CMOS Magnetic Sensor Arrays

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Abstract

We describe the design of a monolithic 64 by 64 element array of magnetic sensors, implemented in a standard 3 micron CMOS process. The individual magnetic field sensors are split drain MAGFETS. A split drain MAGFET is a field effect transistor that has one source, one gate, and two drains. When current is flowing in the FET in the absence of a magnetic field both drains receive an equal current. If a magnetic field is present, with a component perpendicular to the direction of current flow, the current flow is deflected towards one drain and away from the other, resulting in a current differential between the two drains. The current differential is proportional to the applied magnetic field component perpendicular to the current flow in the MAGFETs.

The MAGFETs in the array are scanned in a raster scan fashion, by allowing current to flow through all elements in a given row, while all other rows are turned off. While a row is selected, the differential current output of the sensing elements in the row are amplified by a current mirror which also converts the current differential to a voltage. These voltages (one for each column) are multiplexed onto a common output bus that is connected to a buffer stage which provides additional amplification and lowers the output impedance.

This array has been implemented in 3 micron CMOS, through the MOSIS facility. We present experimental results as to its sensitivity.

1 Introduction

The utility of MOS technology for implementing sensing devices has long been known [1,5]. MOSFET based devices are currently being fabricated to measure quantities as varied as chemical activity [1] and magnetic field strengths [6]. Although much effort has been expended in developing sensors, proportionally less effort has been directed to the task in making integrated arrays of these sensors. This paper describes the development of an integrated magnetic field sensor array. Such an array has many applications, the most obvious being field mapping, for example in determining the fringing fields in an electric motor. Novel applications also exist such as the compliant tactile sensor developed by the author [4], which uses the magnetic field sensor array to measure the deformation of a membrane to which small magnetic dipoles are attached.

2 Split Drain Magnetic Field Sensors

The basic sensing element of the magnetic field sensor array is a device known as a split drain magnetic field sensitive MOSFET, or MAGFET for short. This device is a MOSFET, that has two drains, as shown in figure 1. In operation the MAGFET is biased on so that current flows strongly through the transistor. In the absence of a magnetic field the currents flowing through the two drains of the MOSFET are equal. However, when there is a magnetic field with a non zero component, B_z, perpendicular to the plane of the sensor, the carriers (electrons or holes) flowing in the transistor are deflected, due to the Lorentz force. As the carriers are deflected by this force, an electric field is built up due to the separation of charge. The force on the carriers due to this field will counteract the force due to the magnetic field. Hence an equilibrium will be attained at a certain displacement of the charge carriers. This charge carrier deflection results in an imbalance in the current flowing through the two drains of the MAGFET. This imbalance is a function of both B_z and the geometry of the split drain. If the split drain consists of two equally sized sections, the currents through the two sections are of the form $I_1 = \frac{I}{2} + \Delta I$ and $I_2 = \frac{I}{2} - \Delta I$, where ΔI is a function of B_z [5]. This current differential can be converted to a voltage and amplified by a current mirror acting as a transresistance amplifier as shown in figure 2. The gate of the MAGFET is connected to one of its drains ensuring operation in the saturation region. Note that this drain is connected to the diode connected transistor of the current mirror and thus the voltage at this drain is held virtually constant. Ideally the gate of the MAGFET should be connected to ground, but in practice doing this results in a larger sized cell because of the need to bring in a ground wire.

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The combination of the split drain MOSFET and the current mirror is equivalent to the input stage of an operational amplifier. The sensitivity of this arrangement can be much higher than a circuit utilizing the Hall voltage. A device similar to this has been built and tested by Popovic and Baltes [6]. They claim sensitivities on the order of 1 Volt per Tesla. Their circuit uses complementary split drain MAGFETS, whereas our design uses only a single MAGFET in conjunction with a current mirror. The reason we use the single ended design is to make the sensor as compact as possible. In addition to requiring two transistors in each sensor cell having complementary FETS in a sensing cell requires that both well and substrate contacts be present, and that there be extra space between the P and N channels FETS to minimise the probability of latchup.

3 Design of the Sensor Array

We have designed and laid out a 64 by 64 element array of such split drain transistors in an integrated circuit for fabrication in a 3 micron CMOS process. This circuit has fabricated through MOSIS, which is a service run by the Information Sciences Institute of the University of Southern California for DARPA, that acts as an interface between university IC designers and industrial fabrication facilities. Each of the split drain transistor sensing elements on the chip is 100 microns square. The size of the entire array is 7.9 by 9.2 mm. The chip is shown in figure 3a. A microphoto of one of the split drain MAGFETs is shown in figure 3b.

