Journal of ELECTRICAL ENGINEERING, VOL 57. NO 8/S, 2006, 171-174

MEASUREMENTS, TECHNOLOGY, AND LAYOUT OF SENSITIVE ANISOTROPIC MAGNETORESISTIVE SENSORS

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Magnetic measurements and noise calculation are presented for anisotropic magnetoresistive (AMR) sensors with advanced layout for improved sensitivity. The AMR effect is increased up to almost 4%. Depending on the sensor layout, a field measurement resolution of 380 pT seems feasible.

Keywords: anisotropic magnetoresistance effect, thin permalloy film, demagnetizing factor, sensor noise

1 INTRODUCTION

Related with the detection of weak magnetic fields, the anisotropic magnetoresistive (AMR) effect is utilized in many biomedical and industrial applications. Compared to giant magnetoresistance (GMR) and tunneling magnetoresistance (TMR) it offers the advantage of low hysteresis and low noise.

Philips KMZ sensors consist of patterned NiFe thin film structures in a Wheatstone bridge configuration equipped with Barber-pole structures for output linearization [1]. As periodical flipping by a perpendicular field improves stability and reduces noise and hysteresis, these sensors have built-in flat flipping and feedback (compensation) coils so that they are ideally suited for magnetometers.

Various sensor designs and electronic evaluation circuits have been developed to overcome temperature dependence, offset, and hysteresis, for example [2]. The resistivity ρ in the plane of a thin ferromagnetic film with uniaxial anisotropy varies with the angle between the current density and the spontaneous magnetization which is rotated by the applied field H_α. The sensivity of a Wheatstone-bridge arrangement (supply voltage V_s, bridge output voltage V_b) is

$$S_0 = \frac{dV_b}{dH_\alpha}\frac{1}{V_s} = \frac{\Delta R}{R_0}\frac{1}{H_k}$$

and can be varied by the total anisotropy field $H_k = 2K/\mu_0 M_s$. The effective anisotropy constant K, the spontaneous magnetization M_s, the average resistance R_0, and the field dependent variation ΔR are determined respectively by the material and geometry of the magnetoresistive element.

2 SENSOR TECHNOLOGY

The magnetoresistive films have been deposited by DC cathode sputtering using a triode set-up. The silicon wafer substrate surface has been passivated by a 0.5−0.8 µm insulation layer, consisting either of a thermal silicon dioxide or a low stress silicon nitride deposited by a PECVD process at low temperature.

The AMR effect of dc-sputtered Ni 81%−Fe 19% films has been increased up to $\Delta\rho / \rho$ = 3.93% at 50 nm thickness, close to the theoretical limit of about 4% [3]. The magnetoresistive films have been deposited by cathode sputtering (triode-process). The target is connected to a negative potential of U(T) = -800 V and the substrate is biased by U(S) = – 60 V. The cathode current is I(C) = 43 A, the anode current is I(A) = 3.5 A, and the anode voltage is U(A) = +50 V against ground potential. The following parameters have been varied: Both target and substrate materials, the temperatures of target T(T) and substrate T(S), the distance a(T-S) between target and substrate, and the film thickness d. This value has been determined by resonance frequency measurements with an accuracy of better than 1%.

2 SENSOR LAYOUT

In order to achieve a homogeneous and small demagnetizing field, an elliptical shape of the AMR array is proposed [4, 5]. Several layouts with barber-pole structures on rectangular permalloy strips of different width and separation distance (eg KMZ1010A in Fig.1: both width and distance 10 µm; H3: overall elliptical shape, half shown in Fig. 2) and small elliptical elements (E4060C, see Fig. 3) are compared. The total sensor area was 1×2 mm^2 for each layout.

