

Modular Hall Masterslice Transducer

Abstract: The Hall masterslice transducer combines modern IC (integrated circuit) technology with a modular design concept to provide a flexible multifunction approach to magnetic sensing. Its sensing element, a controllable Hall cell, is integrated with the associated circuitry on a masterslice chip, mounted in a flux concentrator module that forms the basic building block for diverse application packages. The device has several auxiliary control electrodes that allow fixed or externally variable offset voltage control and magnetic field simulation, as well as threshold, hysteresis, and gain adjustments. Integral flux concentrators provide the module with an efficient magnetic flux path and chip cooling. Three application categories—switches, proximity sensors, and current sensors—are discussed and various application package designs are presented.

Introduction

Many different types of transducers are used in computer systems. Transducers are especially important in I/O machines and range from mechanically operated switches to sophisticated proximity sensors. In a printer, for example, transducers may be used to control and check print-paper advance, determine the print-character positions, and monitor print-ribbon motion. They may check for cover closure (interlock switches) or monitor currents in print hammer coils or power supply lines.

This diversity of application has resulted in a proliferation of specialized transducers. To counter this trend in the interest of economy and reliability, a transducer was developed that could cope with a multiplicity of applications, based on a combination of IC masterslice technology and a modular packaging approach. Hardware design, major test data, and application ranges are discussed in this paper. New concepts in the design of a Hall cell and its associated transducer circuitry and a novel packaging scheme based on an improved flux-concentrator sensor module are presented.

A magnetic Hall-effect device [1] was chosen as the basic sensing element for two reasons: Magnetic fields can be easily produced and controlled, and a Hall cell can be readily integrated with a compatible amplifier on a silicon chip [2, 3].

Integrated Hall-effect transducers with logic level outputs, housed in dual in-line packages, have recently become available. However, in these commercial devices the magnetic transfer efficiency is relatively low, the switching threshold is not adjustable, and switching tolerances are large.

The performance of our device relative to switching tolerances and adjustability was improved by adding

special control electrodes to the Hall cell [4, 5]. These control electrodes permit zero-offset compensation and wide-range threshold adjustment. In addition, they facilitate effective feedback arrangements and simplify test procedures through magnetic field simulation.

Circuits have been designed to interface with the Hall cell and to make optimal use of the control electrodes. The circuits are integrated on the same chip with the Hall cell, requiring only a metallization change for modification. They include some new ideas in Hall sensing techniques (e.g., Hall cell current regulation and automatic bias control) to further improve performance and provide special capabilities.

To maximize the magnetic transfer efficiency, a low reluctance path is provided with flux concentrators that form a closed magnetic loop inside the module, leaving an air gap of 0.5 mm, which is only slightly larger than the Hall chip thickness. The flux concentrators are an integral part of the package and also serve as an effective heat sink and mounting base. The efficiency gain resulting from the closed flux loop permits detection of relatively weak magnetic fields and the implementation of low-cost, noncontact current sensors.

Packaging schemes for minimizing magnetic reluctance exist [6, 7]. However, those devices were designed for specific purposes (for example, magnetic read heads) and they need relatively complex structures, special manufacturing techniques, and/or special sensor plates. The design described in this paper, on the other hand, is simple, inexpensive, and uses a standard size silicon chip.

Such a flux-concentrator module containing a Hall cell with control electrodes on a masterslice circuit chip may be used as the basic building block for many different

transducers. Three major application categories—mechanically operated switches, proximity detectors, and current sensors designed around two modifications of the same basic module building block—are described in some detail.

Hall cell with control electrodes

The Hall effect voltage is generated by the action of a magnetic field on an electrical current, and is proportional to both. For a conventional Hall cell with two symmetrically spaced sense electrodes (H_1 and H_2 in Fig. 1), this relationship can be expressed as

$$V_H = V_{H_1} - V_{H_2} = FBI_H, \quad (1)$$

where V_H is the Hall voltage, the voltage difference between sense electrodes H_1 and H_2 , F is R_H/T , a material and geometry related sensitivity factor, where R_H is the Hall-effect coefficient, T is the thickness of the Hall cell, B is the flux density vector perpendicular to the cell and to the current I_H .