The array is scanned in a raster scan fashion by the circuit shown in schematic form in figure 4. Shift registers along the left hand side of the circuit shift a single "turn-on" bit which allows current to flow through all of the split drain devices in a single row. As the scan proceeds, successive rows are turned on. Only one row at a time is one. Shift registers along the bottom shift a single "select" bit which selects the output of one column at a time. All the split drain devices in a given column share a single current mirror transresistance amplifier located at the bottom of the column. Since only one row is on at a time, these current mirrors have current flowing through them from one split drain device only. The row shift register is shifted only when a complete column scan has been finished. The column shift register is shifted by an external clock signal. The output of the selected current mirror is amplified and buffered before it is sent to an analog output pad. The shift registers are initialized by a reset pulse. The amount of current that passes through the split drain devices is controlled by a bias voltage which is switched in when a row is selected. This bias is used to adjust the offset voltage of the current mirror to be roughly half of the supply voltage, in order that the buffer amplifier operates in its linear, high gain region. The sensitivity of the split drain devices are also affected by the bias voltage.

4 Experimental Properties of the Sensor Array

We have measured a number of properties of the 4096 element sensor array chip that we have fabricated. The power dissipation of the chip is 12.5 milliwatts with a 5 volt power supply. The sensitivity of the magnetic sensors to changes in magnetic fields is illustrated in figures 5 and 6. The graph in figure 5 shows the relationship between the sensor output and the magnetic field at the sensor. The $B - V_o$ characteristic of the sensor is seen to be quite linear over most of the range. Figure 6 shows the output of a single sensing element as a function of the lateral position of a rare earth bar magnet, with a surface field of 2KGauss and dimensions 15mm X 9mm X 4mm, when the height of the bar magnet above the sensing plane is kept constant (at 5 mm). This graph indicates the spatial sensitivity of the sensing array. In obtaining this plot the bar magnet was aligned so that the north-south axis was parallel to the sensor plane. The lateral resolution of the sensing array is hidden somewhat in the above graph since the bar magnet has a thickness of about 4mm and acts as a distributed source.

The maximum practical clock speed of the fabricated arrays has been found to be about 500Khz. This works out to a frame rate of about 125 frames/sec (500,000 pixels/sec / 4096 pixels/frame). We are looking at ways in which faster scan rates can be obtained in future array designs.

The current mirrors which amplify the current differential of the split drain MAGFETS have been found to be quite sensitive to process induced variations in their dimensions. As a result we observed some nonuniformity in the offset voltage between the transresistance amplifiers in each columns of the array. This non-uniformity can be compensated for to some extent with a post-processing stage once the array output has been digitized. A new design is currently being fabricated which will solve this problem, albeit at the cost of some loss in speed. In the new design, only a single transresistance amplifier is used and instead of multiplexing the outputs of transresistance amplifiers in each column to an output bus, we multiplex the differential current lines for each column on to a differential bus which is then connected to a single transresistance amplifier. This eliminates the column to column non-uniform offset problem since only one transresistance amplifier isused, but slows down the circuit since we have effectively doubled the capacitance on the differential current busses attached to the split drain magfets.

5 Acknowledgments

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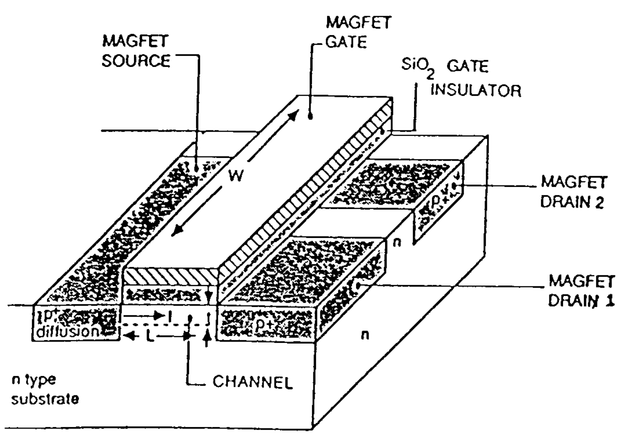

Figure 1. A split drain magnetic field sensitive MOSFET

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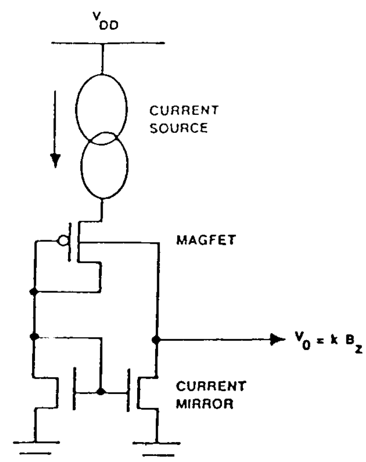

