CCD-Based Magnetic Field Imaging

Nixon O[1] and Arokia Nathan[2]

[1]DALSA Inc., 605 McMurray Road, Waterloo, Ontario N2V 2E9, Canada
Tel: 1 (519) 886-6000 Fax: 1 (519) 886-5767 E-mail: nixono@dalsa.com
[2]Electrical and Computer Engineering, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada
Tel: 1 (519) 888-4803 Fax: 1 (519) 746-3077 E-mail: anathan@venus.uwaterloo.ca

Abstract

A linear array similar to photodiode linescan CCD, but with MOS magnetic sensors replacing the photodiodes, has been fabricated. Magnetic signals are collected as charges and read out as in a conventional CCD. The magnetic sensor pixels have been optimized and exhibit sensitivities of up to 110%/Tesla [1.1%/(10 mT)], which is close to 15 times the 7%/Tesla sensitivity normally found in CMOS magnetic sensors. The improved performance over CMOS is possible because of improved magnetic sensing properties resulting from buried channel conduction and optimized detector architectures. Furthermore, the CCD readout allows the sensors to be optimized independently of the readout circuitry.

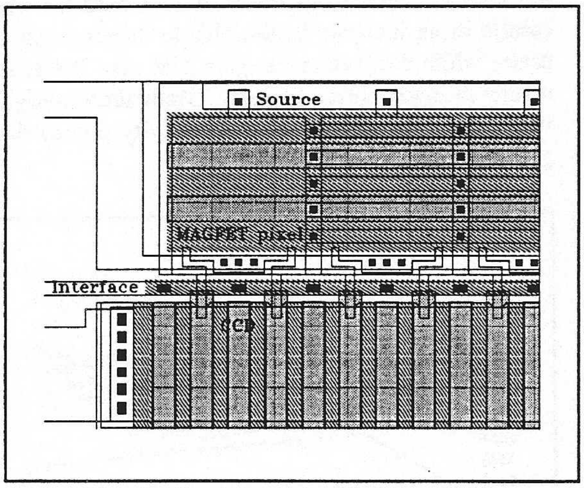

Fig. 1. Portion of the Magneto-CCD.

Introduction

Magnetically encoded signals are found in diverse applications, which include: shaft and gear rotation detection in automobiles for antilock braking, engine control, adaptive suspension, and velocity detection; check, currency, and banknote identification; audio and video tape storage; magnetic stripe data storage in access control cards, credit cards, and subway tickets; computer disk data storage; and non-intrusive current detection. Virtually all of these applications presently employ metal inductive heads for signal detection. Because the output of inductive heads is a function of readout speed, a few high-end applications now use magnetoresistive heads. Magnetoresistive heads however exhibit offsets that vary over time and with environmental conditions.

The detection of magnetic field is an ideal first candidate for extending the utility of CCD fabrication processes. CMOS magnetic sensors suffer from low signal-to-noise ratio. Sensitivity is low in CMOS sensors because surface scattering causes a reduction in mobility and an increase in 1/f noise [1] from bulk values. In semiconductor detection schemes, sensitivity is proportional to mobility [2]. In addition, conventional CMOS magnetic sensor architectures also exhibit high thermal noise and, occasionally, shot noise. This is mainly because a significant portion of the output signal, although non-magnetic-sensitive due to the nature of current distribution, contributes to noise. The low sensitivity and the high noise of CMOS sensors result in magnetic field resolution that is less than the requirements of many applications. This prevents silicon sensors from seriously competing with the non-solid-state sensing technologies.

Some of the above issues can be overcome through the use of CCD fabrication processes, which in any case has been optimized for radiation detection. The use of buried channel MOSFETs [3] available from the CCD processes rectifies the low mobility and high 1/f noise problems. This has been verified experimentally [4]. The use of improved sensor architectures further increases sensitivity and reduces both the 1/f noise and white noise. By employing buried channel MOS magnetic sensors with optimized geometries and biases, we have developed silicon MOS sensors with sensitivities and magnetic resolution that are more than an order of magnitude better than conventional CMOS sensors.

In most CMOS magnetic sensing systems, optimizing the system performance requires the sensor to be designed with suboptimal geometries. As a result, the system magnetic resolution is often poorer than the resolution of a discrete sensor. This limitation is not unrectifiable, but requires the use of more complex CMOS interfaces. A CCD readout, on the other hand, allows the sensor to be easily optimized independently of the readout circuitry.

To take advantage of the aforementioned benefits of CCD technology and improved sensor architectures, we have designed a linear magnetic field sensor array with CCD readout (magneto-CCD, see Fig. 1). The device is an improvement of a similar array that we have reported earlier [5].