The voltage V_H is not necessarily zero for zero field because of limitations in the dimensional accuracy and material uniformity of the Hall cell. A certain zero-offset voltage V_{OH} is to be expected. Though its value may be as small as $\pm 0.2\%$ of the voltage across the Hall cell, it can appreciably affect accuracy at low flux levels. For a 5V supply, 0.2% is 10 mV, which is equivalent to about 250 G at a representative sensitivity of 40 mV/kG for an epitaxial silicon Hall cell. The voltage V_{OH} is additive so that Eq. (1) becomes

$$V_H = V_{OH} + V_H(B) = V_{OH} + FBI_H. \quad (2)$$

Some applications require the elimination of V_{OH} ; others require its increase to higher values. A null method for switching at elevated field levels could be achieved with zero-offset voltage adjustment over a large range. For example, if a Hall transducer is desired to switch at a field level equal to B_x , V_{OH} would have to be adjusted to balance $V_H(B)$ for $B = B_x$. The combined voltage V_H at the Hall electrodes would then be zero at the desired switching level.

A simple and effective way to achieve such an intentional zero-offset is through the addition of control electrodes on the Hall cell, as shown in Fig. 1.

A current I_C flowing in a control electrode produces an offset voltage at the Hall electrodes given by

$$V_H(I_C) = kI_C, \quad (3)$$

where k is the proportionality (or control) factor.

The value of k is a function of the physical location of the control electrode in a somewhat complex manner, relating to the spreading resistance in a finite sheet with partially shorted edges. In general, the k -factor value increases with increasing distance between the nearest

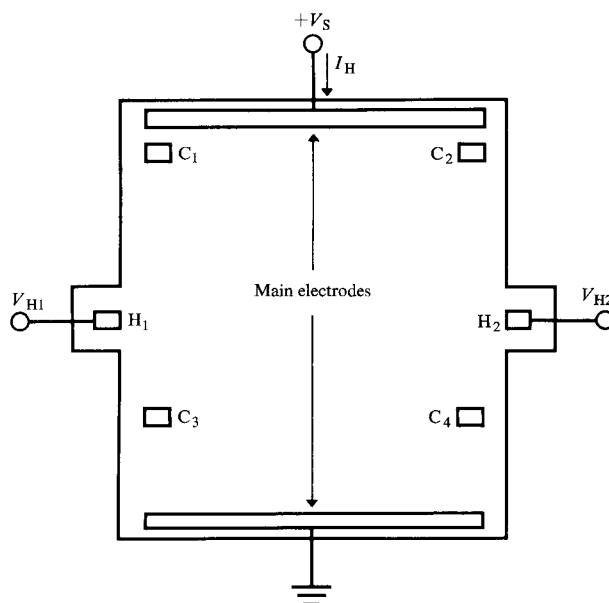


Figure 1 Hall cell for Hall masterslice chip with control electrodes.

Table 1 Representative k values for the control electrodes of Figure 1.

Electrode	k	$VH(I_C)$ (mV/mA)	Equivalent B^* (kG)
C1	50	50	1.25
C2	-50	-50	-1.25
C3	200	200	5.0
C4	-200	-200	-5.0

*This value of B is required to produce the same Hall voltage $V_H(B)$ as the indicated $V_H(I_C)$, produced by a control current of 1 mA, where $V_H(B) = FBI(1)$, $V_H(I_C) = kI_C(2)$, and the sensitivity of the Hall cell is 40 mV/kG at a given value of I_H .

main electrode and the control electrode, and it increases with the distance of the control electrode from the vertical centerline. It has opposite signs on opposite sides of the vertical centerline. Typical k values for representative control electrodes are given in Table 1. For example, control electrode C_3 (Fig. 1) has a k -factor of 200. A control current of 1 mA will produce a voltage $V_H(I_C) = kI_C = 200$ mV. This voltage is equivalent to that produced by a magnetic field of 5000 G (at 40 mV/kG sensitivity). (For more on k -factor values and control electrodes in general, see [5].)

