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Sensors and Actuators 81 (2000) 324–327

SENSORS AND ACTUATORS A PHYSICAL

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Development of magnetoresistive sensors based on planar Hall effect for applications to microcompass

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Abstract

We present here a new magnetoresistive sensor based on planar Hall effect for detection of low magnetic fields (10 nT) in the 1–1000 Hz frequency range. These sensors are suitable for low-cost fabrication. The growth of a Permalloy (FeNi) active layer by conventional sputtering on misoriented silicon substrates leads to a well controlled in-plane uniaxial magnetic anisotropy. Moreover, a magnetisation switching system allows to remove any offset of the measure. The association of two orthogonal sensors will give a micro-compass with an angular resolution, below 0.5°, limited by the precision of assembling, with a device size of the order of 1 mm^2. © 2000 Elsevier Science S.A. All rights reserved.

Keywords: Magnetic sensor; Magnetoresistance; Planar Hall effect

1. Introduction

Magnetoresistive effect is a well known solution for the fabrication of magnetic sensors with a resolution below 1 nT [1]. Such sensors only require thin film technologies, suitable for parallel fabrication of devices, and consequently are good candidates for low-cost sensors. However, as we consider the low frequency range (1–1000 Hz), the thermal drift of the metal resistivity limits the resolution. In fact, the output signal, V_S, is given by $V_S/I = R_0 + 1/2\ \Delta R \cos 2\theta$, where θ is the angle between the current and the magnetisation, I the current in the sensor, R_0 the resistance and ΔR the magnetoresistance. The isotropic part of the resistance, R_0, shows a drastic temperature dependence of the order of 0.3%/K while the sensitivity is currently close to 0.5%/G (50 T^{-1}). This leads to an equivalent noise limitation which is many orders of magnitude above the Johnson noise. Resistance bridges are currently used in the commercially available devices. However, they solve only partly this problem. We have shown recently [2] that, by using a transverse measurement of the magnetoresistance (i.e., in a Hall geometry), we reduce the thermal drift of the output signal by 4 orders of magnitude, and then we take advantage from the ultralow intrinsic resolution with a very simple fabrication process. With an active part of the sensor as small as 20 $\mu m \times 20\ \mu m$, we have achieved an effective resolution below 10 nT at 1 Hz. This configuration, known for more than 30 years as planar Hall effect (PHE) configuration [3], gives direct access to the anisotropic part of the resistance, namely $V_S/I = 1/2\ \Delta R \sin 2\theta$. The angular dependence of the PHE allows also a magnetisation easy axis along the current line without using any biasing technology (like barber-pole) [2].

The first generation of our PHE sensors was obtained by epitaxial growth of a Permalloy ($Fe_{19}Ni_{81}$) thin film directly on a MgO substrate, using Molecular Beam Epitaxy (MBE) [2]. These two points have been considered as limiting factors in order to achieve low cost fabrication. In this article, we describe a second generation of PHE sensors obtained using a standard sputtering deposition method directly on Si substrates. The resolution of the sensors enables the fabrication of micro-compasses by using two orthogonal sensors. For this application, we have introduced a current line to remove the residual offset coming from both the sensor and the read-out electronics.

2. Control of the magnetic anisotropy

As a magnetic field is applied perpendicularly to the easy axis, the magnetisation of the sensor rotates away from its equilibrium position which is along the anisotropy

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PII: S0924-4247(99)00102-8

axis. The rotating mode avoids any hysteresis in the measurement. The sensitivity of the sensor is then $S = V/(IH) = \Delta R/H_a$ where H_a is the strength of the anisotropy [4]. Several sources of magnetic anisotropy have been used: a magnetic field applied during the growth, a shape anisotropy which is directed along the length of strip lines or, as in our first generation of PHE sensor, a non-isotropic epitaxial growth. In order to be compatible with sputtering growth, we chose to use the substrate to induce a magnetic uniaxial anisotropy. Misoriented (111) silicon wafers along the $[11\bar{2}]$ direction present mostly monatomic steps. Cooling down these substrates from 750°C under ultra high vacuum leads to a new equilibrium surface made of large atomically flat terraces separated by step bunches [5]. With a 4° misorientation, terraces are typically 43 nm wide and step bunches formed by about 20 monatomic steps are typically 6 nm high and 20 nm wide.

Our recent work on misoriented (111) silicon substrates showed that magnetic layers deposited on these substrates (either by MBE or sputtering) exhibit an in-plane uniaxial magnetic anisotropy parallel to the steps [6]. The anisotropy can be controlled by the initial misorientation of the substrate.

The fabrication of the sensors starts with a chemical treatment of the silicon wafer inspired by Shiraki in order to fabricate a surface oxide free of contaminants [7]. Heating above 700°C under UHV (in our MBE system) desorbs the oxide. The cooling from 750°C to 500°C is slow enough to set the step bunching mechanism at thermal equilibrium [8]. After having brought back the sample to the air, the growth of the metallic layers by sputtering is performed in an Alcatel A610 system. A Permalloy target is sputtered in a 4 mTorr Ar pressure with 100 W RF power to form a typically 5–10 nm thick layer. A 2-nm thick Au cap layer is then sputtered with a DC plasma.