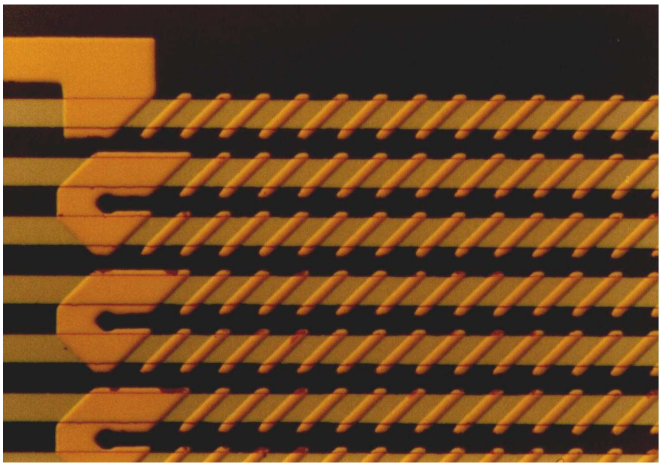

Fig. 1. Structural details of the KMZ1010A design; rectangular permalloy strips with width and distance 10 µm

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Research supported by Schiebel Elektronische Geräte GmbH and by the Fonds zur Förderung der Gewerblichen Wirtschaft (FFF) under grant No. 3/9893.

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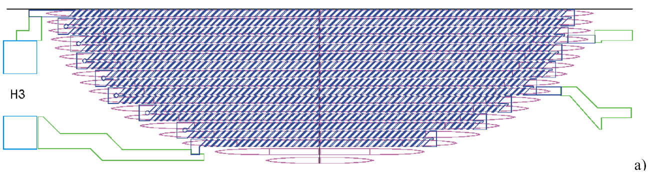

Fig. 2. Layout of the H3 design

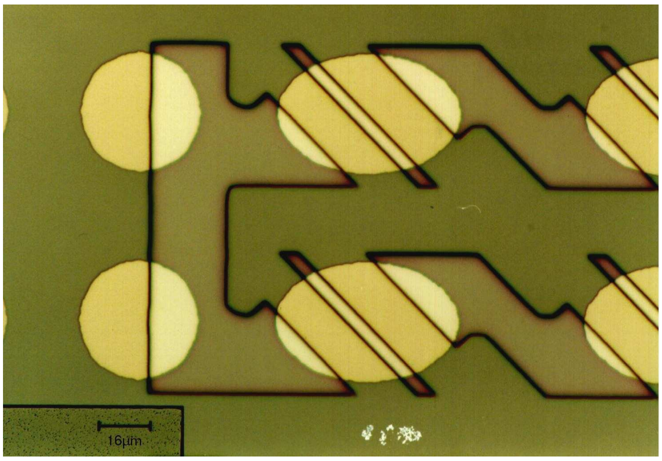

Fig. 3. Structural details of the E4060C design

4 MEASUREMENTS, SIMULATION, AND SENSIVITY

The following section deals with the magnetic properties which are important for sensitive AMR sensors and modeling of optimum flipping fields. Furthermore, the sensor noise and sensivity are discussed.

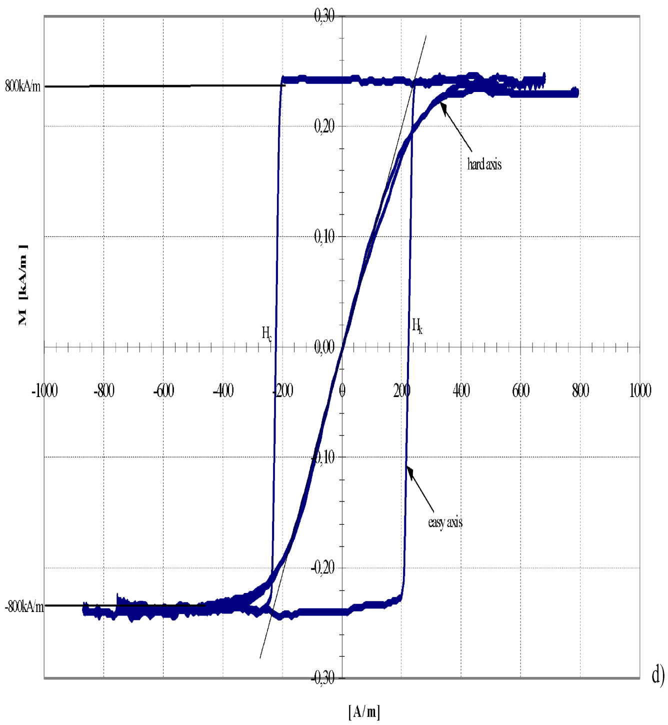

Fig. 4. Hysteresis measurement (applied field H versus magnetization M) of the Ni81-Fe19 permalloy film used for the sensors

4.1 Magnetic measurements

Figure 4 shows the measured magnetization curve parallel and perpendicular to the easy direction of a thin permalloy film.