Combining the effect of a current in a control electrode with that of the two terms in Eq. (2) we get

$$V_H = V_{OH} + V_H(B) + V_H(I_C). \quad (4)$$

As Eq. (4) indicates, the voltage on the Hall electrodes due to the control current is additive to the voltages con-

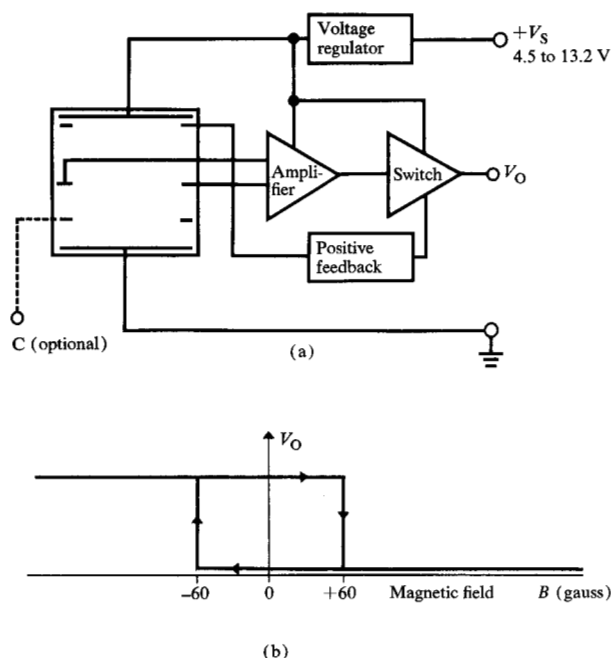


Figure 2 (a) Schematic diagram of the basic switching circuit HMS11 for Hall miniswitch and magnet detector. (b) Typical hysteresis loop.

tributed by the other two sources. Therefore we can use this easily adjustable component of V_H to compensate or balance either of the other two, or to simulate them. Simulation is of special interest in connection with functional testing of the amplifier and switching circuitry on the Hall masterslice chip, and to some extent of the Hall cell itself, for it eliminates the need for an actual magnetic field.

Test results show that the control effect of these control electrodes is highly repeatable among cells manufactured in a production environment. Major advantages relative to other control methods (for example, threshold adjustment of switching circuit, physical offset of Hall electrodes, electrical control of a Hall electrode directly) are the large control range, the low-impedance, low-noise feed-through characteristic, and the overall versatility. The control electrodes can be placed where they provide optimal matching for specific purposes. This affords great flexibility and simplicity in the amplifier and switching circuit design and a practically unlimited threshold and hysteresis range.

There are basically three different ways available to use control electrodes:

- **On-chip control** One or more control electrodes are connected directly or through resistors into the circuit, to one of the main electrodes, or to each other. On-chip control permits the introduction of a predetermined compensation or offset effect. It can provide a

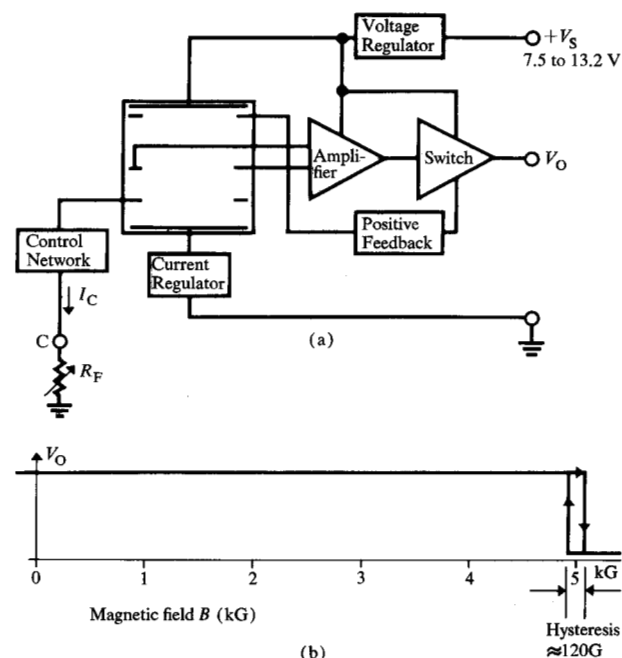


Figure 3 (a) Schematic diagram of the HMS14 current-regulated switching circuit. (b) Switching diagram with a 5000 G switching point offset.

fixed switching point and/or a fixed hysteresis-equivalent from -5000 to $+5000$ G. Because the control electrodes, in this case, are connected by wires on the chip, a change in the compensation or hysteresis values requires a change in the metallization layer of the chip.

- **External adjustment** One or more control electrodes are connected to chip pads. External adjustability permits the greatest flexibility for special requirements. It makes continuous offset adjustment and individual compensation of undesirable offset voltages possible. It lends itself also to external programming (change of switching point or hysteresis based on secondary conditions) or it can be used for functional testing.
- **Automatic bias compensation** A closed-loop feedback connection is made between a control electrode and the chip circuit. Automatic bias compensation permits accurate proximity sensing where a relatively small field change occurs on top of a strong bias field (e.g., emitter-wheel sensing with a permanent magnet bias field).

