Magnetoresistive signal isolators employing linear spin-valve sensing resistors

Zhenghong Qian,[a] Dexin Wang, Jim Daughton, Mark Tondra, Erik Lange, Cathy Nordman, Anthony Popple, John Myers, and Jim Schuetz
NVE Corporation, 11409 Valley View, Eden Prairie, Minnesota 55344

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Feasibility of fabricating low power, high-speed, magnetoresistive signal isolators employing linear spin-valve resistors as sensing elements has been demonstrated. In the fabricated prototype digital isolators, linear spin-valve resistors are physically isolated from an on-chip coil by an 11 μm BCB isolation barrier, which provides the galvanic isolation with a breakdown voltage larger than 2000 V. The devices are high speed (>50 MHz), small size, and low power consumption. Only a 4.5 mA coil driving current is required for the device to be fully functional. The power consumption is estimated to be ~1/6 of NVE's present isolator products, which requires a 50 mA coil driving current. Besides digital signal isolators, linear spin-valve resistors can also be used in analog signal isolators. The response of the linear spin-valve resistors to the current passing through the coil has been demonstrated to have a very good linearity, with a linearity error less than 0.05%. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1541635]

Signal isolator devices are key communication components used in many electronics systems. The commonly used isolators are optical isolators (optocouplers) and transformers. Both of them are slow, bulky, power hungry, and not amenable to integrated circuit fabrication. In order to overcome the disadvantages of currently existing isolators, NVE has developed IsoLoop™ magnetoresistive signal isolators using giant magnetoresistance sensing elements.[1–4] A family of integrated digital signal isolators has been developed using latch mode spin-valve sensing resistors, which can sense and latch the magnetic signal field generated on the other side of the isolation barrier by either one of two remnant states of the free layer. In this work, linear spin-valve resistors have been developed and used as sensing elements in magnetoresistive signal isolators. The motivation is to make digital isolator devices even faster, smaller, less power consuming with an additional fail–safe function, and to explore the possibility for analog isolator applications.

Figure 1 illustrates the function of the currently used magnetic digital isolator technology developed by NVE. This device needs an input drive circuit to convert an input signal to a wave train of very short current pulses that drive the planar coil. A relatively high current of 50 mA is needed to ensure the field (~50 Oe) generated is high enough to switch the magnetization of the free layer from one state to the other in the spin-valve bridge which is separated from the coil by a thick isolation barrier. In this design, the input driver circuit is on a separate die and consumes a major part of isolator power. In the device operation, the signal field generated by a current pulse will cause a switch/latch to one of the two remnant states in the hysteresis loop depending on the signal current direction. The signal detected will then be reconstructed and read out by the output amplifier. Besides the high power consumption, there are two major drawbacks to the aforementioned latch mode operation. The first one is that an output state is uncertain after an unintentional power off and power up. The second one is that magnetization reversal of the free layer involves domain-wall motion, which not only produces Barkhausen noise but also limits the switching speed. As known, the speed of the magnetoresistive signal isolator is mainly determined by two factors: The speed of the semiconductor circuit, and the dynamic properties of the magnetization of the magnetoresistive transducer. The speed of the semiconductor circuit has been increased steadily as the semiconductor industry continually improves. This leaves the magnetic devices as the major consideration.

By using linear spin-valve resistors as sensing elements, the aforementioned shortcomings of the latch mode digital isolator can be overcome. The signal response of linear spin-valve devices is very fast, where the upper limit of their operating frequency is mainly determined by the ferromagnetic resonance. It has been reported that the dynamic response of spin-valve devices with linewidths of 0.8 μm shows very high resonant frequencies in the range of 2–4 GHz.[5,6] Figure 2 illustrates the function of the low power high-speed digital isolator using linear spin-valve resistors as

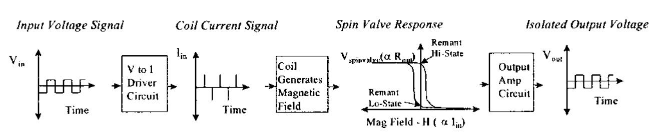

FIG. 1. Conceptual schematic of memory mode spin-valve digital signal isolator.

