devices at acceptable yields in wafer fabrication requires very good process controls [4] that impose a yield limit of 99% for each processing operation in order to achieve an overall yield of ~ 80%.

Today, microfabricated AMR or GMR sensing elements are based on magnetically soft permalloy ($Ni_{81}Fe_{19}$) films that are able to measure the field components lying in the plane of the film, in contrast to Hall-effect semiconducting sensors that are sensitive only in the magnetic field component that is perpendicular to the film plane. Further effort is required in the fabrication of semiconducting microsystems to achieve accurate 2-dimensional (2D) or 3D magnetic field measurements [5]. Very recently [6], thin, horizontal-plane Hall sensors constructed from narrow-gap semiconductors were tested as read-heads in magnetic recording and proved to be competitive with spin-valve GMR heads. The difficulty in fabricating a commercial 2D or 3D magnetic field sensor, through numerous independent process steps with high (> 95%) yield per step, is the only real barrier to use the above devices.

In our approach, a GMR Co/Cu multilayer sensor is proposed that requires less demand on the growth process. The sensing device is connected with a computer controlled system that is able to perform magnetic field mapping in real time using an X–Y scanning system.

2. Selection of Co/Cu multilayers as sensing elements

At ambient conditions the maximum GMR ratio was reported [7] in sputtered Co/Cu multilayers with appropri-

* Corresponding author. Institute of Materials Science, National Centre for Scientific Research NCSR 'DEMOKRITOS', 153 10 Aghia Paraskevi, Attica, Greece. Tel.: +30-1-65-22872; Fax: +30-1-65-19430; E-mail: christos@ims.ariadne-t.gr

0924-4247/99/$ - see front matter
PII: S0924-4247(99)00005-9

superlattices which register a much smaller GMR effect [8], and their switching magnetic field is several times larger. In order to assess their applicability as sensor elements the issue of non-linear GMR response must be addressed. By now, the signal output is usually linearized with geometry intensive GMR sensor designs [9,10]. Thus, patterned spin valve GMR sensors are biased by exchange [9] and soft adjacent layer (SAL) bias geometries [9,10], which require numerous independent process steps with high yield per step. However, for sensor applications GMR multilayers present several advantages relative to spin valves [2]. Specifically, in NiFe/Cu and NiFeCo/Cu multilayer structures it was shown [2] that the use of relatively high current densities results in large internal magnetic fields, and thereby in self-biasing of the GMR multilayers. The high aspect ratio of GMR Co/Cu multilayers can be utilized in sensor applications provided that an adequate self-bias is achieved across all the magnetic layers. The negligibly small magnetic anisotropy of NiFe and NiFeCo layers implies that transverse bias magnetization is facilitated by internal magnetic fields, when the coercive field is close to zero. For Co/Cu multilayers this can be accomplished by reducing the hysteresis in the GMR curves.

Ford research laboratories have reported two different approaches in Co/Cu multilayers that target low coercive (H_c) and switching (H_s) fields. The realization of these consists either in forming multilayers with $t_{Co} \approx 1.5$ nm alternated with $t_{Co} \approx 0.3$ nm layers [11] in the superlattice stacking: Co/Cu/Co/../, or by replacing [12] the Co layers with a codeposit of Co and Cu that forms $Co_{1-x}Cu_x$/Cu multilayers. Our ongoing research in GMR multilayers has shown a third way [13,14] in controlling systematically the GMR parameters in sputter grown $[Co(t_{Co})/Cu(2.1\ nm)]_{30}$ multilayers. In our approach is found that there is a bimodal distribution with two well separated populations of grain sizes below and above ~ 12 nm. The obtained reduction of GMR, coercive and switching as in Refs. [11,12] this effect is due to the decrease of the intrinsic magnetic anisotropy and magnetization in the Co layers. Thus, the developed micromagnetic state is completely different in the two categories of Co/Cu multilayers, leading to different GMR and magnetic properties.

3. GMR device structure and fabrication

The specific microstructure that is developed in our magnetron sputtered $[Co(1\ nm)/Cu(2\ nm)]_{30}$ multilayers leads to GMR curves with very small hysteresis [13,14] and to a GMR ratio of 6%. To evaluate the appllicability of these multilayers as GMR sensor elements, a 2D array design of 2×4 units was adopted. Conventional optical lithography and the lift-off technique were applied for the film patterning. Interconnections were assumed by aluminium stripes. Aluminium pads were used as voltage contacts in a four-probe configuration. The same current was passed through all the sensing elements whereas the resulting voltage drop was measured across each element.

