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High Sensitivity Magnetic Field Sensor Using GMR Materials With Integrated Electronics

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Abstract- This paper presents the first commercially available IC that integrates Giant Magnetoresistive Ratio (GMR) materials with semiconductor devices. This marriage results in a highly sensitive, inexpensive, low power, and temperature stable magnetic field sensor. The chip uses a BiCMOS 1.5μ process and a masterslice design approach that allows rapid prototyping of many custom configurations in a 35 mil by 95 mil size. Sensing of a wide range of magnetic fields (0-500 Gauss) is possible, with digital and linear outputs available. Temperature range of operation is -55C to +150C, making the chip ideal for many automotive, industrial, and military applications.

I. INTRODUCTION

Giant Magnetoresistive Ratio (GMR) materials are a hot area of current physics research and hold great promise for commercially realizable products such as magnetic field sensors and semiconductor-based magnetic memories [3,4,5]. The IC described here is the first chip that integrates GMR materials with semiconductor devices to make a highly sensitive, temperature stable magnetic field sensor. The chip uses a BiCMOS process which is partially finished at the wafer fab in the standard fashion. After receiving the partially finished wafers, Nonvolatile Electronics, Inc. (NVE) sputter-deposits GMR thin films, patterns them into resistors, and connects them into the transistor array on the chip with metallization layers. The final step is deposition of a thick magnetic material that concentrates the applied flux around the GMR resistors, allowing for increased sensitivity. The chip is designed as a masterslice, so the partially finished wafers received from the foundry can be custom configured into many different circuits with different GMR material and metallization masks. Some of the circuits constructed so far include current sinking and TTL output magnetic switches, linear magnetic field sensors with single and double ended outputs, and magnetic pulse counters. In addition, because the parts are all the same through the first level of metallization, rapid prototyping of custom designs can be accomplished in as little as six weeks.

II. GMR MATERIALS AND DESIGN

Magnetoresistance is the property whereby a material changes in electrical resistance when exposed to a magnetic field. Standard Anisotropic magnetoresistance (AMR) materials, such as permalloy (80% Ni, 20% Fe) have been around for many years, and exhibit a maximum of 2-3% ΔR. Giant magnetoresistance (GMR) materials were discovered in 1988; since then, useful engineering materials have been developed which show up to 20% ΔR at applied fields of less than 200 Gauss. These materials hold great promise for use in magnetic field sensors and magnetic memories [1,2,3,4,5,6].

GMR materials are composed of thin films of alternating magnetic layers and non-magnetic conducting interlayers, such as copper. A typical GMR film sandwich is shown in Figure 1. The entire structure is only about 200 Angstroms thick, and requires deposition on a very smooth, step-free surface to maintain the GMR effect and prevent breaks in the line of GMR material.

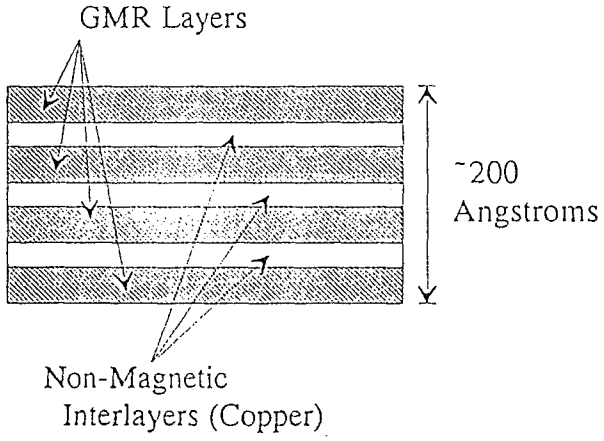

Figure 1

After the GMR material is deposited, it is patterned using standard semiconductor metal processing equipment into serpentine structures that act as resistors. These structures show a sheet resistance of about 11 Ohms/Square, allowing construction of a 5K resistor in a 50μ X 70μ area on the chip. Four of these resistors can be deposited on a blank silicon wafer and connected in a Wheatstone bridge configuration to make a raw magnetic field sensor. Two of the resistors of the bridge are shielded from external field by a thick, plated magnetic material, and so do not change. The other two resistors decrease linearly in value as field is applied, leading to bridge output.