Magnetic Sensor Pixel

The signal-to-noise ratio (SNR) of the magneto-CCD determines whether or not the device can detect the signal levels found in most applications. It has often been argued that the SNR of silicon magnetic sensors can be greatly enhanced merely by reducing the sensor noise. We believe this approach has limitations however, the most important being that the largest noise in the signal chain dictates the system noise. In most cases, the largest noise source is not the magnetic sensor pixel.

In designing the magneto-CCD, while we keep the sensor noise as low as possible, preferably below the level of the system noise, we consider the enhancement of sensitivity as a much more important priority. The techniques used to obtain very high sensitivity values are discussed in the rest of the section.

Since it is difficult to increase the sensitivity of the conventional Hall-voltage sensors, we opted for Hall sensors with current outputs. In Hall-current MAGFETs (short for magnetic-field-senstive MOSFETs), the drain has two or three contacts separated by narrow strips of channel stop. The signal current always consists of only the two outermost drain currents; the central drain current is discarded. A magnetic field induces a difference in the two signal currents. This difference constitutes the output signal.

A. Drain Gap Saturation

The spatial distribution of the current density of the dual-drain MAGFET obtained from numerical solutions to galvanomagnetic charge transport equations [6] is shown in Fig. 2. The two curls at the drain corners result in the difference between the signal currents, which in turn constitutes the magnetic signal. The two current peaks beside the drain gap are not induced by magnetic field, but are rather due to electrons travelling along the center of the channel which have to skirt around the gap to exit through the nearest drain. With higher current densities, the regions adjacent to the drain gap will saturate sooner than the rest of the drain. When these regions have reached saturation, but before the rest of the drain saturates, more electrons from the center of the channel will have to skirt further away from the gap to flow out the drain. This effectively increases the width of the drain gap. Prior works have shown, both numerically and experimentally, that increasing the drain gap results in lower sensitivity. Experimentally, we find that this "drain gap saturation effect" causes sensitivity to drop the most when the charge density near the drain is small, and when current density is large. We have attenuated this effect by modifying the sensor structure in two ways. Firstly, we narrowed the source contact to lower the drain current density. Secondly, we use a multiple-gate structure [7] (see pixel in Fig. 1) that allows the gate bias near the drain to be set differently from the gate bias near the source. Increasing the gate bias near the drain results in an increase in the charge density near the drain, while decreasing the gate bias near the source results in lower current density. Both act to mitigate, if not eliminate, the drop in sensitivity due to drain gap saturation.

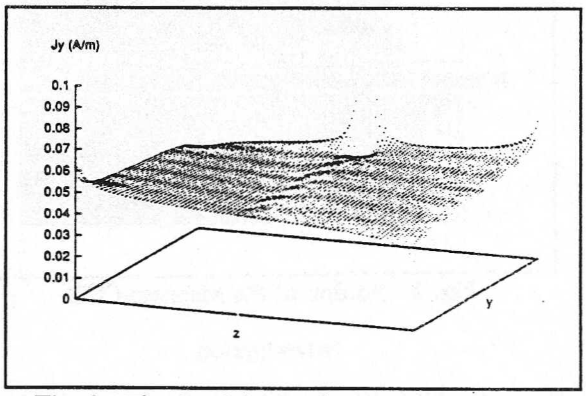

Fig. 2. The Spatial Distribution of the Current Density of a Dual-Drain MAGFET. (The source is in front, two drains are at the back.)

B. Electric Field Dependence of Sensitivity

Experimentally, we find that in buried-channel Hall-current MAGFETs, sensitivity increases when the applied electric field increases. Fig. 3 contains data plotted for non-optimized single-gate MAGFETs. This behaviour is believed to be related to the anisotropies in the electron momentum relaxation time. When properly biased, multiple-gate MAGFETs can achieve higher channel electric field than single-gate MAGFETs, resulting in higher sensitivity. As long as the drain gap saturation effect is suppressed, the electric field dependence of sensitivity can be used to raise the sensitivity from 7%/Tesla in conventional MAGFETs to 25%/Tesla in dual-drain multiple-gate MAGFETs. In triple-drain MAGFETs, sensitivity increases further since the insensitive central drain current is discarded.

