3-axis magnetometers using spin dependent tunneling: reduced size and power

Mark Tondra, Albrecht Jander, Catherine Nordman, John Anderson, Zhenghong Qian, Dexin Wang;
NVE Corp., 11409 Valley View Rd., Eden Prairie, MN 55344

ABSTRACT

A 3-axis magnetometer has been constructed using 3 Spin Dependent Tunneling (SDT) magnetic field sensors as transducers. This magnetometer has been designed for use in low frequency applications such as vehicle detection, security, and Unattended Ground Sensor (UGS). As such, there has been an emphasis on low cost, size, and power. The present version is smaller than previous versions, uses a common software interface, and is ready for prototype sampling. This paper describes the basic properties of the SDT 3-axis magnetometer, including size, power, and noise floor.

Keywords: Magnetometer, Spin Dependent Tunneling, Magnetic Tunnel Junctions, Magnetoresistance, Unattended Ground Sensors, Magnetic Field Sensor, Low Power, 3-Axis

1. INTRODUCTION

Spin Dependent Tunneling (SDT) devices have been employed as magnetic field sensors for several years[1]. As with other thin film ferromagnetic magnetoresistive devices such as those using Giant Magnetoresistance (GMR) and Anisotropic Magnetoresistance (AMR), they have advantages in size, cost, and power that come with the microlithographic fabrication process[2,3]. SDT devices have an additional advantage over AMR and GMR sensors in that their intrinsic signal per unit field is larger by several times. NVE Corp's largest SDT magnetoresistance to date in a sensor-like device is 61%, where comparable AMR and GMR devices have 2% and 12% total signal, respectively. Another advantage of the SDT device for Unattended Ground Sensors (UGS) is their relatively high resistance. This permits a reduction of power, when compared to AMR and GMR devices, required to operate a resistance bridge made of the SDT devices.

Based on these motivating factors, SDT sensor design has been directed towards an intrinsically low-power design that is compatible with a compact circuit platform for 3-axis field measurements. Work reported previously (SPIE-AeroSense 2002) on SDT sensors focused on changes to the intrinsic magnetic design of the tunnel junctions that allowed the sensors to operate in a linear mode with no additional biasing field (nor the corresponding power needed to generate that field) [4]. These intrinsically low-power transducers have been incorporated into a 3-axis magnetometer design. The magnetometer circuit design was performed with an emphasis on minimizing cost, size and power. It is improved over previous designs in all three categories.

This first technical section of this paper describes the 3-axis magnetometer circuit concept, the feedback and amplification scheme, and shows the overall small footprint required. The second technical section describes the performance of the latest SDT transducers and the 3-axis magnetometer board carrying them. Also, expected short term and ultimate performance improvements are described.

2. CIRCUIT DESIGN AND OPERATION

The magnetometer design and operation will be described working downward in level of complexity, starting with the entire board , moving to the magnetic transduction circuit scheme, and then to the SDT transducers themselves. The present 3-axis magnetometer board is much smaller than previous versions[3]. Much of this is due to a reduction in complexity of the communications circuitry. A photograph of the board is shown below in Figure 1.
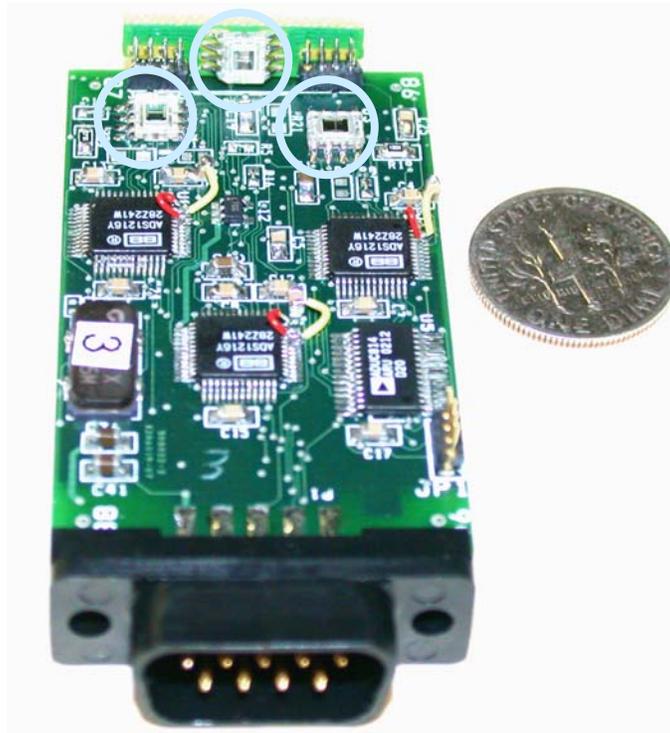
Figure 1. The 3-axis SDT magnetometer board. There is a separate sensor transducer chip for each of the three orthogonal axes. The out-of-plane axis is handled by mounting an in-plane sensor on a small board that gets connected on-edge to the main board. The sensor packages, at the upper end of the picture, are circled.