In this design, the magnetic field resolution of the sensor depends on the active spacing between the voltage pads. Scanning electron microscopy images are indicative of the degree of perfection in the pattern definition (Fig. 1). The 2D array of sensors is designed to detect magnetic field variations near the surface of magnetic materials with uncommon shapes. Since the shape of the GMR curves changes drastically upon changing the direction of the applied field relative to the film-plane, it is optimal to sense the in-plane field that gives a better contrast for the field changes in the horizontal plane. So, we decided to measure the relative difference between the GMR output signal at zero field and its response over the magnetized surface in order to construct a field map as a function of the sensor position at a constant vertical distance from a magnet.

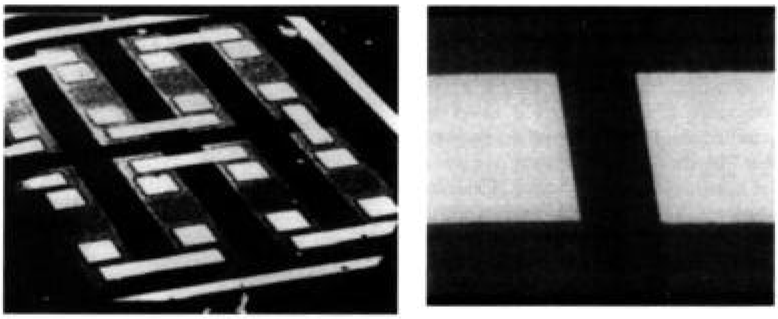
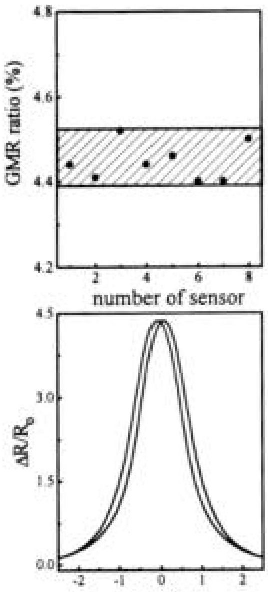


Fig. 1. An overview of the sensing device is shown on the left side, while on the right a detail of the pattern definition after the lift-off process is displayed.

4. Magnetic field mapping of a ring-magnet

The *transfer function*, that determines the output–stimulus signal relationship for the GMR sensor, is given by the output voltage change with the applied field (stimulus). Therefore, the sensor characteristics were defined by the shape of the GMR curves. The observed repeatability of the GMR curves per sensing element (Fig. 2) indicates the high yield factor of the patterning process. Fig. 2 (right) shows that the highest accuracy and linearity occurs between 40 and 900 Oe. Accordingly, this was selected as the full span range of the sensor. The hysteresis error, in this range, is taken into account by fitting a least-square line that defines the calibration function of the sensor.

For the magnetic field mapping measurements, the sensor was mounted on a horizontal bar that was fixed on the moving part of an X–Y scanning stage, and an area of 10×10 cm^2 was scanned over the sample with a constant step of 0.25–1.25 mm along both the X- and Y- directions. The X–Y stage (Parkers Motors) was equipped with two independent stepping motors and was controlled by a computer by means of an AT-6400 card. The current source (Keithley 220) and the voltmeter (Hewlett Packard 3457A) were controlled with an IEEE-488 interface. The test object in our experiments was a sintered NdFeB ring-magnet that was placed beneath the sensors at vertical distance L ($3 < L < 35$ mm). The scanning direction was always along the Y-axis.



g. 2. The variation of the $\Delta R_{max}/R_o$ output signal from each sensing ement is shown on top, while a representative GMR curve obtained th a homogeneous field applied perpendicular to film plane is shown at bottom. The measurements were performed with the four-point-probe thod, using a dc current of 10 mA.