Figure 2. Amplification of the split drain MAGFET current

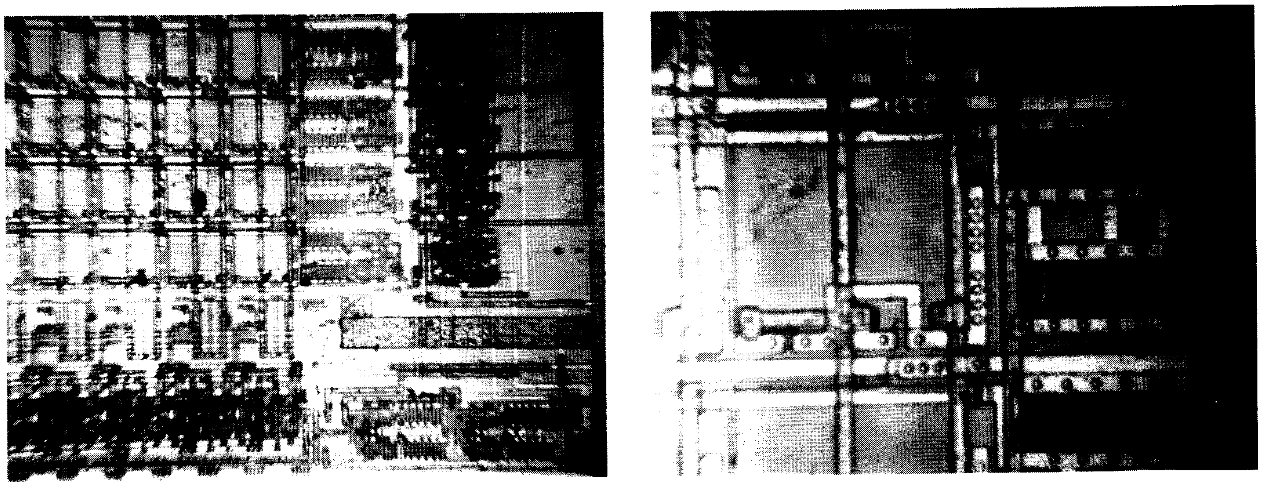

Figure 3. a) A portion of the magnetic field sensor array chip. b) Detail of the split drain MAGFET as fabricated.

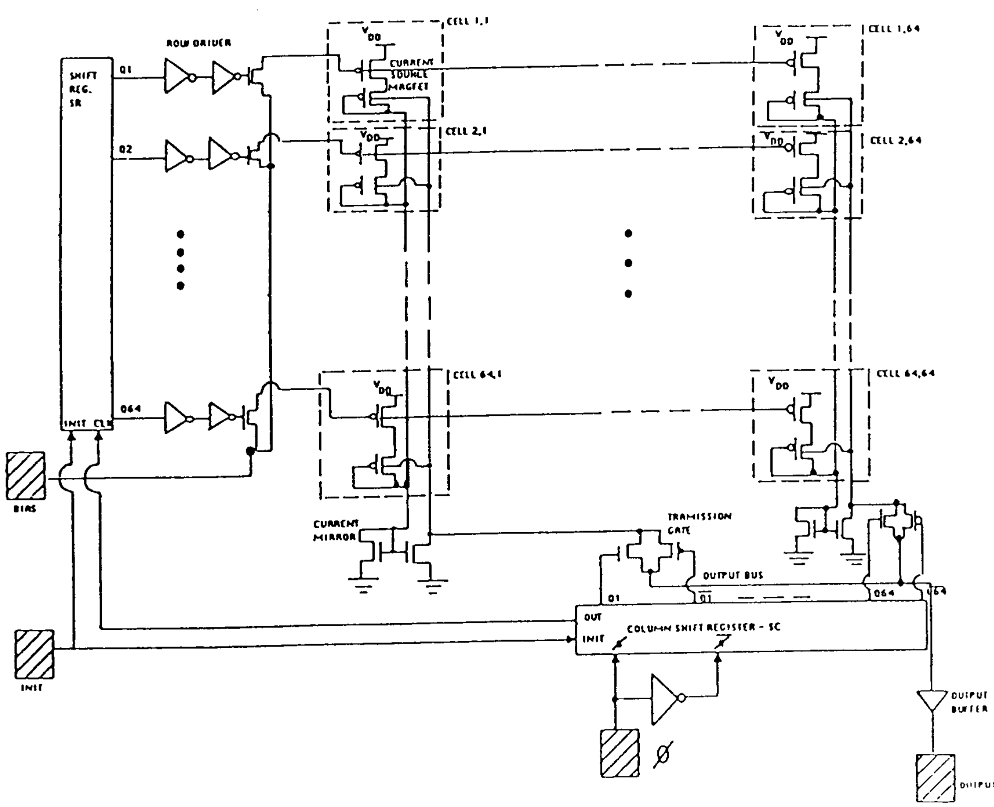

Figure 4. The circuitry of the sensor array.

