Monolithic spin valve compass for autonomous MEMS navigation in geomagnetic field

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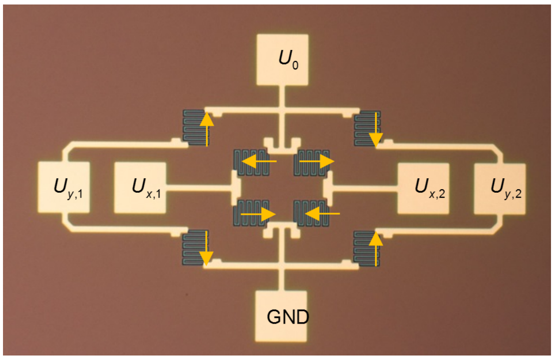
***Abstract*—The natural geomagnetic field has been used for millions of years by various organisms for navigation. The determination of the local field direction (in terms of magnetic north and inclination) enables, for instance, migratory birds to find their annual routes from one continent to another and back home, or magnetotactic bacteria to move towards soil areas rich in nutrients. In analogy, for microelectromechanical systems (MEMS), the capability of detecting the local direction of the geomagnetic field as a 2D or 3D vector enables a reliable autonomous navigation through environments with a complex or unknown topology while being independent of GPS or any other radio-based navigation system (and thus being operable also in obstructed or shielded environments). Such mobile MEMS applications demand, however, a very low power consumption and a high miniaturizability of the sensor, as well as a very fast sensor response time. In the following, we present an innovative 2D GMR spin valve sensor on the basis of exchange-biased NiFe-CoFe / Cu / CoFe / IrMn nanolayers in monolithic integration that fulfils all these requirements. For a maximum signal-to-noise ratio, we have realized a focused double full-bridge layout with an antiparallel alignment of the pinned layers of neighbouring meanders by means of microscopic laser heating and subsequent in-field cooling. A systematic optimization of geometry and magnetic structure further contributed to a maximum signal level and a minimum sensor hysteresis. On the basis of fabricated prototypes with a size of 1.5 mm times we demonstrate that these sensors are readily employed to detect the geomagnetic field as a 2D vector with temporal (1 ms) resolution.**

***Index Terms*—Giant magnetoresistance (GMR), spin valve, multi-axis magnetic sensor, electronic compass**

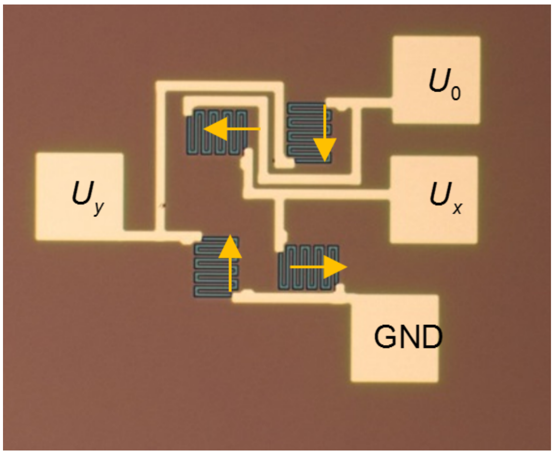
I. Introduction

Spin valve (SV) sensors as first proposed by Dieny et al. 1991 allow significant improvement of device performance for mobile navigation systems and angle sensors because of their high sensitivity and field resolution [1]–[3]. The advantage of a monolithic integration enables a very economic fabrication process and a compact design.

In general, SVs make use of the giant magnetoresistance effect (GMR) that originates from an asymmetry in the spin-dependent scattering at magnetic/non-magnetic interfaces for spin-up and spin-down electrons. SVs consist of two ferromagnetic layers separated by a non-magnetic conducting spacer film. The magnetization of one of the ferromagnetic layers, the so called reference layer, is pinned via exchange coupling with an antiferromagnetic film. The second ferromagnetic layer, the so-called free layer, can freely respond to an external magnetic field. The GMR effect between the free and the reference layer leads to a state of maximum resistance for an antiparallel alignment of the two ferromagnetic layer magnetizations and to a state of minimum resistance in the case of parallel alignment [4], [5].