HMS circuits and chip design

Several experimental HMS (Hall masterslice) circuits have been designed. The first circuit, HMS11, is implemented on a small $1.15\text{-mm} \times 1.50\text{-mm}$ ($45\text{-mil} \times 60\text{-mil}$) chip together with the Hall cell. Figure 2 shows this circuit in block diagram form. It is suitable for use in

mechanically operated switches and magnet detectors or proximity sensors.

Circuits HMS13 and HMS14 (Figs. 3 and 4) are designed to fit on the same chip as HMS11 with a modification only in the component interconnection (change in metallization). These two circuits are intended mainly for current sensing.

Circuit HMS13, shown in Fig. 5, is a specialized circuit for automatic bias compensation. It is designed for use in dynamic proximity sensing where relatively small flux changes, superimposed on large bias fields, are to be detected.

All HMS circuits use a regular two-stage differential amplifier with constant current sources, followed by a pnp switching transistor and an output driver. The switching hysteresis of HMS11 and HMS14 is produced by a positive feedback loop from the switching stage output to one of the control electrodes. The hysteresis is set at 120 G nominal. It can be altered by changing a resistor in the feedback loop (chip metallization change).

All circuits have a voltage regulator that limits the voltage for the circuit and across the Hall cell to 6.4 V nominal, allowing supply voltages up to 13.2 V (12 V $\pm$ 10%). While there is no voltage regulation below 7 V, the circuit can still be used down to 4.5 V with a reduced but maximum possible sensitivity. (Sensitivity is about 8 mV/mA-kG, or about 51 mV/kG at 7 V or higher supply for typical cell impedances of about 1000 ohms. At 4.5 V, with about 3.8 V across the Hall cell, sensitivity drops to about 30 mV/kG. If regulation were extended down to 4.5 V, this 30 mV/kG would apply for any voltage $\geq$ 4.5 V.) The effect of the control electrodes remains proportional to this sensitivity change if the control current is derived from the same internal supply voltage. If a constant I_c is used, the control effect remains constant.

In addition to an on-chip voltage regulator, HMS13 and HMS14 contain a current regulator for the Hall cell current. This is important for temperature compensation. Because the Hall cell consists of n-doped silicon that changes its resistivity at about 0.7% per $^{\circ}\text{C}$, the current (and with it the sensitivity) changes at about the same rate if a constant voltage is applied across the Hall cell. Stabilizing the current is about the only way to eliminate about 95 percent of this temperature dependency for critical applications.

Circuit HMS14 (Fig. 3) is a digital circuit similar to HMS11. For supply voltages of 7.5 to 13.2 V, it provides high switching threshold accuracy and temperature compensation up to a junction temperature of 100 $^{\circ}\text{C}$ by virtue of the constant current regulator. The graph in Fig. 3 shows the switching characteristic for a maximum switching threshold offset of 5 kG. This threshold is

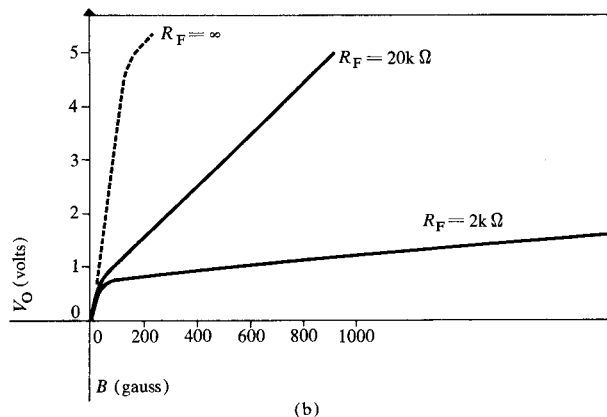
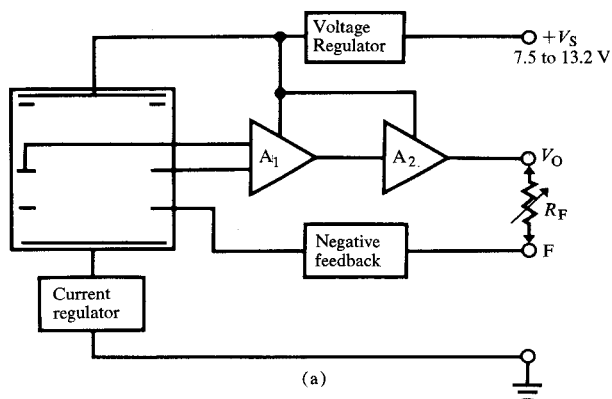
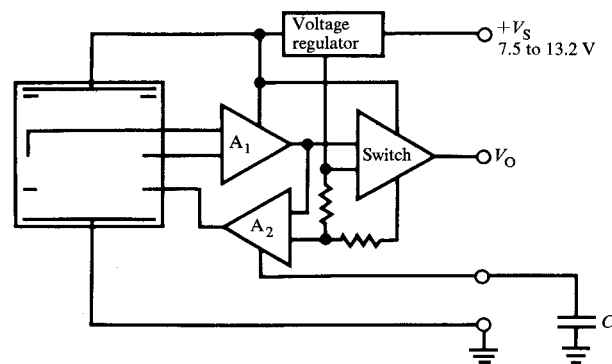