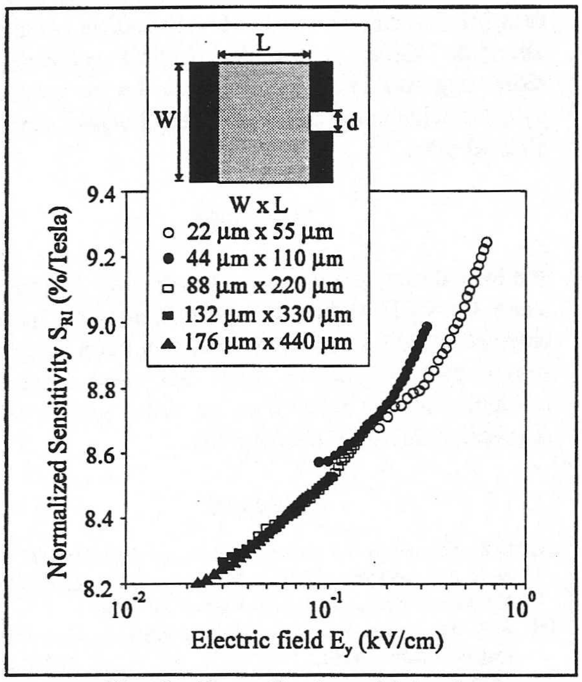

Fig. 3. Normalized sensitivity S_{RI} as a function of electric field.

C. Bias-Induced Conduction Path Narrowing

From our galvanomagnetic numerical models, we have found that if the total current of a triple-drain MAGFET remains constant, reducing the current density of the edge drains while increasing the current density of the central drain results in further increase in sensitivity. This is because the magnitudes of the magnetic-field-induced curls in Fig. 2 depend only on the total current. One way of channelling more current to the central drain is to bias the central drain higher than the edge drains. Unfortunately, this technique is effective only when the MAGFET is operating in the linear region, a region which we have found to provide unstable signal. To induce current redistribution in the saturation region, we employ a "bias-induced conduction path narrowing effect". This effect is illustrated in Fig. 4. In a multiple-gate MAGFET with a narrow source, as V_{DS} and the electric field increases, the segment near the source saturates sooner than the drain. We call this bias the multiple-gate V_{DSsat} since this premature saturation is unique to multiple-gate MOSFETs. This early saturation has the effect of lowering the current density, making drain-gap-saturation effect less likely to occur. As V_{DS} increases past the multiple-gate V_{DSsat}, the electric field in the channel continues to increase. Mobile electrons from the narrow source are increasingly attracted more strongly to the central drain. The central drain current increases and the edge drain current decreases until the drain saturates. We refer to this point as the single-gate V_{DSsat}, since this is the bias at which single-gate MOSFETs saturate. The lowering of the edge drain currents causes more extraneous current to be removed through the central drain, resulting in increased sensitivity.

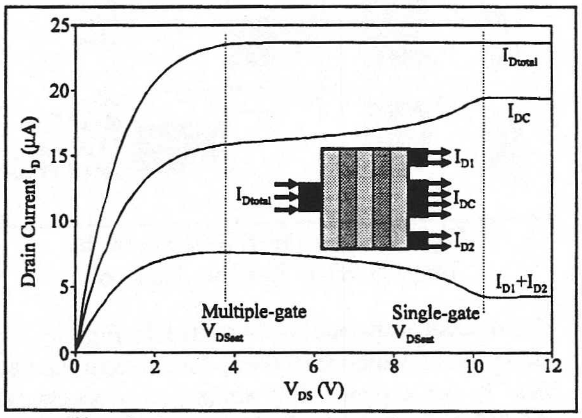

Fig. 4. Measured V_{DS} dependence of the edge and central drain currents of the MAGFET structure shown at zero magnetic field.

D. Non-Orthogonal Channel

The sensor structure that exhibits the highest sensitivity is the triangular-channel (narrow source, wide drain, channel diagonally tapered in between) multiple-gate narrow-source buried-channel MAGFET. In this structure, the stream of electrons emanating from the source is further prevented from spreading laterally by physically restricting the width of the channel near the source.

Sensor-CCD Interface

A portion of the magneto-CCD illustrating the interface between narrow-source multiple-gate triple-drain MAGFETs and the CCD is shown in Fig. 1. The two edge drains are connected to the CCD through n+ diffusions that have floating potentials. The gates of the multiple-gate MAGFET are connected to two fixed external biases: V_{GH}, the larger gate bias applied to the drain end, and V_{GL}, the smaller gate bias applied to the source end. The biases of the other gates are interpolated, using an on-chip resistor network, between V_{GH} and V_{GL}.