[a]Electronic mail: zqian@nve.com

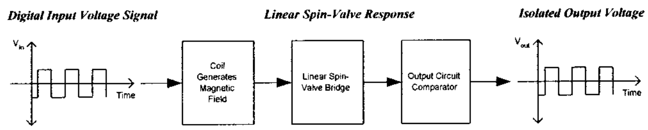

FIG. 2. Conceptual schematic of linear mode spin-valve digital signal isolator.

sensing elements. The device does not necessarily require a voltage to current driver circuit to drive the planar coil, if the linear spin-valve is highly sensitive so that little driving current in the coil is needed and, therefore, can be provided directly by the digital signal source. The isolator can be designed to work either in a unipolar mode where the driving current in the coil is unidirectional or a bipolar mode where the driving current in the coil is bidirectional. If designed to work in the unipolar mode, the devices will have a similar functionality with the optocouplers and, therefore, can be used to directly replace the optocoupler. A typical optocoupler consists of a light-emitting diode (LED), a transparent isolation barrier and a photodetector. The photofield signal emitted by a forward current I_F (usually 5 mA) through an LED is transmitted and detected by the photodetector on the other side of the isolation barrier. With a different principle but similar functionality, the magnetoresistive digital isolators using linear spin-valve sensing elements can be made to be fully compatible with the existing digital optocoupler.

Figure 3 shows schematically the signal response of a linear spin-valve resistor working in the unipolar mode with an operational field range of 0 to 7.5 Oe. Note, a field of 7.5 Oe on the spin-valve resistors can be generated with a driving current of 5 mA with a coil efficiency of 1.5 Oe/mA. The bridge was designed to have an offset (−35 mV), and this offset could represent a ‘‘0’’ state and would be read with an output comparator/amplifier. The bridge output (e.g., 35 mV) produced with a positive 5 mA current in the coil would represent a ‘‘1’’ state. If the sensitivity of the linear spin-valve resistor is larger than 0.2%/Oe, the resistor bridge with 5 V power supply should produce a signal difference of at least 75 mV between the state low and the state high, which is differentiable to the output amplifier/comparator. The device should intrinsically work with a fail–safe function

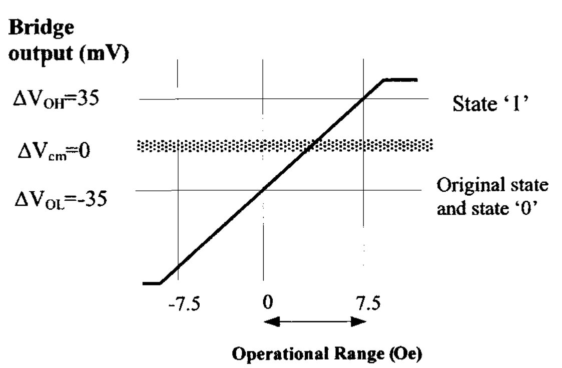

FIG. 3. Operation in the unipolar mode where the signal field is unidirectional.

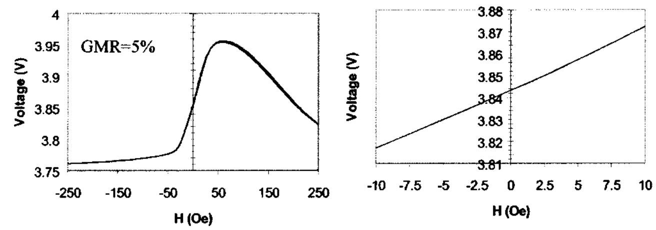

FIG. 4. MR trace of a 4 μ serpentine resistor. Note the spin valve is with a structure of Ta(40 Å)/NiFeCo(50 Å)/Ta(50 Å)/NiFeCo(40 Å)/CoFe(10 Å)/Cu(25 Å)/CoFe(40 Å)/CrPtMn(325 Å).

where the device output always returns to a known state (state low) in the case of an unintentional power off.

Besides digital signal isolators, linear spin-valve resistors can also be used in analog isolators as sensing elements. However, in order to make error-free linear spin-valve sensors for analog isolator applications, the hysteresis should be minimized or eliminated to achieve the linearization and better signal to noise ratio. With regard to this requirement, a technique has been developed to reduce the hysteresis by employing double free layers in the spin valves. Figure 4 shows the magnetoresistance (MR) transfer curve of a 4 μ serpentine resistor. No hysteresis is observed. The sensitivity is about 0.073%/Oe. The linearity error is less than 0.05%, which is suitable for high-precision analog isolator/sensor applications.

The basic fabrication process is the same for both digital and analog isolators. Figure 5 shows the cross section of the device indicating its fabrication process. Spin valves were first deposited on Si_3N_4 or foundry circuitry wafers, and devices were constructed using a five-mask process. The first mask patterned the spin valve sensor into a Wheatstone bridge configuration. Spin-valve resistor stripe geometries were 2–4 μm lines and 2 μm spaces. A BCB polymer dielectric was spin coated over the sensor to provide isolation from the input coil. An aluminum layer was then deposited on top of the BCB dielectric and patterned with the second mask to form the input coil. The geometries for the input coil are 2–6 μm lines and 2 μm spaces. A second BCB layer of 6 μm was spin coated to cover the input coil. The thickness of the two BCB layers were determined by breakdown voltage and sensitivity. After a final cure of the BCB dielectric, a two-mask via process was used to make contact to the input coil and the pads of the foundry circuitry. A thin layer of