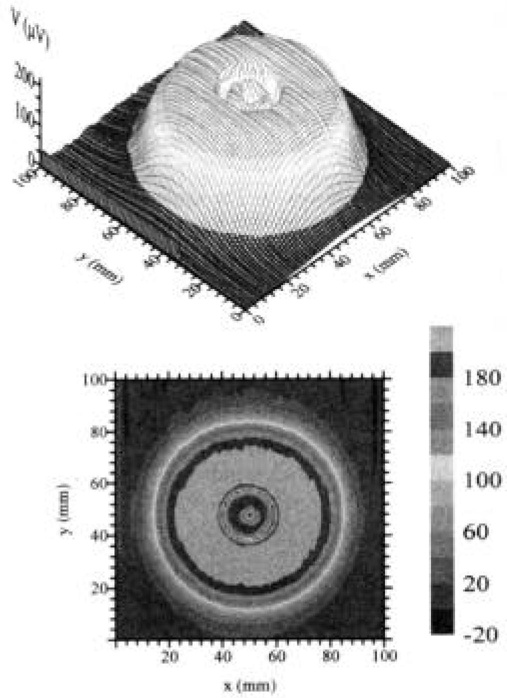


Fig. 3. Magnetic field mapping of the ring-magnet with 4 cm outer, 3 cm inner diameter, and thickness of 1 cm. The magnet-to-sensor distance was 8 mm and the scanning direction was along the y-axis. The GMR sensor is without shielding.

A scan performed for $L = 8$ mm, without shielding, shows (Fig. 3) an artificial internal ring. This ring is observed because the GMR sensor cannot distinguish the up and down magnetic field directions (the R versus H dependence is an even function of the applied field) and the magnetic field near the center of the ring is directed downwards. To overcome this artifact and isolate only the in-plane field component a mu-metal shielding plate (~ 1 mm thick) was placed in front of the GMR sensor. As a result, the artificial ring disappeared and the physical dimensions of the magnet were recovered. In Fig. 4 three representative field maps for the distances $L = 15$, 25 and 35 mm are shown. At $L = 15$ mm the exact shape and dimensions of the ring magnet were accurately reproduced. On increasing L, we observe a significant truncation of the magnetic field image, accompanied with an enhancement of the detected signal above two opposite arcs of the ring that are located along the scanning direction.

Finally, since the GMR sensor cannot distinguish changes of the field sign, to evaluate the error that is introduced from this inefficiency we have performed simultaneous scans of the field, having a non-shielded Hall sensor attached next to the shielded GMR sensor. Three separate scans were performed with the Hall sensor positioned so as to measure each time the x, y and z component of the magnetic field. The three magnetic field components were then added to give the overall magnetic field shown in Fig. 5. Two major differences can be seen between the two sensors: (i) The change in the field sign (negative field) that occurs near the center and at the edges of the ring-magnet is sensed from the Hall-sensor but not from the GMR sensor. Instead, it causes a positive signal in the place of negative field thereby making the image of the magnet wider. (ii) The output voltage is in millivolts (mV) for the Hall-sensor and in microvolts (μV) for the GMR-sensor.

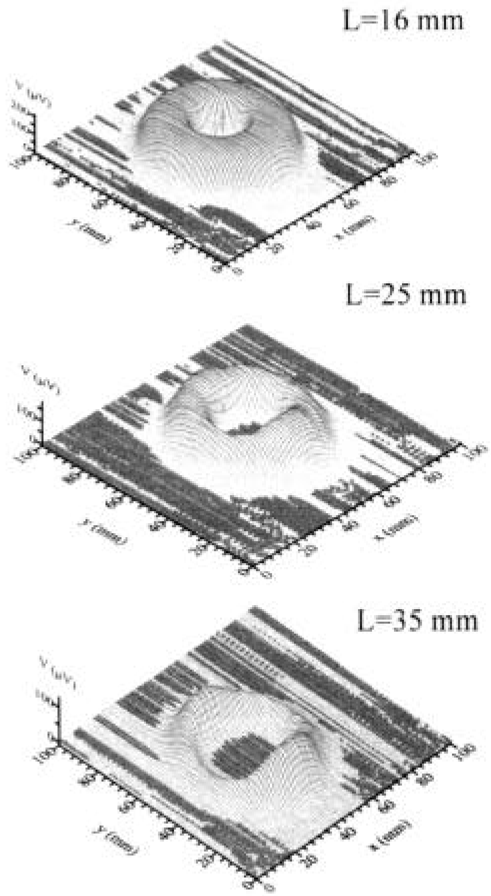


Fig. 4. Magnetic field mapping of the ring-magnet as a function of the magnet-to-sensor distance L. The scanning direction was along the y-axis. In front of the GMR sensor we placed a mu-metal shielding plate.