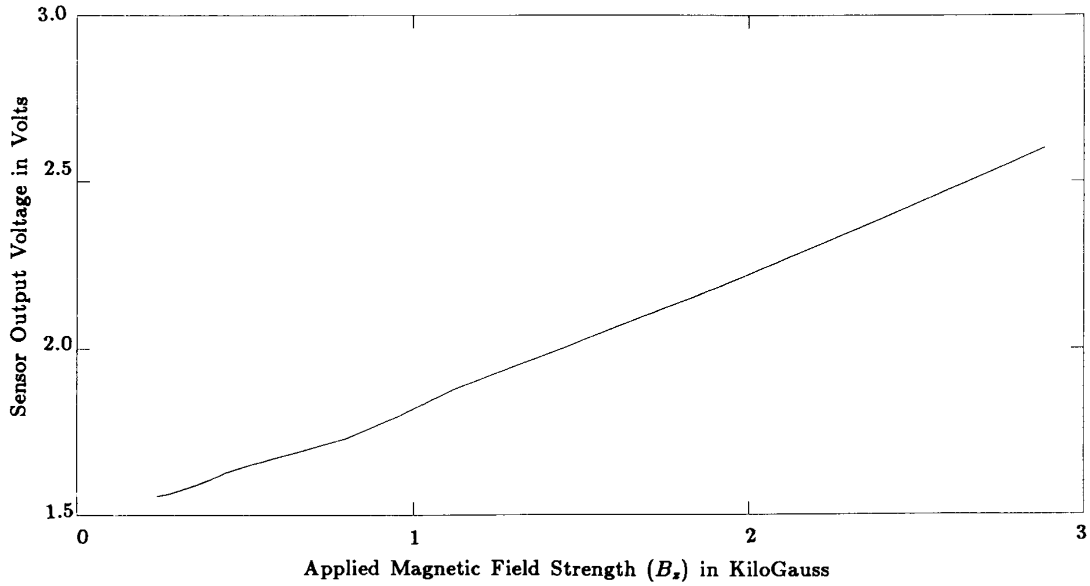

Figure 5. The output of a sensing element (after buffering) as a function of the applied magnetic field strength.

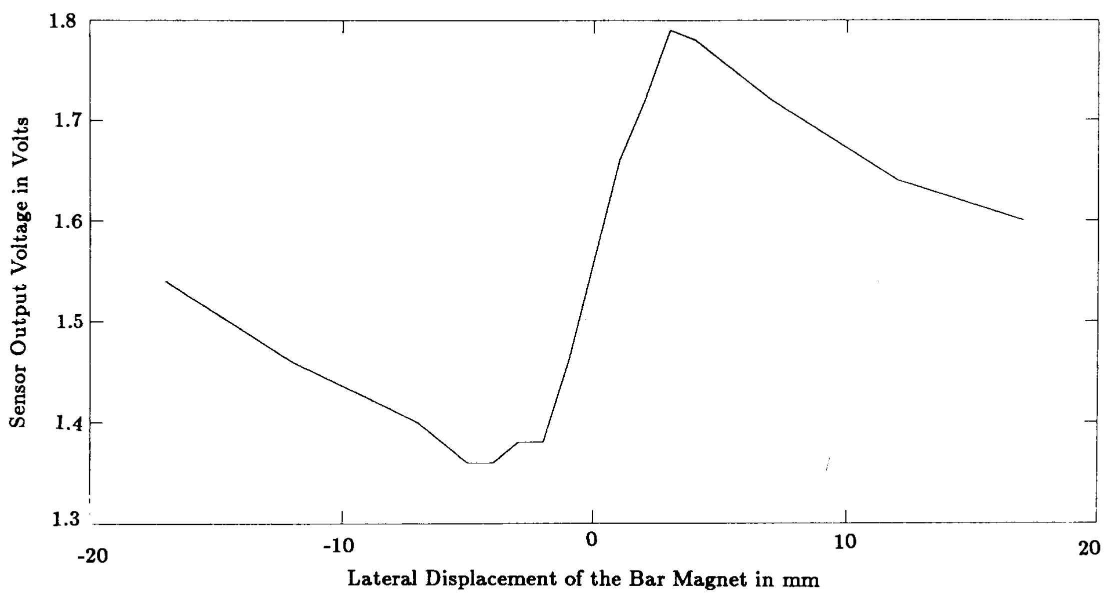

Figure 6. The output of a sensing element as a function of the lateral displacement of a bar magnet located above the sensor array.