

360 Degree Angle Sensor Using Spin Valve Materials with SAF Structure

Dexin WANG, Jay BROWN, Tim HAZELTON, and Jim DAUGHTON

Abstract— A microchip of 360-degree angle sensor using spin valve materials was designed, fabricated and tested with excellent performance. The spin valve material used for the angle sensor has a structure of Ta-NiFeCo-CoFe-Cu-CoFe-Ru-CoFe-CrMnPt. External magnetic fields have little torque on the CoFe-Ru-CoFe structure upto at least 500Oe which is the highest value available during the test. This is due to the strong antiparallel exchange coupling between the two CoFe sublayers of the same thickness via a thin layer of Ru and the resulting zero net magnetic moment. There is a sharp switching of the free layer with a low coercivity of 4 Oe along the easy axis. Both high standoff field and small coercivity ensure the sensor to operate properly with large tolerance in mechanical assembly. The angle sensor is used stationary in combination with a disc-shaped permanent magnet attached to a rotating shaft near the sensor. The permanent magnet is magnetized in-plane thus creating a field that is rotating with the shaft. The magnetic field from the permanent magnet forces the free layer magnetization to follow the field and rotate with it. With a fixed reference layer magnetization and an in-phase following of the free layer magnetization, the magnetoresistance is a simple cosine function of the angle between the rotating permanent magnet and the stationary sensor. A special Wheatstone-bridge with four spin valve resistors is used to compensate the thermal drift expected in application environments. One half-bridge has a 90 degrees phase delay from the other, resulting in a cosine and a sine function, in combination to uniquely determine any angular relationship between the permanent magnet and the sensor between 0 to 360 degrees.

Index Terms—magnetic sensor, angular position sensor, spin valves, GMR, sputtering, microchip.

I. INTRODUCTION

Magnetic sensors are attractive in measuring positions in mechanical systems [1,2,3] in both automotive and industrial applications. Magnetic field acting as the transmitter provides a contact-free means which is inherently wear-free. Unlike optical sensors that require transparency, magnetic sensors can tolerate dirt, dust, and other unintended or unavoidable coatings during its operation lifetime. For a given magnetic angle sensor, it is also desirable to use only the direction, rather than the magnitude, of the magnetic field to

determine the angular position, mainly because it relaxes the precision requirement in assembling the sensors relative to the permanent magnets. Other requirements include upset-free with high magnetic field excursion, wide operating temperature range, easy to interface with control electronics, small size, and low cost. Spin valve (SV) materials have been widely used for read head in data storage industry [4] and others [5] for its high signal, small size, and readily available mass quantity manufacturability. It is natural to extend its application for other magnetic field sensing areas such as angular position sensing. This type of devices also has the potential to be integrated on chip with conditioning electronics. [6]

II. EXPERIMENTAL PROCEDURES

Spin valve wafers were deposited using DC magnetron sputtering, with a base pressure lower than 1.0×10^{-7} Torr. A magnetic field was applied during magnetic layer deposition to induce a magnetic easy axis and the pinning direction [5,6]. Annealing was done in forming gas with a magnetic field applied. The spin valve stack wafers were patterned into serpentine stripes using photolithography techniques. The wafers were diced and packaged by a commercial packaging service provider. Four spin valve resistors were packaged in a Wheatstone bridge form in a leadless TDFN surface mount frame. Magneto-transport properties were measured at room temperature using a computer controlled test station. Angular response was measured using a lab bench setup.

III. EXPERIMENTAL RESULTS

The top-pinned spin valve material has a layering structure of Ta-NiFeCo-CoFe-Cu-CoFe-Ru-CoFe-CrMnPt. The synthetic antiferromagnet (SAF) pinned layer of CoFe-Ru-CoFe is for better standoff fields. [7] Because of the extremely strong antiparallel coupling via a thin layer of Ru, external field provides little torque to the trilayer SAF structure due to its zero-net magnetic moment. The standoff field is higher than 500 Oe, the maximum field available for this test, as can be seen from Figure 1. The actual pinning is provided by an antiferromagnetic CrMnPt layer, which has sufficiently high blocking temperature and thermal stability after annealing at 250 °C for 1 hour. To achieve a soft free layer without degrading the GMR, which is proportional to the signal and sensitivity of the device, a composite free layer of NiFeCo/CoFe was used. The easy axis coercivity is about 4