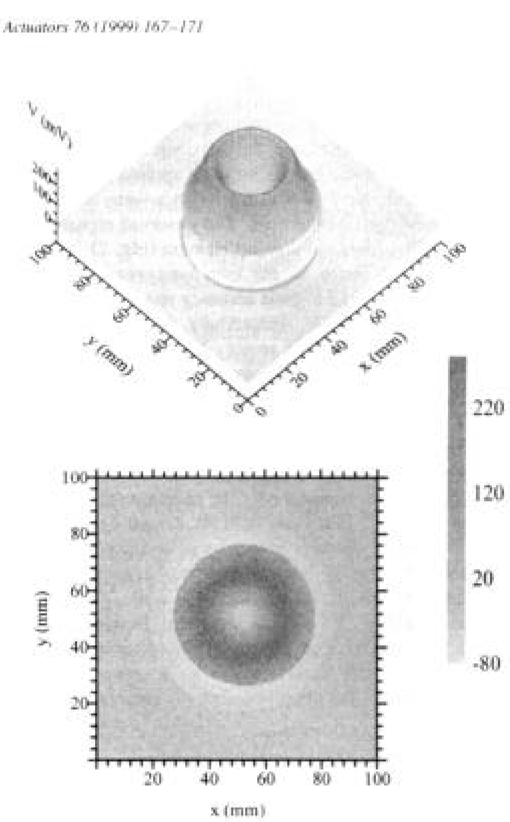


Fig. 5. Magnetic field mapping of the ring-magnet using a commercial Hall-sensor without shielding. The scanning direction was along the y-axis. The magnet-to-sensor distance was 6 mm.

5. Discussion and conclusions

To the best of our knowledge, so far, the technological effort has been focused exclusively on GMR materials with high sensitivity in small saturation fields (less than 100 Oe) because of their potential use in information storage systems as sensors or random access memory (MRAM) elements. Here, a first attempt to use GMR multilayers for magnetic field mapping of permanent magnets is presented. A simple array of 2×4 GMR sensing elements, with physical dimensions of 4 mm^2, was successfully combined with an X–Y scanning system to determine the exact shape of a permanent magnet. This kind of GMR sensors can be useful for other applications, such as magnetic resonance imaging (MRI) or electric motors, where accurate magnetic field mappings of macroscopic areas are required. In that case, a centimeter sized array of sensors should be preferred instead of the X–Y

scanning system. For this purpose a large area magnetic field sensor array (LAMSA), using redundancy and defect avoidance procedures with high yield, should be employed to create a working system [15].

In summary, using a simple magnetic sensor design we have demonstrated that the developed microstructure [13] in Co/Cu GMR multilayers complies with the qualifying factors needed for field-difference mapping in real time. The obtained results indicate that an adequate electronic design of the device might enable the application of the specific Co/Cu multilayer [13,14] in commercial sensors.

Acknowledgements

This work has been supported by the EKBAN-280 project of the General Secretariat for Research and Technology of the Development Ministry in Greece.

References

[1] S.S.P. Parkin, in: B. Heinrich, J.A.C. Bland (Eds.), Ultrathin Magnetic Structures II, Chap. 2, Springer, Berlin, 1994.

[2] N. Smith, A.M. Zeltser, M.R. Parker, GMR multilayers and head design for ultrathin density magnetic recording, IEEE Trans. Magn. 32 (1996) 135–141.

[3] J.K. Spong, V.S. Speriosu, R.E. Fontana, M.M. Dovek, T.L. Hylton, Giant magnetoresistance spin valve bridge sensor, IEEE Trans. Magn. 32 (1996) 366–371.

[4] G. Baubock, H.Q. Dang, D.C. Hinson, L.L. Rea, Y.K. Kim, MR head wafer fabrication technology: current and future perspectives, IEEE Trans. Magn. 32 (1996) 25–30.

[5] Ch. Schott, D. Manic, R.S. Popovic, Microsystem for high accuracy 3D magnetic field measurements, 11th European Conference on Solid State Transducers (Eurosensors XI), Warsaw, Poland, September 21–24, 1997, pp. 635–638.

[6] S.A. Solin, R.A. Stradling, T. Thio, J.W. Bennett, Thin horizontal-plane Hall sensors for read heads in magnetic recording, Meas. Sci. Technol. 8 (1997) 1174–1181.

[7] S.S.P. Parkin, Z.G. Li, D.J. Smith, Giant magnetoresistance in antiferromagnetic Co/Cu multilayers, Appl. Phys. Lett. 58 (1991) 2710–2712.