As a function of the applied magnetic bias field, the easy-axis coercivity is between 100 A/m and 200 A/m due to induced anisotropy. Depending on the film thickness, the coercivity of the hard axis magnetization curve is very low. These dc-magnetization curves have been measured by the transversal magneto-optical Kerr-effect and represent an almost ideal Stoner-Wohlfarth behaviour.

4.2 Flipping field and simulation

Recently developed switched-capacitor flipping circuits give up to 2.8 A @ 1 kHz current peaks [6]. Such unusually high current deeply saturates the sensor and thus removes hysteresis, reduces noise, and increases the resistance against field shocks of any direction.

These necessary strong flipping fields can be predicted by the energetic model (EM) [7-9], applied to the magnetization reversal in thin films. The EM parameters are correlated to microscopical variables, revealing the field dependence of the magnetization reversal velocity. This is responsible for the value of the critical switching field (and therefore for the stability of the sensor) in the easy axis directions, depending on the saturating field amplitude.

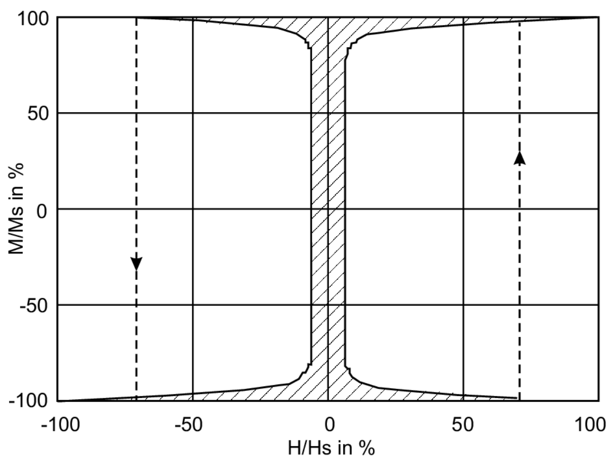

Fig. 5. Magnetization reversal (*H* vs *M*) parallel to the easy axis; the measured loop (dashed line) deviates from the calculation (solid line) because of the instability at H_{cr} (related to the anisotropy field H_k in the ideal case) and the lack of control of the applied field

Figure 5 shows an EM simulation of the principle behavior of the magnetization reversal in a thin permalloy film (spontaneous magnetization M_s = 800 kA/m). The real path of $M(H)$ is plotted as a solid line, showing only a small coercivity. The losses during switching are indicated by the hatched area. The nominal critical field H_{cr} (dashed line) and the corresponding stability can be achieved only if the film is deeply saturated (maximum magnetization $M_m = M_s$). In the case of lower maximum magnetization H_{cr} is decreased, causing increased instability and noise [9].

4.3 Sensivity and noise

To achieve a high sensivity, the coercivity in the hard axis magnetization direction must be close to zero (see Fig. 4) and the resistivity variation $\Delta\rho/\rho$ must be as high as possible. Depending on the applied magnetic field direction, the resistance variation has been measured by a four-wire method. The AMR film was characterized by $\Delta\rho/\rho$ = 2.96%, H_k = 240 A/m and $H_c \approx 0$ in the hard axis direction.