There are many design considerations involving the GMR resistors that form the Wheatstone bridge. The two resistors that are shielded from the applied magnetic field can be modelled as static resistors. The other two GMR resistors form the opposite legs of the bridge structure and decrease in resistance with applied field depending upon the material characteristics. NVE varies the GMR resistor characteristics by varying the % GMR and the saturation field of the material. The % GMR is defined as:

$$\% \text{ GMR} = \Delta R / \text{Minimum R};$$

for example, a 5K resistor that drops to a 4.5K resistor with application of the saturation field would have a % GMR of (500/4500), or 11.11%. The saturation field H_{sat} is the magnetic field strength required to achieve this maximum resistance change; typical H_{sat} values for use in this sensor chip are in the 100-300 Oersted (Gauss) range.

The thick plated magnetic material that shields two of the bridge resistors is used for the additional purpose of flux concentration. The two bridge resistors that are exposed to the applied field are placed in a gap between two of the flux concentrators. The external magnetic field is then multiplied in the gap. The multiplication factor is roughly equivalent to the length of one of the flux concentrators divided by the length of the gap. For example, if the GMR material provides maximum output at an applied field of 200 Oersteds, the gap containing the resistors is 100 microns wide, and the length of the flux concentrators is 400 microns, maximum bridge output will be at an applied field of:

$$200 \text{ Oe}(100\mu/400\mu) = 50 \text{ Oe}$$

Figure 2 shows a representative layout of this design, which is currently in production by NVE.

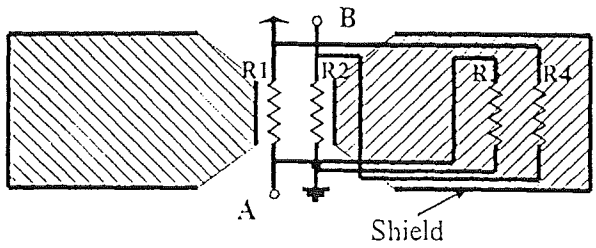

Figure 2

Integration of a GMR bridge such as this onto a silicon wafer with underlying transistors is a difficult problem, because of the many layers of polysilicon, metal, and oxides over the transistors. This underlying topography is detrimental to the performance of the GMR thin films. Special design and processing steps were developed during this work in order to ensure proper integration of a GMR bridge with the transistors on semi-finished silicon wafers.

III. CIRCUIT DESIGN AND LAYOUT

NVE selected a BiCMOS process available at American Microsystems, Inc. (AMI) for the design of this chip. The bipolars allow the use of a small on-chip voltage regulator, which is important in many sensor applications because of high system voltages. In addition, bipolar matching is very good, allowing for a high gain, low offset on chip amplifier. The CMOS devices available are used for logic devices and low power switching circuitry, and a special high voltage N-channel transistor is employed as a current sinking output device.

For a linear application, the bridge is designed to be balanced with no applied field. Because of the tight tolerances maintained during the deposition of the GMR films, the GMR resistors match very well as deposited; offset voltage of the bridge is maintained within the +/- 20 mV range, with a 5 volt supply. For some applications this is adequate; however, more precise parts require some way to adjust the bridge offset to zero. This is accomplished by designing one of the shielded resistors to be 500 Ohms less than the other three bridge resistors, and leaving one leg of this resistor available as an output. A 1K pot is attached to this leg externally, and adjusted for zero bridge offset.