1. Basic Schematic

Below in Figure 2 is a basic block diagram of the circuit concept. Each magnetometer axis has its own field feedback and Analog to Digital Converter (ADC). The three axes share a common microprocessor, which manages the ADCs and the communication with external instrumentation. The communication method is a standard RS232 interface. The field feedback is set up to give a wide dynamic field range with high linearity and low hysteresis. The board is designed to operate with a +5 Volt power supply.
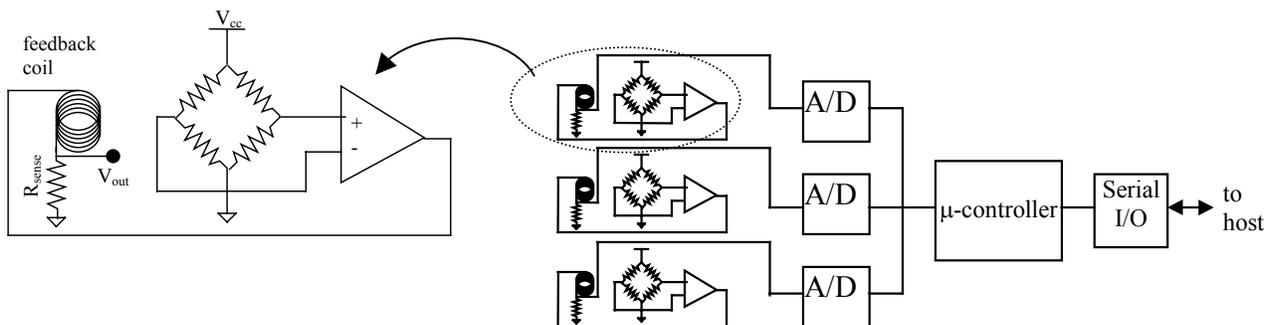

Figure 2. On the right is a system block diagram for the 3-axis magnetometer design. On the left is a detailed block diagram of the feedback scheme. The actual output that gets digitized is the voltage across a reference resistor that is in series with the feedback coil. Each of the 3 axes has its own coil and reference resistor.

2. Sensor Package and Circuit Board Footprint

The SDT sensors are fabricated using a standard integrated-circuit-like microlithographic process. A typical sensor lot will have 8 4" wafers upon which will be about 1000 sensors on each wafer. The fabrication process includes several