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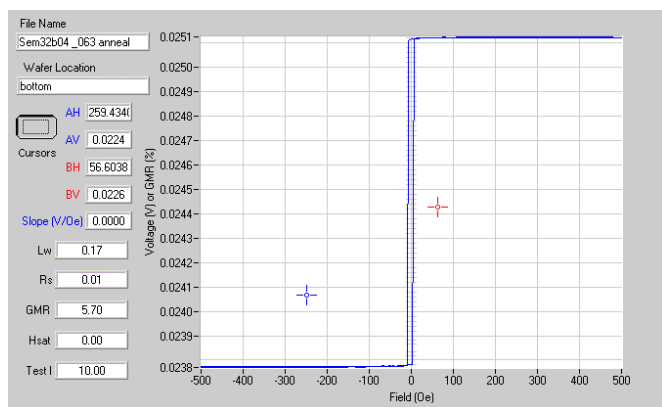


Figure 1. MR plot for a typical spin valve with a structure of Ta-NiFeCo-CoFe-Cu-CoFe-Ru-CoFe-CrMnPt, an easy axis loop exercised with a field of 500 Oe.

Oe, as shown in Figure 2 for a minor loop, and the maximum saturation field for all orientations is ~30 Oe as indicated by the saturation field from the hard axis loop (not shown here).

All wafer level processing steps were finished in-house. The mask set has four layers. The device designs have several types of serpentine windings with different end shapes. The final choice has a serpentine structure with rounded ends and with a direct magnetic layer connection of a single orientation with a wide linewidth. Wider line reduces the shape anisotropy without affecting the chip area, which is limited by the size of the bonding pads thus maintaining low cost for the device.

Below the working principle of a spin valve angle sensor is briefly described. It is well known that the resistance R of a spin valve is related to the angle θ between the free and the reference layer magnetizations in (1):

$$R/R_p = 1 + \frac{1}{2} GMR (1 - \cos\theta) \quad (1)$$

where the R_p is the lowest resistance when the two magnetizations are parallel; and the GMR is the maximum percentage magnetoresistance. An applied magnetic field of adequate magnitude, in the range greater than the saturation field for the free layer and smaller than the standoff field for the pinned layer, will force the free layer magnetization to follow the field when it rotates. With a fixed reference layer magnetization, and an in-step following of the free layer

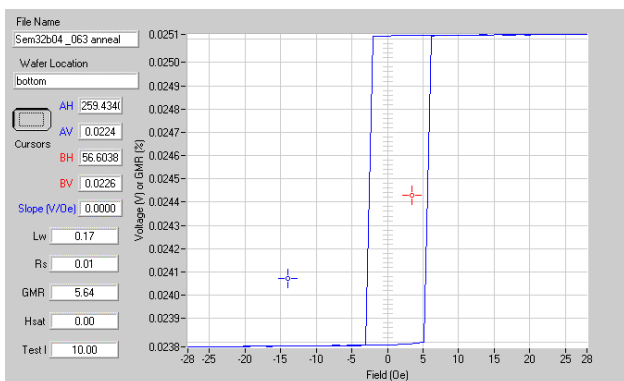


Figure 2. MR plot for a typical spin valve with a structure of Ta-NiFeCo-CoFe-Cu-CoFe-Ru-CoFe-CrMnPt, an easy axis loop exercised with a low field of 28 Oe.

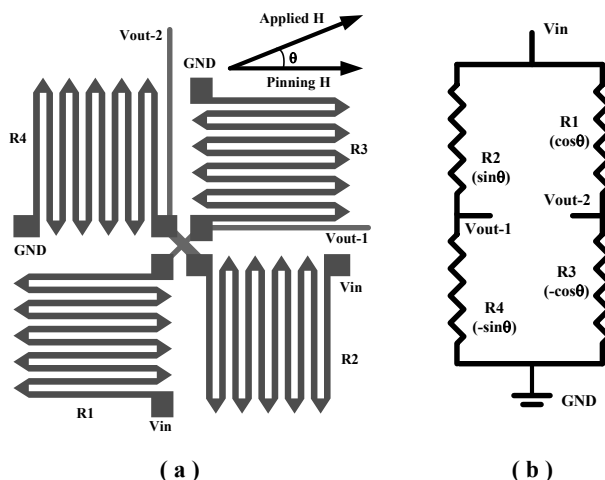


Figure 3. Schematics of (a) layout; and (b) circuit diagram of the angular sensor. Vout-1 and Vout-2 are connected out separately, rather than as a single differential signal.

magnetization, magnetoresistance is a simple cosine function of the angle of the rotor relative to the stationary sensor.

Due to the nature of the cosine function, a unique angle can only be determined between 0 to 180 degrees. In order to have a 360 degree angle sensor, another otherwise identical spin valve resistor but with a 90 degree delay relative to the first one is used. These two spin valve resistors form one cosine and one sine function of the same angle thus capable of uniquely determining any angular relationship between 0 to 360 degrees.