Figure 4 (a) Schematic diagram of the HMS13 analog sensor circuit. (b) Analog output voltage as a function of B for different values of R_F .

produced by the externally adjustable current I_c . Switching occurs at or near this $V_H = 0$ level, exactly as in the HMS11 circuit of Fig. 2.

Circuit HMS13 is designed for analog field or current sensing. It uses heavy negative feedback from the output to a sensitive control electrode. The amount of feedback, and with it the overall gain or transfer slope (in

Figure 5 Schematic diagram of the HMS12 self-compensating circuit for dynamic proximity sensing.



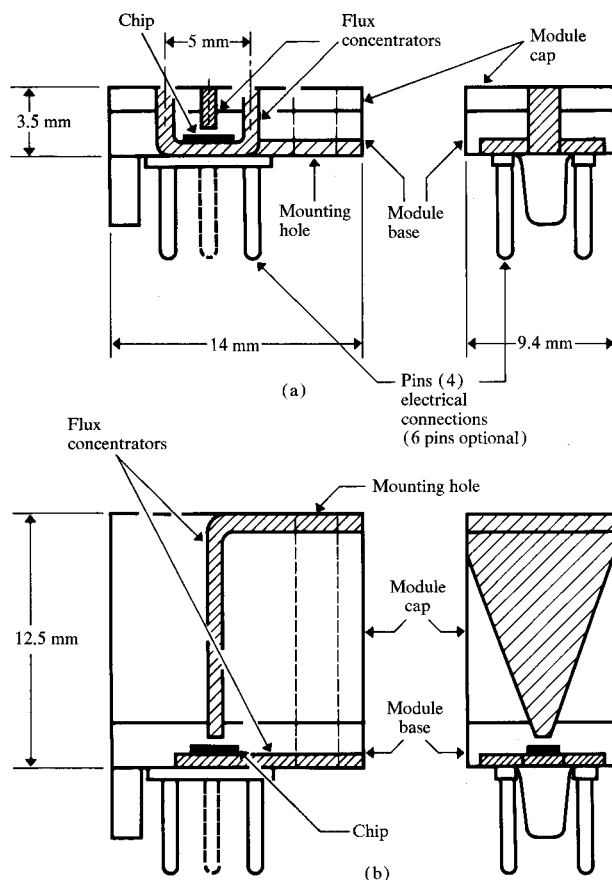


Figure 6 (a) Magnetic detector module. (b) Current sense module.

V/kG), can be externally adjusted with the resistor R_F . Values between 0.1 and 10 V/kG are attainable. Figure 4 shows curves for different feedback resistors. The vertical offset for $R_F < \infty$ is caused by a diode drop in the feedback network. It can be compensated for if required. The zero point can be offset along the horizontal axis with any one of the other control electrodes.

Circuit HMS12 (Fig. 5) is a self-compensating circuit with a digital output. It has a negative feedback loop from the differential amplifier output via a low-pass filter network to a control electrode. Capacitor C of this low-pass filter has to be located off-chip. This circuit has the following main features:

- Full compensation for initial offset voltage due to bias fields of up to 3000 G.
- Full compensation for field (within ± 3 kG), temperature (up to 100 °C at the junction), voltage (within 8.5 to 12 V, $\pm 10\%$), stress, etc. changes as long as the rates of change are relatively slow (< 2 Hz).
- Dynamic switching threshold as low as 50 G for signals with a relatively high rate of change (> 50 G/ms).