layers of Al metal for interconnection and integrated planar coils, the SDT devices themselves, and some plated NiFe flux concentrators. Once the wafers are finished, they are diced and sent to a packaging house where they are diced, wire bonded, and molded into standard integrated circuit packages. A diagram and photograph of a finished SDT sensor chip is shown below in Figure 3. Automated testing of packaged parts allows for rapid winnowing away of lesser-performing parts. The SDT parts are mounted on and soldered to a printed circuit board just like any other chip. The magnetic operation of the sensors is described elsewhere (SPIE AeroSense 2002)[3].
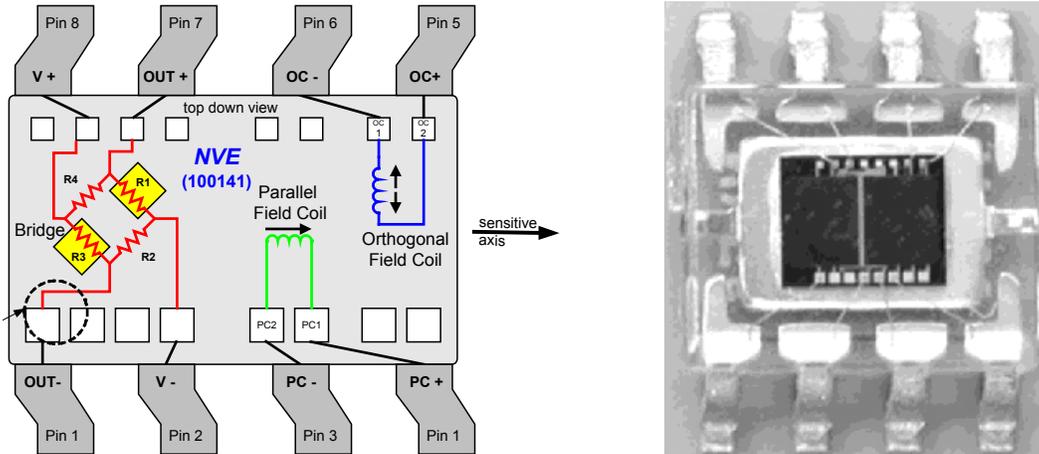

Figure 3. The drawing on the left shows schematically the components that are contained within the SDT sensor package. The photograph on the right is of an SDT sensor die packaged in an SOIC-8-pin package. The package material in this case is clear, which allows one to see the die, wirebonds, and bonding pads of the finished device.

3. PERFORMANCE

This section will discuss the performance of the 3-axis SDT magnetometer in terms of power, and noise. The SDT transducer itself has the greatest influence on both power and noise. The SDT transfer curve, a plot of Output Voltage vs. Magnetic Field, is described in section 3.1. The noise performance of the board is described in section 3.2. Then are discussed the power and overall specifications for the board.

1. Transducer Transfer Curve

The SDT low-power transducer curve has been evolving towards an ideal shape over the past several years. In this case, "ideal" means a wide range of field over which the output is linear with little or no hysteresis. Further, the transfer curve should be centered on zero field and zero volts. The curve shown in Figure 4 below comes close to this ideal. There is still some hysteresis and offset. The offset occurs both in voltage and field. The voltage offset is from a mismatch of the resistors in the transducer bridge (offset of .05 Volts out of 5V excitation = 1%offset). The field offset is a function of the sensor's magnetic design. There are efforts underway to continue reducing these non-idealities. The transducers come in two designs, a 60 kOhm (6 Volt max) and a 300 kOhm (12 Volt max). These designs vary in the number and size of the tunnel junctions that make up the resistance bridge.
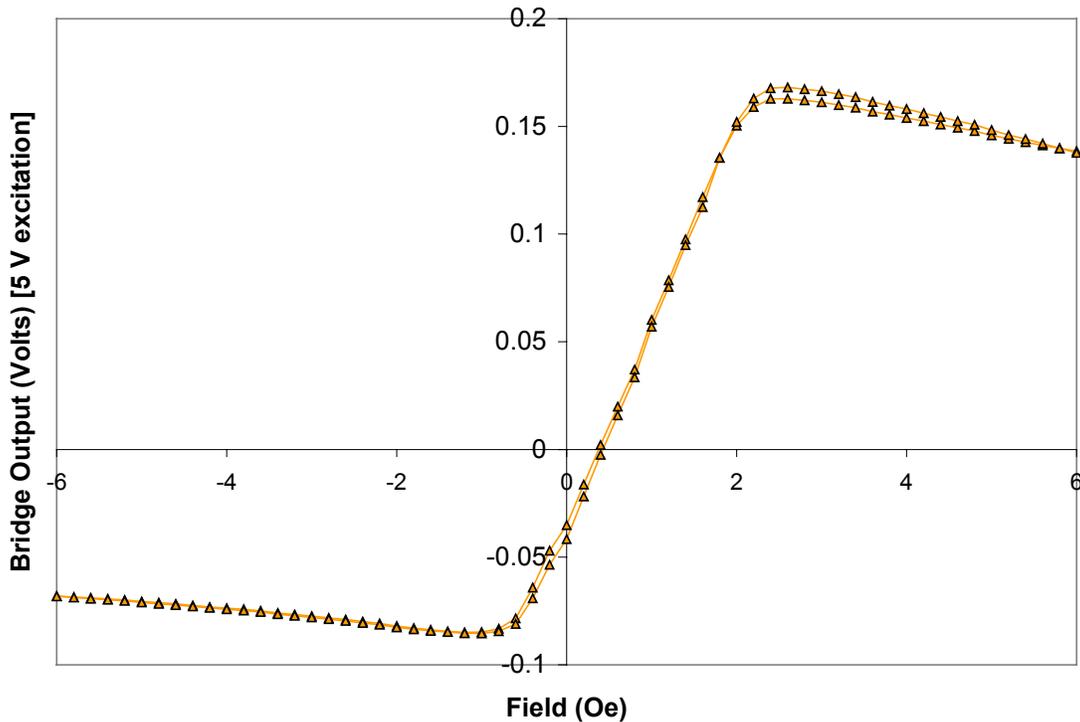
Figure 4. Transfer curve for low power SDT sensor. This is a measurement of the 4-terminal bridge output. That is, a 5 Volt supply is applied from the top of the bridge to ground, and the voltage between the other two bridge leads is monitored and plotted as a function of applied magnetic field. The field starts at +6 Oe, sweeps to –6 Oe and then back to +6 Oe.

