TA7.4: A Magnetic Field Sensitive Amplifier with Temperature Compensation.*

John Ryan, John Doyle, Michael Buckley+, Michael Flynn#

National Microelectronics Research Center, University College, Cork, Ireland
+Now with Silicon & Software Systems, Dublin, Ireland.
#Now with Dept. of EE & CS, Carnegie Mellon University, Pittsburgh.

Most, if not all commercially-available silicon-based magnetic field sensing devices used for current sensing use bipolar technologies. These devices can sense fields in the range of 1 to 10^4 Gauss and generally rely on a Hall voltage being induced in a low-doped diffused region. There has recently been much work published on the split-drain MOS device (MAGFET) that senses magnetic fields through a current difference in two symmetric drains [1]. The current difference varies linearly with applied magnetic field over wide ranges of applied field. Hence this device can be used as the sensing element in sensors based solely on CMOS technology.

This paper reports on the use of the split-drain device in an operational amplifier configuration where the amplifier input offset voltage is modulated linearly by the incident magnetic field. The sensitivity can be adjusted by changing the closed-loop gain. With reasonable gains (10) and 50µA bias currents, equivalent sensitivities of 16kV/AT are obtained. This figure is in excess of any sensitivity reported in the literature for Si magnetic field sensors [2].

In common with the Hall plate sensor, the split-drain magnetic field sensor has a large temperature coefficient of sensitivity since the deflection of carriers is proportional to mobility. Although not previously reported in the literature, we have measured this sensitivity to be about 5000ppm/°C near room temperature, in line with that expected if mobility varies with $T^{-1.5}$ [3]. The MAGAMP structure affects some partial compensation due to the difference current being translated to a voltage by a transconductance stage. Further cancellation is achieved by a bias current varying inversely with mobility.

The prototype circuit is fabricated in a 2.4µm, double-poly, double-metal, 12V analog CMOS process. Because the circuitry is all CMOS, further conditioning of the output signal (i.e. gain error and offset compensation) can easily be accomplished by adding, for example, a sampling ADC and calibration logic. Furthermore, these functions can be added at little extra cost in power drain. These advantages are not easily matched by the equivalent bipolar functions. In addition, because large devices do not increase the sensitivities, the devices used in this sensor use significantly less space than Hall plate devices with similar performance [3].

Figure 1 shows the MAGAMP circuit configured in a closed-loop, inverting gain determined by R1 and R2. The differential-stage current mirror loads M3 and M4 are the split drain MAGFET devices which are cross-coupled to reduce offsets. M3 and M4 are square devices as this gives optimum current deflection sensitivity [3]. The choice of W/L ratio for the differential pair transistors M1 and M2 is determined by the need to minimize their transconductance. Thus a long thin device would be ideal but would also contribute to a high systematic amplifier offset voltage. A compromise unity W/L ratio was chosen to minimize this offset voltage and still maintain high sensitivity.

When there is no incident magnetic field, the circuit operates exactly like any two-stage amplifier with an output voltage Vout determined by the closed-loop gain and the device-mismatch-induced amplifier Vos. However, when a magnetic field is applied, a current mismatch in M3 and M4 proportional to the field is induced which in turn modulates the offset voltage. This induced offset is amplified by the closed-loop amplifier gain to appear as a single-ended, ground-referenced signal at the amplifier output. Thus the signal format is ideal for subsequent signal processing.

Vosm, the input-referred offset voltage generated by the magnetic field is given by Equation 1 of Figure 2. Sensitivity has a square root dependence on bias current. This is confirmed by calculated and measured sensitivity data in Figure 3 for the amplifier operating in unity gain configuration.

Equation 1 also shows that the output voltage will be strongly temperature dependent since both n- and p-channel gain factors, Kn and Kp, depend on mobility. To remove this temperature dependence, the gm of the differential pair and the sensitivity of the MAGFET pair must be constant over temperature. Assuming Kn and Kp track over temperature, the output voltage follows a square root function of Kn and Ids (Equation 2). This implies that the temperature dependence of sensitivity for the MAGAMP structure will be a factor of two lower than for the MAGFET pair.

Equation 2 also shows that a fully-temperature-compensated sensor can be achieved by ensuring that the amplifier and hence sensor bias current varies with the inverse of Kn.

Figure 4 shows a circuit generating the bias current. The amplifier OP1 nulls the voltage difference between nodes 1 and 2 ensuring the same current in M1b and M2b. Because of their scaled aspect ratios, they will have different overdrives with the difference appearing across Rb. It should be noted that the bias current is not dependent on the variation of threshold voltage with temperature. Rb was implemented as an off-chip resistor since a resistor with low temperature coefficient was not available on the target process technology. Ideally however, this would be implemented as an on-chip thin-film resistor. It can be shown that the output current is given by Equation 3. It can be seen that the output current varies with the inverse of the n-channel current gain factor Kn.

Figure 5 shows the measured variation of bias current with temperature. A Ptat current is also plotted for reference purposes. The bias current follows a $T^{1.59}$ law which is as expected. Figure 6 shows the measured MAGAMP sensitivity with both a fixed bias current and the current produced by the circuit in Figure 3. The uncompensated MAGAMP (fixed bias) exhibits a 2300ppm/°C temperature coefficient showing a 2x improvement over the basic split-drain MAGFET device. This temperature coefficient is improved to 200ppm/°C when compensation bias is used. Figure 7 is a chip micrograph.