- Switching threshold independent of velocity and frequency over a range of about 50 to 10000 Hz.
- Two stable states, OFF and ON. The circuit stays in either state indefinitely after it has been switched (as long as power is on), with approximately the same switching threshold in either direction.

The rate-of-change requirements are determined mainly by external capacitors, whereas the threshold levels are fixed by internal resistors that are changeable with chip metallization.

Module design

Figure 6 shows two module configurations, a magnet detector and a current sensor. Both contain an HMS IC chip and two flux concentrator parts. This configuration produces a closed flux path between the bottom and the top of the current sensor and between the two ends of the E-core and the center top in the magnet detector with an effective air gap of about 0.5 mm. This air gap, only slightly larger than the thickness of a regular IC chip, may be reduced with a special, thinner chip to provide for an even greater flux density at the chip site.

An approximation of the flux density at the Hall cell both with and without flux concentrators provides a quantitative assessment of the advantages of the flux concentrators as seen from

$$B \approx M/L, \quad (5)$$

where M is the magnetomotive force in gilberts or oersted-cm (ampere-turn) and L is the length of average active flux lines in air or nonferrous material. For the flux concentrator case with its relatively short air gaps and the small Hall cell area relative to the air gap cross section, Eq. (5) is reasonably accurate as long as the flux density in the external air gap is about the same as in the chip air gap.

For the open flux-loop case, the situation is more complex because the length of the average active flux lines is difficult to define, and the flux density is certainly not constant along their length. However, assuming that the chip is placed close to the inside surface of the module, we can estimate how much larger the flux density is at the chip than (on the average) along the active flux line path and adjust the value of L accordingly. For typical configurations the values of L for the flux concentrator and nonflux concentrator cases are about 1 mm and 3 mm, respectively, indicating according to (5) that the flux concentrators provide about a three-fold increase in the value of B at the chip. Measurements on modules with and without flux concentrators show an improvement factor in flux density at the Hall chip of from 2.5 to 3.5 for small external air gaps, depending on the actual dimensions and on the size and type of permanent magnet used.

The material of the flux concentrators is not critical, as long as it is magnetically soft and has a reasonably high permeability. Only in the case of the current sensor, in which an external flux loop of up to 60 mm total length becomes part of the flux concentrator path, do material properties play a significant role. Here, low coercivity, high permeability, and high saturation limits become important for accuracy up to high current levels.

The chip in the flux concentrator module is backbonded with heat-conducting epoxy directly to the flux concentrator base plate. In addition to maximizing flux density, this technique provides a heat-sink effect that permits greater power dissipation levels and higher ambient temperature operation.

Initially a single module for all applications was planned. But it soon became apparent that two different arrangements of the flux concentrators would be desirable: an E-core structure for magnet detector applications and an open U-structure for current sensing and some special applications. Whereas the module base with the chip, baseplate, and connector pins remained the same, the module cap with the upper flux concentrator evolved in different directions, as indicated in Fig. 6. The top flux concentrator at the current sense module was widened and the module height was increased to 12.5 mm (the magnet detector module is only 3.5 mm high) to match the open end of a U-shaped external flux loop that can be slipped over an insulated wire or cable up to 12.5 mm in diameter. At the same time, the extra height reduces the amount of stray flux between the top and the bottom sections of the current sense module. The magnet detector module, on the other hand, was built as thin as possible, with the E-shaped flux loop opening to the top and facing the N and S poles of a small flat magnet.

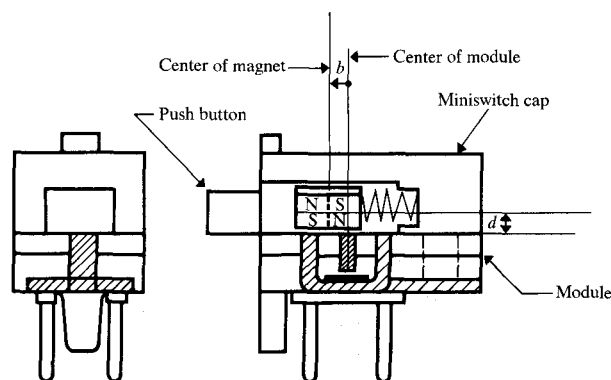


Figure 7 Miniswitch built with magnet detector module. Distance parameters b and d are defined for use in Fig. 8.