2. Noise Floor

The sensor noise floor is dominated, at low frequencies (below 1 kHz), by "1/f" noise. The "1/f" refers to the functional relationship between the noise power (V^2 / Hz) and frequency. The noise is fundamentally related to resistance fluctuations in the tunnel junctions. Because the signal due to an external field also appears as a resistance change, electrical "chopping" is not an effective technique for removing it. Rather, only "magnetic chopping" can allow the signal to noise floor to be lower than the 1/f noise present in a DC field measurement. Magnetic chopping means, in practice, either changing the amplitude of the otherwise steady external field, or changing the magnetic characteristics of the SDT transducer in time. Such magnetic chopping is possible, and has been shown to improve the signal to noise ratio (S/N) for SDT sensors. For this application, however, it was decided that the power and complexity of chopping circuitry was not worth the improvement in S/N. The noise floor for all three axes of the 3-axis SDT magnetometer are shown below in Figure 5. Note the strong 1/f behavior. The plot below is in units of Tesla / sqrt. Hz. One nanoTesla = 10^{-5} Gauss = 10^{-5} Oersted. These data are obtained by measuring the noise in Volts / sqrt. Hz and dividing by the transducer slope (Volts / Tesla). Since the field noise goes as the voltage rather than the voltage squared, the 1/f noise appears as 1 / sqrt. f in this plot.
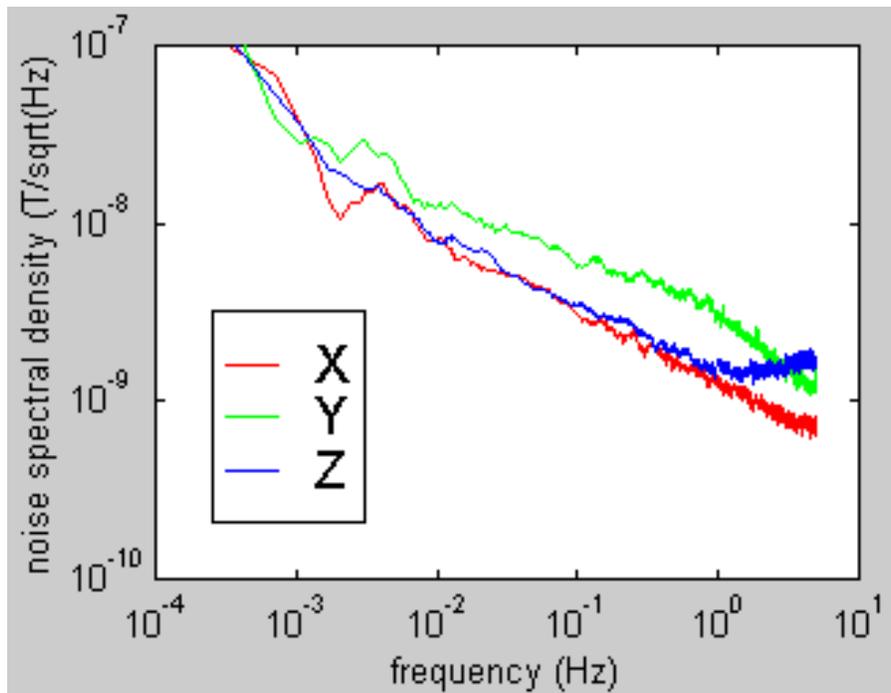
Figure 5. Noise spectral density vs. frequency. The units of noise are Tesla / sqrt. Hz. This means that one must multiply the noise spectral density by the square root of the measurement bandwidth to get the root-mean-square noise at a given measurement frequency.