(a)



(b)

Fig. 1. (a) Microscopic image of the focused double full-bridge spin valve sensor in monolithic integration. The yellow arrows illustrate the locally set magnetization of the pinned layers. (b) The sensor signal of the inner bridge (x axis) for a 360° rotation in the geomagnetic field (red curve). To verify that it is indeed the Earth's field being sensed, the same measurement is additionally carried out with the entire setup rotated by 90° (blue curve).

For sensing position, speed or current with high sensitivity, a full-bridge configuration constituted by four single SV elements is best suited because it offers a differential read-out with a null output in absence of a signal field. In addition, any thermal drift within the resistors is intrinsically compensated for [6]. To provide a two-dimensional sensitivity, we designed a nested double full-bridge (DFB) configuration with differential output voltages. To achieve this, the meander pinning is set antiparallel for (nearest) neighbouring meanders and orthogonal for inner and outer meanders, respectively, cf. Fig. 1 (a). This precise alignment is accomplished by laser modification as described below. Complementary to this configuration, we also realized a more compact and simplified alternative layout in terms of a double half-bridge (DHB) configuration, providing similarly a two-dimensional sensitivity, as presented in Fig. 1 (b). The signal output, however, is a modulation of the half input voltage and thus not differential, resulting in a lower achievable resolution.

In general, these double full-bridge and half-bridge configurations are suitable for the detection of small magnetic fields as a 2D vector quantity with high spatial ($\sim$ 200 µm) and temporal (theoretically up to $\sim$ 1 ns) resolution, cf. Fig. 2. This capability arises from the dependence of each meander's GMR on the angle between pinned reference and the free layer (which follows the external field), reading

$$\frac{\Delta R(\theta)}{R} = \frac{\Delta R_{max}}{2R}(1 - \cos\theta) \tag{1}$$

In the following, we compare the signal output of monolithically integrated double full-bridge and double half-bridge configurations for small magnetic fields as employed in combination with conventional read-out electronics (i.e. sourcing, amplification, A/D conversion). In particular, we test the sensitivity to the geomagnetic field. A functional 2D geomagnetic sensor may be readily applied as electronic compass.

II. Materials and Methods

A. Deposition and meander patterning

Spin valve films consisting of substrate / Ta 5 nm / $Ni_{81}Fe_{19}$ 2 nm / $IrMn_3$ 5 nm / $Co_{90}Fe_{10}$ 2.1 nm / Cu 2.054 nm / $Co_{90}Fe_{10}$ 1 nm / $Ni_{81}Fe_{19}$ 2 nm / Ru 0.4 nm / Cu 0.5 nm / Ta 30 nm are prepared by DC magnetron sputtering on thermally oxidized Si substrates. By design, the Cu layer thickness results in a zero exchange coupling between the pinned and the free layer.

The individual SV elements are patterned into simple meander structures by photolithography and subsequent dry etching (plasmas of SF_6 and Ar). The uppermost Ta layer serves as a hard mask during etching and is thinned therein to a low value of $\sim$ 10 nm. Although representing a shunt parallel to the (current-in-plane) layer stack, it ensures material integrity. The width and length of the single stripes to be respectively 4 µm and 50 µm, provided that the present dimensions are based in a previous geometry optimization work and have been found to provide optimal magnetic properties, cf. [7]. For electrical contacting, Cu bond pads and connections paths are added.

B. Magnetic alignment

The pinning of the reference layer is accomplished by laser heating and subsequent cooling in the presence of a magnetic field. The local temperature of the antiferromagnetic IrMn layer is first increased above its Néel temperature ($\sim$ 250°C [8]) in overlapping spots with a diameter of (8.0±0.5) µm in diameter. The magnetic field during cooling is set to a user-defined orientation and magnitude, sufficient in strength to reset the exchange bias direction. Details are described in [9]. In the present case, the exchange bias direction is set to be perpendicular to the meander stripes (cf. Fig. 1), providing a crossed zero-field configuration, i.e. perpendicular, alignment of the magnetic anisotropies of the free layer (by shape anisotropy) and the fixed layer (by dominant exchange bias pinning). Further details can be found in [7].