Generally either a half or a full Wheatstone bridge is used for such a sensor [8] in order to compensate the thermal drift inevitable when the device is put in use in real environments. This further increases the number of spin valve resistors in an angle sensor to be four to form two half-bridges. With the special arrangement as depicted in Figure 3(a), one half-bridge has one sine and one -sine spin valve resistors connected in series, thus the total resistance of this half-bridge is constant. Similarly, the other half-bridge also has a constant total resistance with one cosine and one -cosine spin valve



Figure 4. Photo of a spin valve rotation sensor packaged in a leadless TDFN6 format (on a penny background).

resistors in series. The constant resistance values make it easier to energize the two half-bridges by using a single supply of either constant current or voltage, as shown in Figure 3 (b). However, the two outputs are taken out separately, rather than as a differential of the two nodes usually used for a full bridge.

The final angle sensor is packaged into leadless TDFN6 frame of 3.0 x 3.0 x 0.9mm in size, with a photo shown in Figure 4. Test devices have also been bonded to SOIC8 leadframes for evaluation only. Inside the angular sensor package there are four SV resistors with their pinning directions 90 degrees apart from each other. The SV resistors were fabricated on the same wafer, with the same design, patterning process and identical performance, with a nominal resistance for each one is 1.5k Ω .

The angle sensor is used in combination with a planar permanent magnet attached to a rotating shaft (rotor), as depicted in Figure 5. The permanent magnet is magnetized in-plan thus creating a field that is in the plane of the sensor chip and rotating with the shaft. This field forces the free layer magnetization to rotate in phase with it and thus the rotor. Therefore the output signal is a sinusoidal function of the angle. With the permanent magnet, sensor design, and their axial configuration the same, the distance between the magnet and the sensor, or airgap, determines the magnitude and distribution of the magnetic field acting on the free layer of the SV resistors. The basic requirement for the magnet and the airgap is that the lowest field acting on the free layer is large enough to saturate it, and the highest field does not distort the reference layer. This range between 30 Oe and 500 Oe is quite wide for practical purposes. Higher temperature will reduce this field range, which will be partly compensated by the supply field reduction from the permanent magnet.

Precision alignment including the airgap for the bench test setup is achieved using a commercial positioning stage. The devices are tested with different airgaps of 2, 4, and 6 mm. When a constant voltage is applied to the bridge, Figure 3, the output voltage Vout-1 is a sine function and Vout-2 a cosine function of the angle between sensor and the rotor, with a common DC offset half of the supply voltage Vin. The output signals are captured on a computer, and plotted in Figure 6 with a 2 mm airgap, along with the theoretical sine

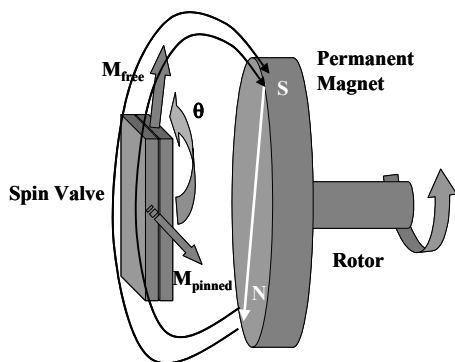


Figure 5. Schematic of an angle sensor---permanent magnet rotor assembly. A spin valve stack is used to represent the spin valve angle sensor.

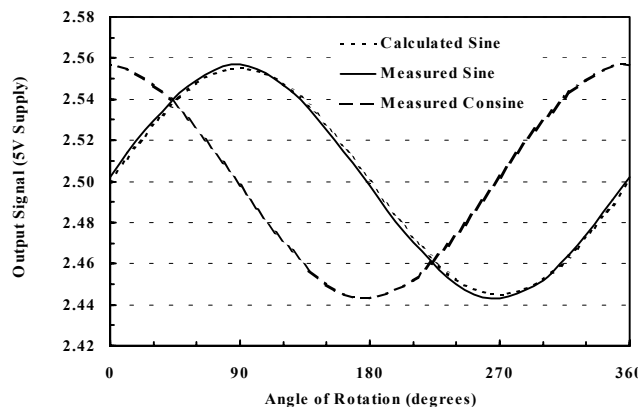


Figure 6. Output waveforms, Vout-1 and Vout-2, of the two half-bridges from a spin valve angle sensor as a function of the angular position with a 2 mm airgap, comparing with theoretical sine and cosine curves.

curve. The deviation of the measured data from the theoretical curves represent about 1 $^\circ$ inaccuracy in angular measurement. The operating temperature range is determined to be from -40 to 150 $^\circ$ C.

Because that the free layer is always in the saturated state, the sensor evaluate the direction, not the strength, of the magnetic field. Therefore, the device can tolerate some variations in field strength caused by temperature, degradation over time, disparity in the permanent magnets, airgap, as well as other mechanical inaccuracy during assembling.

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