Layers grown on substrates misoriented 4° show an anisotropy field between 20 and 30 G depending of the FeNi thickness. These values are increased by about an order of magnitude when the misorientation angle is 8°.

Sensors are then fabricated by a single step patterning performed by optical lithography and Ar ion milling. The resistance per square is about 50 Ω for 10 nm thick FeNi layer. The magnetoresistance ΔR, measured in PHE configuration is typically 500 mΩ.

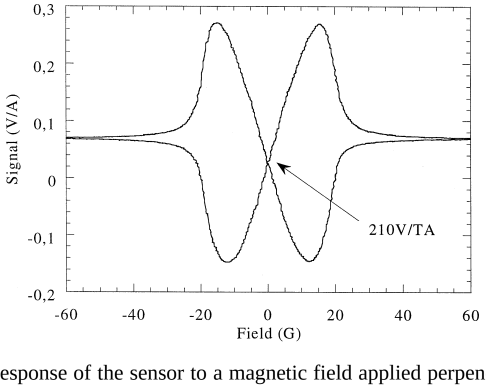

Fig. 1. Response of the sensor to a magnetic field applied perpendicularly to the easy axis.

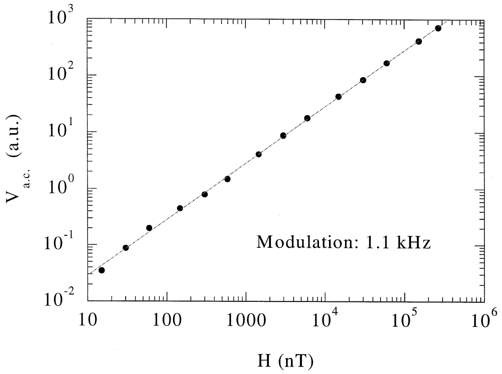

Fig. 2. Linearity of the sensor measured with synchronous detection.

Fig. 1 shows the signal obtained by varying the field perpendicularly to the easy direction. Around zero, the signal is linear for fields below 5 G. At higher fields, the magnetisation goes near the perpendicular direction and the signal saturates. The reversal of the magnetisation is close to coherent rotation along the entire cycle. The sensitivity (slope of the signal vs. field in the linear regime) is about 200 V/TA. The lowest magnetic field we have detected in our experimental room is 10 nT. However, we are limited by the magnetic noise of our laboratory. Preliminary measurements of effective noise performed in a zero field environment have shown a resolution limit below 0.5 nT [9]. Fig. 2 shows that the response is linear over at least 4 decades. For these measurements, we modulate the current in the sensor at 1.1 kHz and use a synchronous detection of the signal.

3. Offset suppression

Although, ideally, PHE is directly proportional to the field without any offset, in practice, the measure is degraded by several sources of offset. The typical offset is about between 10^{-4} and 10^{-3} of the sensor resistance. However it corresponds to an equivalent field of few tenth of a Gauss. We can distinguish three distinct sources.

- Constant voltage V_0 induced for example by the amplification electronics or thermal electro-motive force.
- Longitudinal contribution of the resistance induced by lithography imperfections (particularly in the pattern corners). It introduces a constant resistance, R_{off}, but also a weak field dependant error, α, due to the anisotropic magnetoresistance.
- Misalignment between easy axis and current direction. A phase shift d of the signal results from such a misalignment, leading to a non zero value at zero field.

So, the real signal can be expressed as

$$V = V_0 + R_{\mathrm{off}} I + \alpha I \cos 2(\theta + d) + \frac{\Delta R}{2} I \sin 2(\theta + d)$$

The main part of the offset does not depend on the magnetic state. So, we can suppress it by doing two measurements in two different magnetic states, i.e., the two opposite easy directions. The switching of the magnetisation is performed by applying a field large enough H_{off} along the easy direction (cf. Fig. 3). This field is generated by a wire deposited on top of the sensor. The wire is large enough to create an homogeneous field over the entire magnetic surface so the generated field depends only on its width and the current flowing through it. After the fabrication of the sensor, a metallisation layer is used to take the four contacts. This layer of $\mathrm{Ti}_{50}/\mathrm{Au}_{50}$ is defined by lift-off. An insulator layer of silicon nitride is then deposited by reactive sputtering. Finally, the wire ($\mathrm{Ti}_{50}/\mathrm{Au}_{250}$) is also defined by lift-off.

After applying a current in the wire in both polarities, we obtain two signals that we can differentiate. If θ_+ and θ_- are the angle of the magnetisation in each of the two configurations, the subtraction of the two signals is:

$$\begin{aligned} \Delta V = {} & \frac{\Delta R}{2} I\left[\sin 2(\theta_+ + d) - \sin 2(\theta_- + d)\right] \\ & + \alpha I\left[\cos 2(\theta_+ + d) - \cos 2(\theta_- + d)\right] \\ = {} & \Delta R I \sin(\theta_+ - \theta_-)\cos(\theta_+ + \theta_- + 2d) \\ & - 2\alpha I \sin(\theta_+ - \theta_-)\sin(\theta_+ + \theta_- + 2d) \end{aligned}$$

At low fields, $\theta_+ = H_y/H_a$ and $\theta_- = \pi - H_y/H_a$, so:

$$\Delta V = I \sin\left(2\frac{H_y}{H_a}\right)\left[\Delta R \cos 2d - 2\alpha \sin 2d\right]$$

Finally, if we consider the effect of the H_x component of the field (which superimposes to the anisotropy field), we can show that this effect is considerably reduced by the offset suppression allowing wider measurement range.