For digital applications, the bridge is purposely left unbalanced. The bridge offset is taken into account during the design phase, so that no trimming of the digital parts is required. The output of the bridge goes to a comparator, and the trip point of the comparator is determined by the degree of bridge offset. For example, if a digital output device is desired that turns on at an applied field of 10 Oersteds, NVE might start with GMR material that exhibits 11.1% GMR and saturates at 250 Oersteds. A flux concentration factor of 5 would be used, so that the GMR resistors in the gap would provide maximum signal at an applied field of 50 Oersteds. Then, the shielded GMR resistors would be designed to be 4900 Ohms and the gap GMR resistors would be designed to be 5000 Ohms. This would result in the bridge output transitioning from negative to positive at an applied field of 10 Oersteds, tripping the comparator and giving a digital output.

Since the chip was designed using a masterslice approach, the amplifiers available on the chip can be custom configured with different metallization masks to provide numerous different functions. The comparator is simply a bipolar differential pair with CMOS loads that provide positive feedback. The amplifier is powered either by a separate GMR resistor, or by an on-chip current source. Figure 3 shows a typical comparator used on this chip.

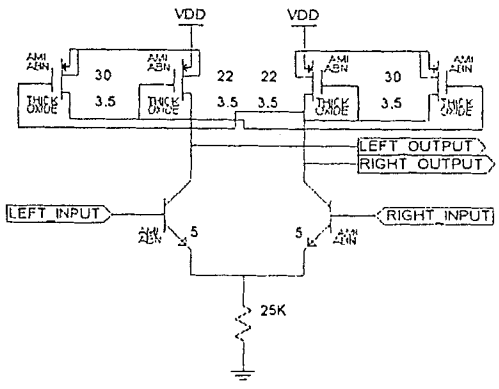

Figure 3 - Comparator Schematic

As mentioned, there are two potential ways to drive a comparator or some other amplifier on this chip, and both methods utilize precision GMR resistors. The thickness tolerance of the thin films that make up the GMR resistors is held to within a few Angstroms across the entire wafer. As a result, the material sheet resistance is held to the same tight tolerance. Therefore, GMR resistors made of these thin films can be held to a +/- 10% tolerance specification on the chip. NVE uses these precision resistors as current sources for the on-chip amplifiers, as resistive loads for these amplifiers, and as resistors in the bandgap and current source circuitry. In order to keep the resistor value constant as magnetic field is applied to the chip, the GMR resistors that must remain stable in value are placed directly beneath a thick shield made of highly permeable magnetic material, just like the one shielding two of the bridge resistors. This shield shunts the external field away from the GMR materials underneath.

IV. PROCESS

NVE receives partially completed wafers from the foundry and deposits GMR thin films, plated shields and flux concentrators, and the second metallization layer. As received, the wafers are completed up through the first metallization layer, and are covered with a glass for protection. The first process step is deposition of the GMR materials. In order to ensure a smooth surface for the deposition of the GMR thin films, certain discrete areas on the IC are dedicated for GMR devices only. These areas are free of the field oxide deposited during construction of the transistors, and have no transistors, polysilicon, or metal lines within their boundaries. This ensures a good surface for the GMR thin films. After the films are deposited, they are patterned into serpentine shapes to form resistors, and then covered with a silicon nitride passivation layer.

The next step in the process is to make contact to the GMR resistors and the first metallization layer. This requires two separate masking steps, because the passivation is thicker over the first metallization layer than it is over the GMR resistors. In order to ensure consistent etching, these contacts are processed separately. Once the contacts are cut, NVE deposits the second metallization layer on the wafers, essentially connecting the GMR resistors into the circuit. Many of the transistors on the chip are left unconnected after the first metallization step. These devices can be connected into circuits with the second metallization layer as well, allowing for many different circuit configurations on the IC.