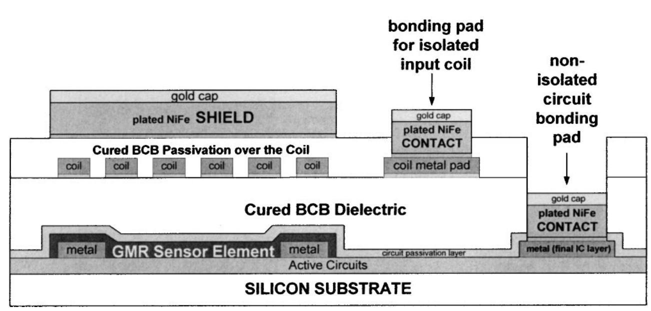

FIG. 5. Cross section of the isolator fabrication process.

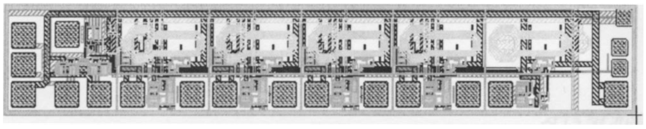

FIG. 6. Five-channel linear mode spin-valve digital isolator device.

metal was deposited over the top BCB layer to form a plating seed. The final mask was used as a plating mold where a thick layer of NiFe was plated to concentrate the magnetic flux from the input coil down onto the sensor, and also shield from the influence of outside fields. The plating seed was then removed from the finished device with a wet-chemical etch.

Figure 6 is a die layout of a fabricated five-channel digital isolator device. The die area is only 650 μm $\times$3920 μm. The highly sensitive linear spin valves were deposited directly on foundry wafers, and then patterned and processed to form devices. In the fabricated prototypes, the spin valve resistors are physically isolated from an on-chip coil by an 11 μm BCB isolation barrier. This isolation barrier provides an isolation with a breakdown voltage larger than 2000 V. The device is fully functional with a coil driving current of only 4.5 mA. If running in the bipolar mode, the power consumption is estimated to be 1/6 of NVE's current latch mode isolator products, which requires a 50 mA coil driving current. The device is also very fast. Figure 7 shows the measured signal responses. The output is driving a 26 pF load through a 50 ohm resistor. The bandwidth per channel is greater than 50 MHz with propagation delays between 10.5 to 11.5 ns, and rise and fall times less than 4.5 ns. Note the upper limit of the device speed could not be evaluated due to the bandwidth limitation of the testing circuitry.

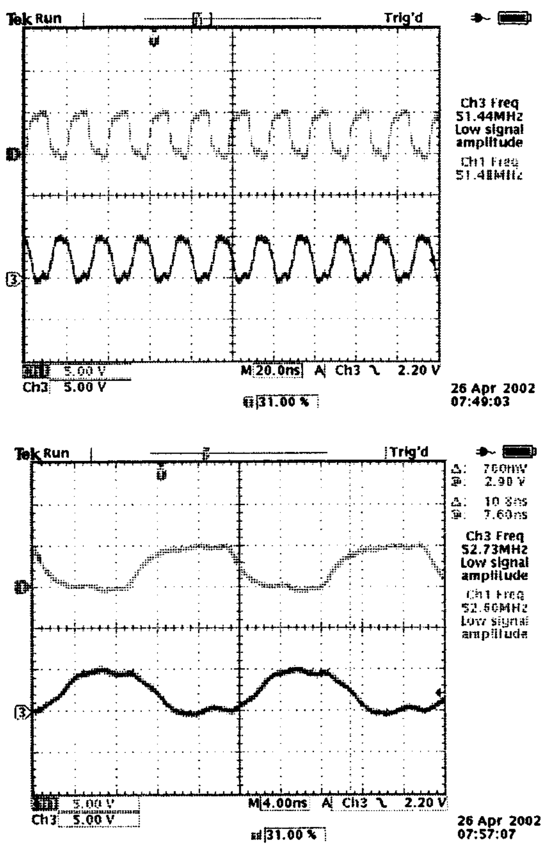

FIG. 7. The signal response of the linear mode digital isolator device. The top and bottom traces represent the input and output, respectively.

Besides digital isolators, linear spin-valve sensing resistors suitable for analog isolators have been demonstrated. The response of the linear spin-valve sensor/resistor to the current separated by an isolation barrier of 11 μm BCB polymer is very linear. No noticeable hysteresis is observed and the linearity error is less than 0.05%. In summary, the feasibility of fabricating magnetoresistive signal isolators using linear spin-valve resistors as sensing elements have been demonstrated. These types of isolators offer high potential for universal isolation devices in many applications.

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