These two modules form the basic building blocks of all application packages, which are grouped in three classes: mechanically operated switches, proximity sensors with or without an internal permanent magnet, and current sensors with an external flux loop. Table 2 provides an overview of some sample application packages.

Application packages

• Mechanically operated switches

A pushbutton miniswitch is illustrated in Fig. 7. Its base is the magnet detector module with the E-core flux concentrator. It has four pins, of which at least three are active with the HMS11 circuit chip. The top section contains a permanent magnet mounted on the pushbutton. The magnet slides on the module surface against a compression spring. The E-core flux concentrator in the module provides the desired closed flux path for the

Table 2 Hall transducer application chart.

Transducer type	Circuit	Package design and application reference
S1 Standard pushbutton switch	HMS10 or HMS14	Figure 7
S2 Slide switch	HMS10 or HMS14	
P1 Basic proximity sensor or magnet detector	HMS10 or HMS14	Figure 9
P2 Proximity sensor with internal permanent magnet	HMS14 with external threshold adjustment	
P3 Dynamic proximity sensor with internal permanent magnet	HMS12	
C1 Current sensor with closed flux loop	HMS13 or HMS14	Figure 10
C2 Current sensor with primary coil for $I_N < 20$ A	HMS13 or HMS14	

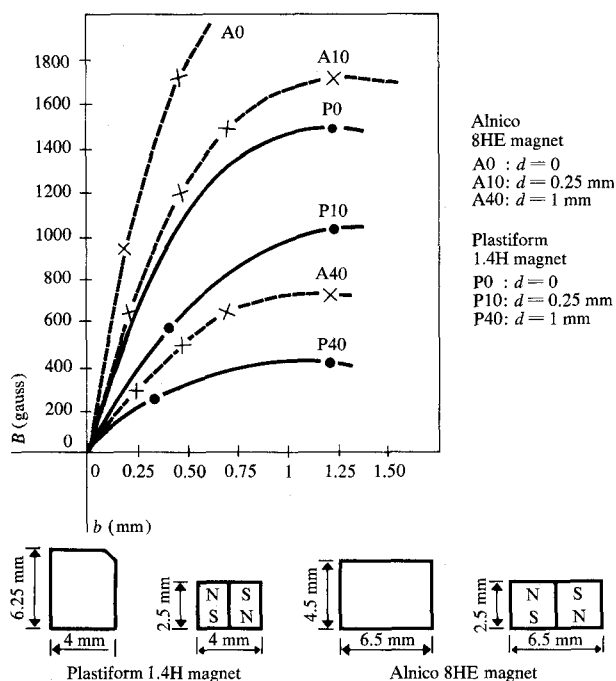


Figure 8 Flux density profiles as a function of magnet position (see Fig. 7); magnetic and dimensional data are shown for two magnet types.

magnetic field from the permanent magnet over its top. In the fully released position, shown in Fig. 7, the Hall cell sees a maximum flux in one direction. As the pushbutton is depressed, the flux through the Hall cell decreases to zero and then increases to a maximum in the reverse direction.

With a 2.5-mm thick, 4-mm long barium ferrite magnet sliding at a distance between 0 and 0.25 mm above the module, the initial flux density is around 1000 and 1400 G as shown in Fig. 8 by curves P0 and P10 [for 0 and 10 mils (0.25 mm) distance above the module]. If the Hall transducer circuit switches at ± 60 G (120 G nominal hysteresis), the miniswitch switches at about 0.02 mm (0.8 mil) on either side of the pushbutton mid-position with a mechanical switching overlap (hysteresis) of about 0.04 mm. For a total pushbutton travel of 2.5 mm, there is about 1.25 mm pre- and post-switching travel. Including worst-case tolerances for an uncompensated Hall cell and for the mechanical parts, the actual pre- and post-switching travel may vary between 0.75 and 1.75 mm. If desired for special applications, the switching point can be moved to either side by shifting the switching threshold with one of the control electrodes. The hysteresis can also be adjusted to a level where latching occurs and an electrical reset pulse is required for resetting.