Once the metal-2 is defined, the thick plated magnetic flux concentrators and shields are

deposited. These structures are made of permalloy (80% Ni, 20% Fe), and are plated up to a thickness of about 12 microns. NVE uses a thick photoresist similar to the one used for gold bumping, and plates the permalloy up through a hole in the photoresist. The shields are deposited anywhere the GMR resistors are to be used as static precision resistors, and the flux concentrators are deposited around two of the GMR bridge resistors. The final step in the process is opening up vias to the bonding pads for the package bonding wires. Figure 4 shows a photomicrograph of one of NVE's completed digital magnetic field sensors.

V. CONCLUSION

A family of magnetic field sensor ICs using GMR materials as the sensing element has been designed and manufactured in prototype quantities. The chips feature extremely high sensitivity, digital or linear output, very small size, and custom configurability for rapid prototype designs. This is the first IC that integrates GMR materials with semiconductor signal conditioning circuitry, and the combination results in a low power, inexpensive, and highly sensitive magnetic field sensor suitable for use in many automotive, commercial, and industrial applications.

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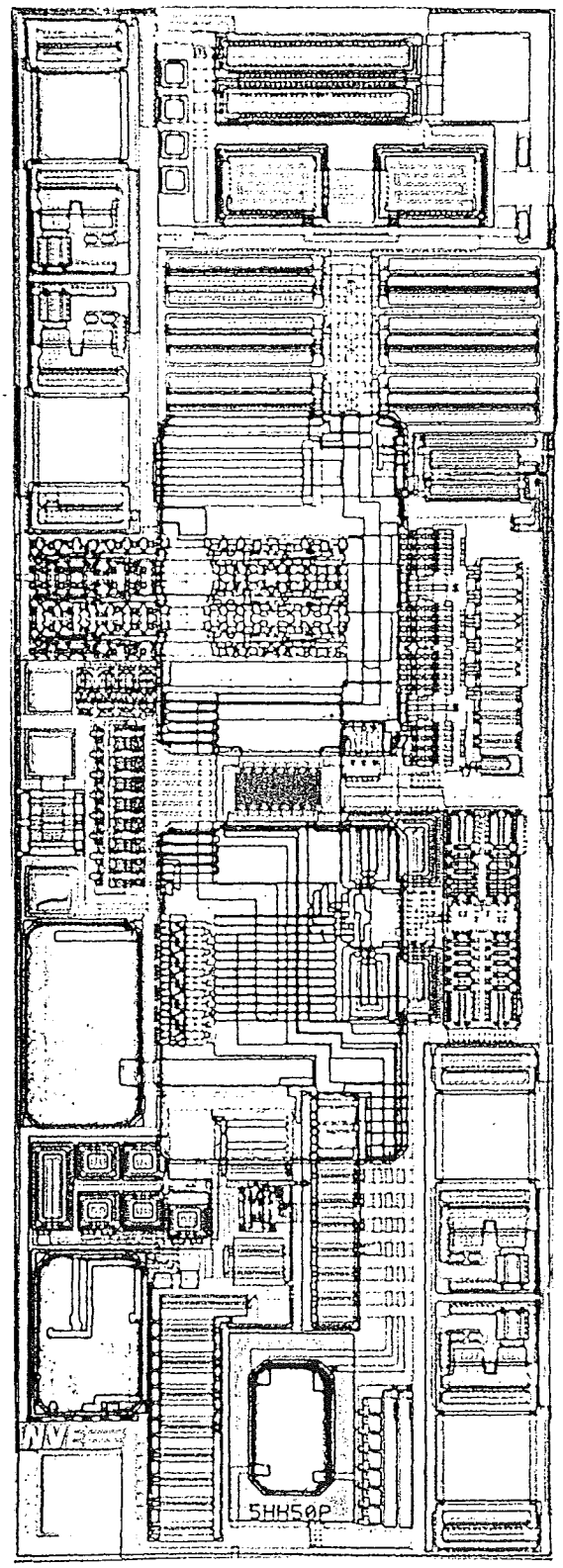

Figure 4: Photomicrograph of a GMR magnetic field sensor with integrated electronics