The inset of Fig. 4 shows the difference of the signals, ΔV, measured after applying a current in the wire with both polarities. At low currents (lower than 100 mA, generating field below 4 G), there is almost no difference between the two signals, indicating that the magnetisation returns back to its original position after the pulse. For stronger fields, a difference, corresponding to the amplitude of the applied external field, is obtained confirming that the magnetisation is reversed by the field. Above the transition, ΔV is constant, which shows that the whole magnetic area is reversed.

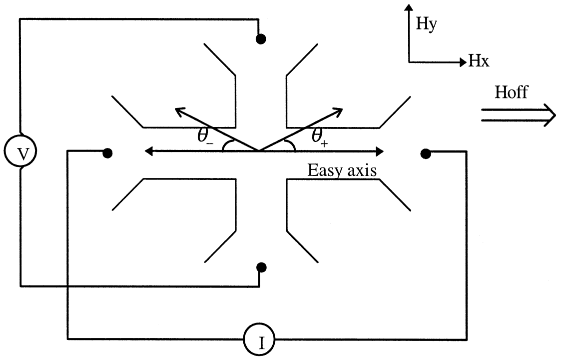

Fig. 3. Scheme of the offset suppression.

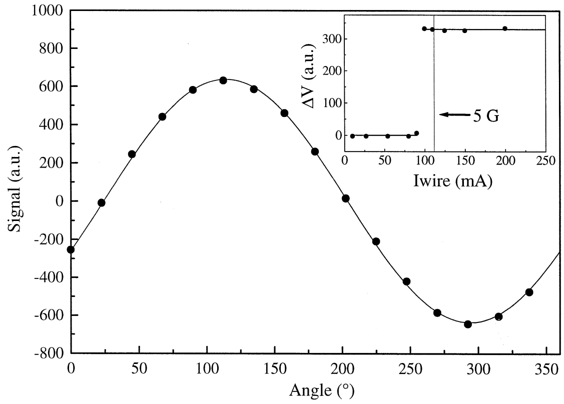

Fig. 4. Angular measurement of the earth's field. In inset, ΔV vs. the current applied in the wire.

As expected, we did not notice any influence of the field application time on the signal from 1 μs to 100 ms. Short pulses, more than decreasing consummation of the device, allow to use a synchronous detection and differentiation of the two states, decreasing dramatically the noise below the frequency of modulation.

Fig. 4 shows an angular measurement of the in-plane component of the earth's field. The current pulses are about 1 μs long (obtained by RC derivation of a rectangular signal) and the frequency is about 1 kHz (although frequencies above 1 MHz are possible). The signal is then demodulated after amplification. The angular resolution is below 0.5° (which is about the mechanical precision of our experimental set-up). In fact we estimate the offset reduction to be of the order of 1000 which allows to use a 10 nT resolution for the measurement.

4. Conclusions

We have presented here a new PHE magnetic sensor. Deposition of a FeNi thin film onto misoriented silicon wafers by sputtering provides a good in plane uniaxial anisotropy with a simple technology. Such a sensor has a sensibility about 200 V/T.A and a resolution below 10 nT. The magnetisation switching allows to drastically remove the residual offset. Moreover, suppressing the offset at high frequency by continuous modulation, improves considerably the signal to noise ratio at low frequencies.

The association of two orthogonal sensors will give a micro-compass with an angular resolution limited only by the precision of assembling. A special ASIC electronic developed for this purpose should lead to a device size of the order of 1 mm^2.

Acknowledgements

This work had been supported in part by French Ministry of Industry and Telecommunications under grant number 95 MMFIM 71. We would like thank J. Humbert and T. Wochenmayer for technical assistance. One of us (A.E.) would like to acknowledge CONACyT (Mexico) for loan number 92948.

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Biographies

François Montaigne was born near Paris in 1974. He graduated in 1996 from Ecole Supérieure d'Ingénieurs en Electrotechnique et Electronique where he specialised in microelectronics and microsystems. After having graduated from the University of Paris, he is now a PhD student at Unité Mixte CNRS-THOMSON. His main field of interest is tunnelling between ferromagnetics and magnetic sensors.

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Armando Encinas was born in Mexico City, Mexico in 1968. He graduated from the physics department at the University of Sonora in 1993 and obtained a MSc degree at the Institute of Physics 'Manuel Sandoval Vallarta', Mexico in 1995. Now in his third year as a PhD student at the University of Paris-Sud. His main field of interest is the fabrication and magnetic properties of magnetic nanostructures.