[8] M.J. Hall, B.J. Hickey, M.A. Howson, M.J. Walker, J. Xu, D. Greig, N. Wiser, Magnetoresistance of Co/Cu superlattices grown by molecular beam epitaxy, Phys. Rev. B 47 (1993) 12785.

[9] R.E. Fontana Jr., Process complexity of magnetoresistive sensors: a review, IEEE Trans. Magn. 31 (1995) 2579–2584.

[10] C. Tsang, Unshielded MR elements with patterned exchange-biasing, IEEE Trans. Magn. 25 (1989) 3692–3694.

[11] H. Holloway, D.J. Kubinski, Giant magnetoresistance in Co/Cu multilayers with Co layers of alternating thicknesses: reduction of magnetoresistive hysteresis, J. Appl. Phys. 79 (1996) 7090–7094.

[12] D.J. Kubinski, H. Holloway, Giant magnetoresistance in $Co_{1-x}Cu_x$/Cu multilayers: a new approach to reduced magnetoresistive hysteresis, J. Appl. Phys. 82 (1997) 322–325.

[13] C. Christides, S. Stavroyiannis, N. Boukos, A. Travlos, D. Niarchos, Microstructural modification in Co/Cu giant-magnetoresistance multilayers, J. Appl. Phys. 83 (1998) 3724–3730.

[14] C. Christides, S. Logothetidis, M. Gioti, S. Stergioudis, S. Stavroyiannis, D. Niarchos, Structural, magnetotransport, and optical properties of sputtered Co/Cu multilayers examined as a function of Co layer thickness at the second antiferromagnetic maximum, J. Appl. Phys. 83 (1998) 7757–7768.

[15] Y. Audet, G.H. Chapman, Yield improvement of a large area magnetic field sensor array using redundancy schemes, IEEE Trans. VLSI Syst. 5 (1997) 28–33.

Christos Christides received his BSc in Physics from the University of Crete in 1984 and his PhD degree from the University of Athens in 1991. His thesis work involved the experimental study of the intrinsic properties of rare-earth based permanent magnets. He has been employed as a post-doctoral fellow by the University of Sussex, England, (1991–1993) and currently he is Assistant Professor in the School of Engineering, University of Patras, and Research Associate in the Institute of Materials Science, NCSR 'DEMOKRITOS', Greece. His main research interests are focused on the fundamental properties and applications of magnetic thin films.

Stavros Stavroyiannis received his BSc in Physics from the University of Patras in 1989 and his MSc degree from the City College of the City University of New York in 1992. Since 1995 he is a graduate student in the Technical University of Athens and his thesis work is focused in the experimental study of ultrathin metallic multilayers that exhibit the giant-magnetoresistance (GMR) effect. His research work is carried out in the Institute of Materials Science, NCSR 'DEMOKRITOS', Greece.

George Kallias received his BSc in Physics in 1987 and his PhD degree from the University of Athens in 1993. His thesis work involved the experimental study of Hall effect in high-T_c superconducting oxides. At present he is employed as a post-doctoral fellow in the Institute of Materials Science, NCSR 'DEMOKRITOS', and his recent experimental work is related with the study of the magnetic properties of high T_c superconductors and with the evaluation of a SQUID sensor based on high-T_c materials.

A.G. Nassiopoulou is currently the Director in the Institute of Microelectronics at the National Center for Scientific Research (NCSR) 'DEMOKRITOS', Greece. She received her BSc in Physics from the University of Athens in 1975 and her MSc and PhD from the University of Paris XI (ORSAY). She then worked as Research Associate and Associate Professor at the University of Reims, France, from where she received the 'Doctoral d'Etat' in 1985. Since 1986 she is senior scientist at IMEL/NCSR Demokritos and she is the Director of the Institute since 1997. She is the head of the groups of 'silicon integrated sensors' and 'silicon nanostructures for integrated optoelectronics'. Her current interests are focussed on silicon integrated sensors and silicon based optoelectronics.

Dimitrios Niarchos is currently the Director in the Institute of Materials Science and vice-president of the National Center for Scientific Research (NCSR) 'DEMOKRITOS', Greece. He received his BSc in Physics in 1972 and his PhD degree from the University of Athens in 1978. Between 1978 and 1981 he was a distinguished post-docrtoral fellow at the Argonne National Laboratory and from 1981 to 1985 he was an Assistant Professor at the Illinois Institute of Technology, Chicago, USA. Since 1985 he is a research scientist at NCSR 'DEMOKRITOS'. His main research areas are in magnetic materials, high-T_c superconductors and sensors based on these materials.