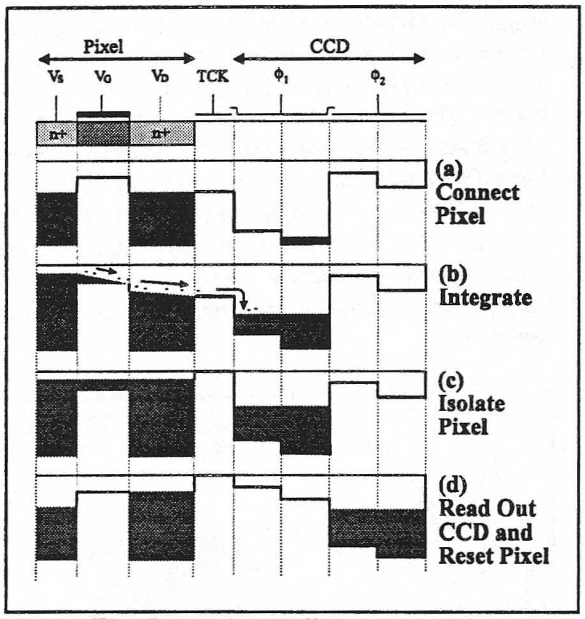

Fig. 5. Device Well Diagram of the Magneto-CCD Readout Sequence.

The readout sequence is illustrated in Fig. 5. The central drain, which is connected to an external clock bias, is not shown. For simplicity, a single-gate MAGFET is used. The readout sequence is as follows. First, the pixel is connected to the CCD by turning TCK (the transfer gate) on [Fig 5(a)]. Although the pixel is already connected at this stage to the CCD, the pixel V_{GS} is still less than V_T, and no current flows to the CCD. Charge integration begins after V_S is lowered [Fig. 5(b)]. A mobile electron starts from the source, travels through the gate where it is deflected by magnetic field, exits through one of the drains, crosses TCK, and is finally deposited into the CCD. The central drain bias merely needs to be greater than the edge drain V_{Dsat} to ensure that the entire device is in saturation. At the end of the integration time, TCK is closed to isolate the pixel from the CCD [Fig. 5(c)]. The extra charges that remain in the gate and in the floating drain need to be removed to prevent these insensitive charges from filling the CCD during the next integration cycle. These charges are removed either through the source [Fig. 5(d)] or through the central drain.

The magneto-CCD has 24 sensing elements, 60 µm pixel pitch, and has been tested at data rates of up to 2 MHz. The CCD cell holds up to 2.8 million electrons. Each pixel uses two CCD cells. Sensitivity is 1.1±0.1%/10 mT. Minimum detectable magnetic flux density (B_{min}) is 100 µT with an SNR of 17 at 2 MHz and 54 at 30 kHz. This may seem small compared to the SNR of optical CCDs. Most magnetic applications however only need to detect two opposite magnetic polarities. B_{min} can go down to 10 µT if high data rates are not required and if lower SNR can be tolerated. Non-linearity is less than 6%, but can be better if lower sensitivity can be tolerated. Offset is 10-15% of CCD full well — rather large but is time invariant so can be removed by subtraction at the output. Power dissipation is less than 40 mW.

Conclusions

We have designed a magnetic sensor array fabricated using the CCD technology. By employing buried channel MOSFETs and by extensively optimizing the sensor architecture, we have achieved magnetic resolution that is more than an order greater than conventional CMOS counterparts.

References

[1] D.M. Fleetwood, T.L. Meisenheimer, and J.H. Scofield, "1/f noise and radiation effects in MOS devices," *IEEE Trans. Electron Devices*, vol. 41, pp. 1953-1964, 1994.

[2] H.P. Baltes and R.S. Popović, "Integrated semiconductor magnetic field sensors," *Proc. IEEE*, vol. 74, pp. 1107-1132, 1986.

[3] M.J. van der Tol and S.G. Chamberlain, "Potential and electron distribution model for the buried-channel MOSFET," *IEEE Trans. Electron Devices*, vol. 36, pp. 670-689, 1989.

[4] N. O and A. Nathan, "Magnetic pattern recognition sensor arrays using CCD readout," *Proc. of the 25th European Solid State Device Research Conference*, pp. 273-276, 1995.

[5] N. O and A. Nathan, "CCD-based sensor array for magnetic pattern recognition," *IEDM Tech. Digest*, pp. 167-170, 1995.

[6] A. Nathan and W. Allegretto, "Geometric factor for Hall mobility characterization using the van der Pauw dual configuration," *IEEE Trans. Electron Devices*, vol. 40, no. 8, pp. 1508-1511, 1993.

[7] F.J. Kub and C.S. Scott, "Multiple-gate split-drain MOSFET magnetic sensing device and amplifier," *IEDM Tech. Digest*, pp. 517-520, 1992.