C. Electrical characterization

Magnetic and electrical transport measurements are done using a customized mechatronic setup for the characterization of multi-axis GMR sensors. This set-up provides a platform for automated scans of (arbitrary) magnetic field angles in 2D, cf. Fig. 3, assisted by voltage supply for the sensor along with an analogue-digital convertor and an amplification system for

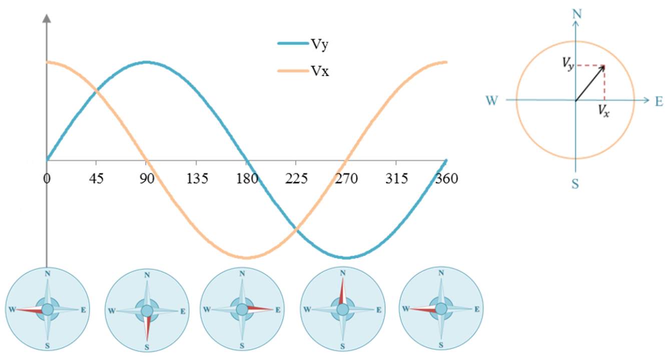


Fig. 2. Schematic representation of the angular sensor output in response to an external magnetic field.

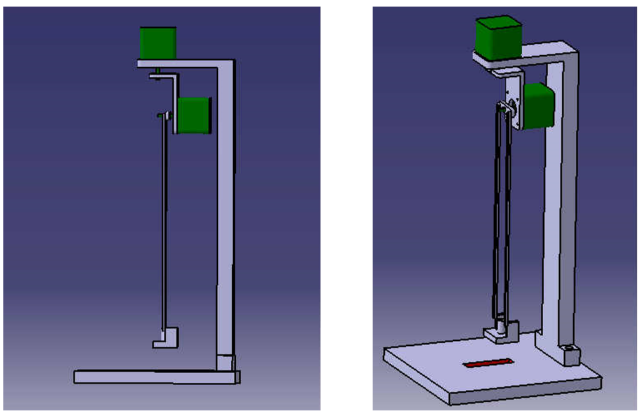


Fig. 3. (a) Side and (b) isometric view of the angular measurement setup developed for the electrical characterization.

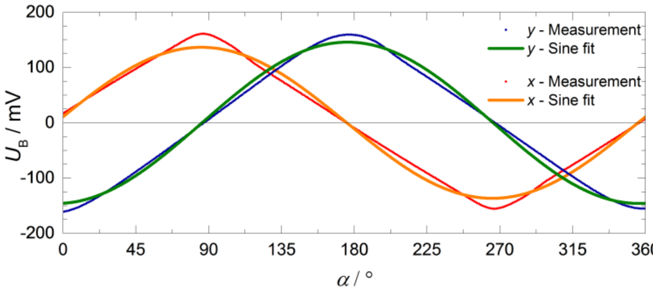


Fig. 4. Magnetic response of the inner (U_x) and outer (U_y) bridges in a DFB as function of the angular alignment with respect to a permanent magnet. Acquisition made with $U_0 = 10V$ input voltage and 600 readings for each degree. The rotation followed the alignment N (0°) → W (90°) → S (180°) → E (270°) with respect to the permanent magnet's stray field.

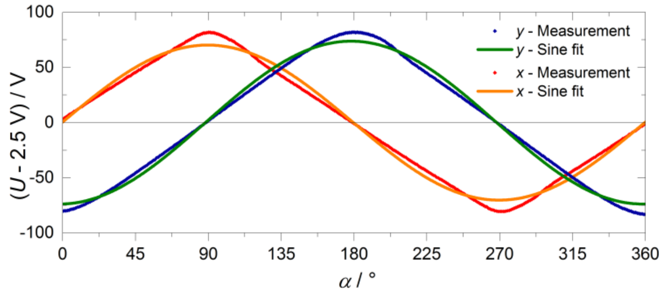


Fig. 5. Angular dependency of the signal for a DHB in the presence of a magnet. Alignment and rotation in analogy to Fig. 4.