Furthermore, the magnetic noise due to domain wall displacement and nucleation must be suppressed by the geometrical layout of the AMR elements and saturation flipping fields (see Section 4.2). The possible signal gain is then limited by the thermal noise voltage V_n of the resistor at a given frequency bandwidth Δf :

$$V_n = \sqrt{4K_B T R_0 \Delta f}$$

The sensivity and resistor noise voltage results (calculated at Δf = 100 Hz and T = 300 K) of the designs investigated are the following:

KMZ1010A:

R_0 = 1.34 kΩ, S_0 = 1.36 (mV/V)/(kA/m), V_n = 44 nV which corresponds to 11 mV/mT at V_s = 10 V. If the magnetic noise is not considered, then the lowest detectable field is about 4 nT.

E4060C:

R_0 = 270 Ω, S_0 = 2.00 (mV/V)/(kA/m), V_n = 20 nV which corresponds to 8 mV/mT at V_s = 5 V. Therefore, the theoretically lowest detectable field is about 2.5 nT.

H3:

R_0 = 850 Ω, S_0 = 1.60 (mV/V)/(kA/m), V_n = 40 nV which corresponds to 13 mV/mT at V_s = 10 V for this half bridge design. Due to the higher R_0 we find a higher V_n and the minimum field resolution is then 3 nT. But the magnetic noise is much smaller compared to the other designs and a full-bridge design with the ellipse axes rotated by 90° would increase S_0 by 8 times and a field resolution of 380 pT seems feasible.

6 CONCLUSIONS

As the resisitivity ρ decreases with the crystallite size, both the AMR effect and the magnetic properties are improved. The film thickness has been varied between 20 nm and 50 nm, with $\Delta\rho/\rho \approx 3\%$ each.

Magnetic noise is the limiting factor to AMR sensors. Elliptical layouts of the sensor elements reduce the sensor noise due to homogeneous demagnetizing fields. This allows to increase the signal amplification and thus the overall sensitivity of the sensor system. The regions near the corners of rectangular layouts mainly contribute to magnetic noise because of residual magnetic domains and the domain wall displacements instead of coherent magnetization rotation. Therefore, the best signal-to-noise ratio is achieved with the H3 layout, followed by E4060C and KMZ1010A designs.

Furthermore, the noise is reduced by strong, deeply saturating flipping current pulses, which can be predicted by magnetic hysteresis modeling.

REFERENCES

[1] RIPKA, P.: Magnetic Sensors and Magnetometers. Artech House, Boston 2001

[2] MAPPS, D. J. — MA, Y. Q. — AKHTER, M. A.: Sensors and Actuators 74 (1999), 128.

[3] AIGNER, P. — STANGL, G. — HAUSER, H. — HOCHREITER, J.: Cathode Sputtered Permalloy Films of High Anisotropic Magneto-resistive Effect. Journal de Physique IV, 8 (1998), 461-464.

[4] HAUSER, H. — STANGL, G. — HOCHREITER, J.: High-Performance Magnetoresistive Sensors. Sensors & Actuators A 81 (2000), 27-31.

[5] HAUSER, H. — HOCHREITER, J. — STANGL, G. — CHABICOVSKY, R. — JANIBA, M. — RIEDLING, K.: Anisotropic Magnetoresistance Effect Field Sensors. J. Magn. Magn. Mater. 216 (2000), 788-791.

[6] VOPALENSKY, M. — RIPKA, P. — HAUSER, H.: Magnetometer s AMR, GMR a SDT Senzory (Magnetometer with AMR, GMR and SDT Sensors, in Czech). Acta Avionica 5 (2003) no (8/S), 23-28.

[7] HAUSER, H.: Energetic Model of Ferromagnetic Hysteresis: Isotropic Magnetization. J. Appl. Phys. 96 (2004), 2753-2767.

[8] HAUSER, H. — FULMEK, P. L.: Magnetization Process Modeling of Anisotropic Magnetoresistive Permalloy Films. J. Magn. Magn. Mater. 254 (2003) 293-295.

[9] HAUSER, H. — FULMEK, P. L. — HAUMER, P. — VOPALENSKY, M. — RIPKA, P.: Prediction of the Flipping Fields in AMR Sensors. Sensors and Actuators A 106 (2003), 121-125.

Received 13 November 2006

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Michael Janiba (MSc), biography not supplied.