References:

[1] Misra, D., et al., "A Novel High Gain MOS Magnetic Field Sensor," Sensors and Actuators, 9, pp. 213-221, 1986

[2] Baltes, H., and R. Popovic. "Integrated Semiconductor Magnetic Field Sensors," Proceedings of the IEEE, Vol. 74, No. 8, 1986.

[3] Buckley, M. A., "Integrated Magnetic Field Sensors in CMOS," M.Eng.Sc Thesis, University College Cork, Ireland, Sept. 1991.

*This work was funded by EOLAS ST/404/89]

92CH3128-6/92/0000-0124$1.00 © 1992 IEEE

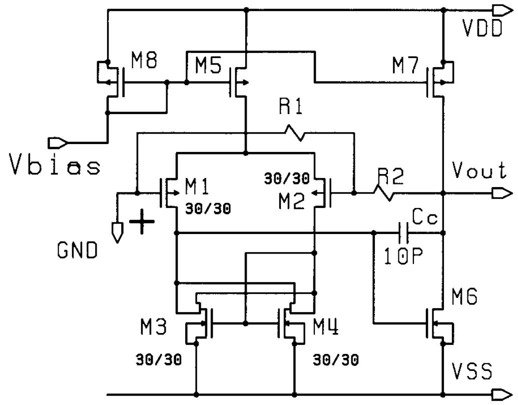

Figure 1: MAGAMP.

$$Vosm = \frac{C1 \times Kn \times \vec{B} \times \sqrt{Ids}}{2 \times \sqrt{Kp \times (\frac{W}{L})_{m1}}} \qquad (1)$$

$$Vosm = C3 \times \vec{B} \times \sqrt{Kn \times Ids} \qquad (2)$$

$$Ibias = \left(\frac{\sqrt{A}-1}{\sqrt{A}}\right)^2 \times \frac{1}{R_b^2} \times \frac{1}{Kn \times (\frac{W}{L})_{m2b}} \qquad (3)$$

Figure 2: Equations.

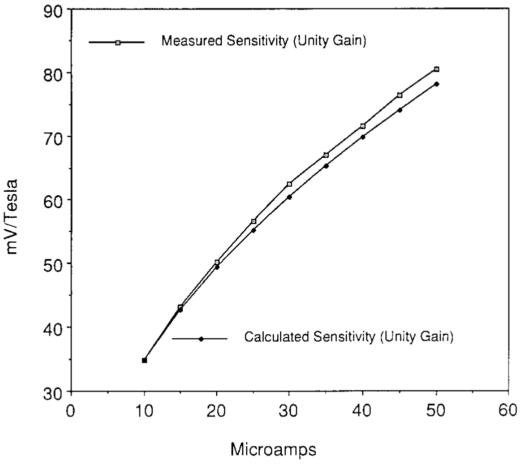

Figure 3: Sensitivity versus bias current.

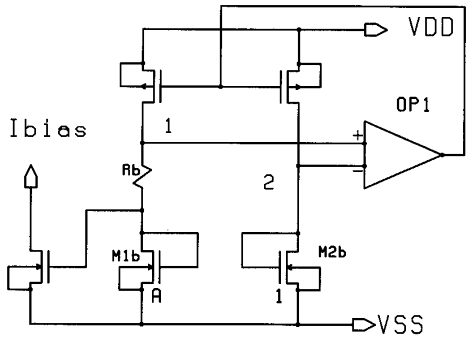

Figure 4: Bias generator.

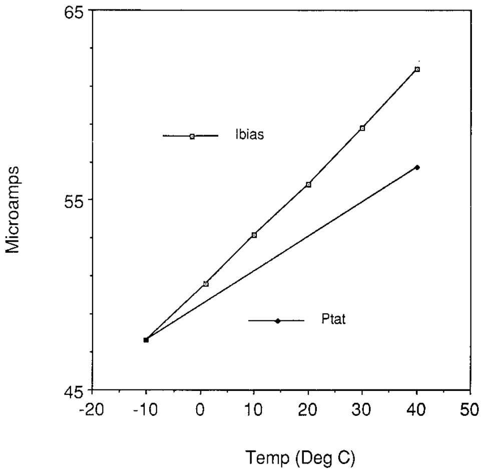

Figure 5: Ibias versus temperature.

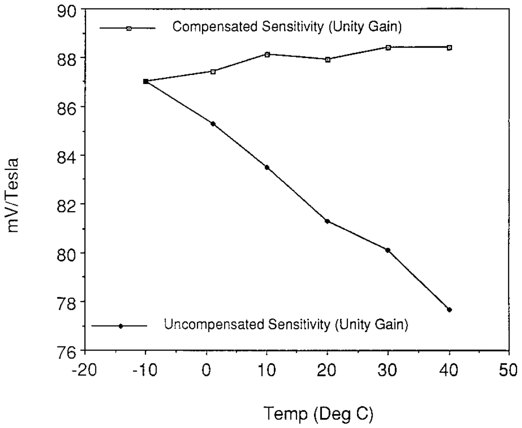

Figure 6: Sensitivity versus temperature.

Figure 7: See page 263.