3. Power Requirements

The power requirements for the 3-axis SDT magnetometer are shown in Table 1 below. For the present mode of operation the largest power user is the field feedback. The power required for feedback is specified in mW per Oe for a given transducer. For example, measuring the ambient earth's field, which has a vector magnitude of about 0.7 Oe, requires approximately 50 mW if the field is oriented along the sensing axis of one of the transducers. Note that the total power required for feedback will vary with orientation (the worst case being when the field is oriented with equal components in each axial direction where the total would be 90 mW).

Table 1:

Sensor bridges	0.5 mW
Op-amps	2 mW
A/D converters	3 mW
Microcontroller	10 mW
Serial I/O	20 mW
Feedback coil drive	75 mW per Oe
Total	~100 mW (typical in earth's field)

4. Overall Specifications

The specifications for the 3-axis SDT magnetometer are shown below in Table 2. The digital resolution is 0.1 nT with a full scale range of 0.2 mT. In practice, the resolvable signal is limited by the intrinsic sensor noise shown in Fig. 5. For example, for a signal frequency of 1 Hz, the system noise level is approximately 1 nT per square root bandwidth. The sample rate is user selectable over a range of 10 Hz to 125 Hz. All three axes are sampled simultaneously. Commands are sent to the magnetometer and data is transmitted over a standard RS232 serial interface. A multi-drop RS485 protocol is also supported to allow bussing of multiple units.

Table 2:

Field Range:	+/- 0.2 mT (2 Gauss)
Noise level:	~ 1 nT/$\sqrt{HZ}$ at 1 Hz
Digital Resolution:	0.1 nT (24 bit)
Sample rate:	10 Hz - 125 Hz
Power:	100 mW (typical, for all axes combined)
Interface:	RS232, RS485
Cost :	~$100 / magnetometer (in quantities >= 10,000)

4. DISUCSSION AND CONCLUSIONS

The 3-axis SDT magnetometer is a fully functional prototype with a standard software command set for serial computer interface. It has the benefit of several iterations of development, both of the SDT transducer and the circuit. However, there are many aspects of the magnetometer that are the subject of ongoing and intense improvement. Here we briefly outline these efforts, and make an estimate of the ultimate possible performance at some later date.

1.   Lower Feedback Power

The feedback power can be reduced in several ways. One elegant method under development is the fabrication of a feedback coil on the SDT transducer chip that physically goes around the on-chip NiFe flux concentrators. Thee existing versions are planar coils. The gain in field per unit power would be on the order 10, bringing the feedback power donwn from ~100 mW to ~10 mW. Another intermediate step is to reconfigure the magnetometer to operate with no field feedback coil. This would sacrifice some performance in linearity and hysteresis. This may, at times, be an acceptable trade since the feedback is the largest power consumer.

2.   Signal to Noise

The noise floor of the SDT transducer is still far from optimized. Efforts over the past two years, which have focused on reducing overall power consumption, are moving back to increasing the signal and reducing intrinsic noise.   Continuing refinements of the magnetic thin films that respond to the external field, and the micromagnetic design, are expected to contribute ~10x in signal per unit field. The 1/f noise is a stubborn problem that, if solved, could reduce the noise at low frequency by ~ 100x. Thus, the overall fully optimized noise floor will approach 1 pT/ sqrt. Hz.

5.   REFERENCES

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