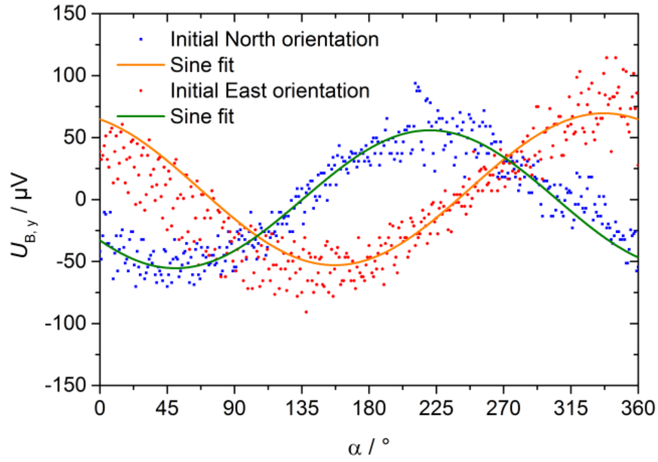


Fig. 6. DFB in geomagnetic field (inner bridge). Comparison between measurements starting with an orientation towards North (blue / green) and East (red / orange). The observable 90° signal phase shift is in full accord with these different initial alignments.

data acquisition. The sensor under study can be rotated along two independent axes, thus allowing any angular orientation in an external field. The latter can be either given by the geomagnetic field of by artificial sources such as permanent magnets or coils. The sensor response in each of these possible orientations is acquired and analysed in real-time with a data rate of 1000 Hz.

III. Results

A. Measurements in a presence of a magnet

The sensor response was first analysed in the presence of a magnetic field originating from a permanent magnet (NeFeB, 50 mm times 15 mm) possessing a flux density of 200 mT at its surface. The magnet was placed in a constant distance of 3 cm from the sensor. The inner and outer bridges, respectively represented as Ux and Uy show an exact 90° difference in phase, providing a further evidence of the accuracy of the magnetic patterning. As a result of the relatively high field generated by the permanent magnet, a certain deviation from the expected sinusoidal response is observable. Even at the present distance between sensor and magnet a certain degree of rotation of the fixed layer takes place, which results in a "faster" transition to the parallel arrangement of the free and reference layer, as can be seen in Fig. 4 for the DFB case. The reasons for this behaviour is that the field generated by the magnet overcomes the exchange bias field that pins the magnetization of the reference layer ($\sim$ 35 mT).

In the case of the DHB sensors, the results are in principal comparable to those of the DFB. Yet they exhibit, as expected, only half the signal amplitude of the DFB and an absolute signal offset of U_0 / 2.

B. Geomagnetic field measurements

Regarding the geomagnetic field measurements, these were carried out starting with an alignment towards the Artic magnetic pole (magnetic south pole). In the case of the DHB sensors, the sensitivity proved to be inadequate for such small fields because of the much higher offset voltage . The DFB sensors, however, proved to provide the necessary sensitivity to sense the geomagnetic field, cf. Fig. 5. As an additional confirmation of these results, the same measurements were carried out once again, this time starting with an East alignment. As shown in Fig. 6, comparing both measurements we can identify the 90° change in phase corresponding to the change in the initial angular alignment of sensor, confirming the geomagnetic origin of the sensor signal.

IV. Conclusions

A spatially resolved detection of magnetic fields can be efficiently provided by SV sensors arranged in a double bridge configuration, offering a two dimensional magnetic resolution. The sensors showed to provide the necessary information to reconstruct a 2D vector both in the case of a permanent magnet and a geomagnetic field, proving their ability to be used in industrial applications or even for compass applications with high resolution and low power consumption, amongst all other benefits of GMR-based technology.

V. Acknowledgment

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