This switch replaces mechanical snap-action switches and has application as a general purpose pushbutton switch for logic level signals. While subject to the wear of a moving part and the failure of a conventional spring, it is free of contact problems and can be actuated by small forces and with any desired hysteresis. The switch can be mounted with the pins in any orientation. A locator stud on top of the package permits two-point mounting with the screw inserted from the pin side. Electrical connections may be made through a mating connector, wires can be soldered directly to the pins, or the pins can be soldered into a PC card. Other switches, such as slide switches with different mounting and/or actuating levers, can be designed with appropriate package modifications.

• Proximity sensors

The Hall module used for the miniswitch can be used directly as a magnet detector or as a proximity sensor when an external magnetic field provides the required amount of flux through the Hall chip. Figure 9 illustrates a typical application.

Flux density profiles, measured with a Hall chip inside a representative flux concentrator module, are given in Fig. 8 together with the dimensions for the two permanent magnets used for these measurements. In its basic, uncompensated form, with an HMS11 or HMS14 chip, the magnet detector switches within a ± 300 -G tolerance range and has a switching hysteresis of about 120 G. The switching point can, however, be adjusted more precisely with the control electrodes. External and continuous adjustment requires that a control electrode be connected to the fourth pin. The hysteresis can be altered by a metallization layer change, or it, too, can be made externally adjustable. If both the switching point and the hysteresis are to be externally adjusted, at least five module pins are needed. This requirement has been considered in the design of the module, which can be equipped with as many as six active pins.

To sense the proximity of ferromagnetic targets, a permanent magnet is incorporated in the module package to provide a bias field. In a proximity sensor the switching point must be offset precisely through an externally accessible control electrode. However, a self-compensating circuit is often more satisfactory. The HMS12 circuit has been specifically designed for dynamic proximity sensing, in which a relatively small dynamic signal is superimposed on a strong and perhaps unpredictable magnetic bias field. This circuit (Fig. 5) automatically compensates for the bias field and responds only to rapid changes produced, typically, by the teeth of a rotating emitter wheel. Mounting and electrical connections for proximity sensors are similar to those for the mechanically operated switch.

• Current sensors

Figure 10(a) illustrates a simple one-turn current sensor. An iron loop around a wire provides a low-reluctance path for the magnetic flux surrounding the current through the wire. Because the reluctance of the air gap inside the HMS module is much higher than the reluctance of the iron parts, the flux density at the Hall cell is determined mainly by the air gap length:

$$B \approx M/L = 0.4\pi NI/L, \quad (5')$$

where NI is the number of ampere-turns.

For an air gap of 0.5 mm, Eq. (5') indicates theoretically a flux density of about 25 G per ampere-turn. Fringing effects in the air gap and a small drop in field along the flux loop and at the flux-loop-to-module interface reduce the flux density measured at the chip to about 20 G per ampere-turn.

Assuming a ± 20 -G basic tolerance for a well compensated Hall sensor on top of a $\pm 5\%$ overall tolerance (including the flux loop), one can see that at least 400 G would be needed to achieve a $\pm 10\%$ total accuracy. This is equivalent to a 20 ampere-turn input that has been arbitrarily designated as the lower limit for satisfactory current sensing. The upper limit is determined by saturation in the flux loop. Because the total stray flux is much higher than the flux passing through the air gap, the flux density in parts of the loop can exceed the air gap flux density considerably. For a flux loop as shown in Fig. 10, saturation effects start at approximately 200 to 300 ampere-turns, depending on the dimensions and materials used.

The ratio of the minimum and maximum currents that can be measured by a current sensor of the type considered here ranges, therefore, from about 1:10 to 1:15. For a single-turn configuration this would be equivalent to a range from 20 to 300 amperes. For smaller currents a multi-turn device as illustrated in Fig. 10(b) can provide the same flux levels.

To achieve accuracy over a reasonably large temperature range, temperature compensation of the Hall cell is mandatory. This is achieved in the HMS13 and HMS14 circuits through the use of a constant-current regulator for the Hall cell current, combined with a voltage regulator for the circuit supply voltage.

The HMS13 circuit, designed for analog sensing, produces an output voltage that is proportional to the magnetic field at the Hall cell, which in turn is proportional to the current through the flux loop. The transfer ratio in volts/ampere-turn can be adjusted with an external resistor (see Fig. 4) that determines the current in the negative feedback loop from the output to one of the control electrodes.

The HMS14 circuit can be used as a digital current sensor. The switching point (e.g., for overcurrent or

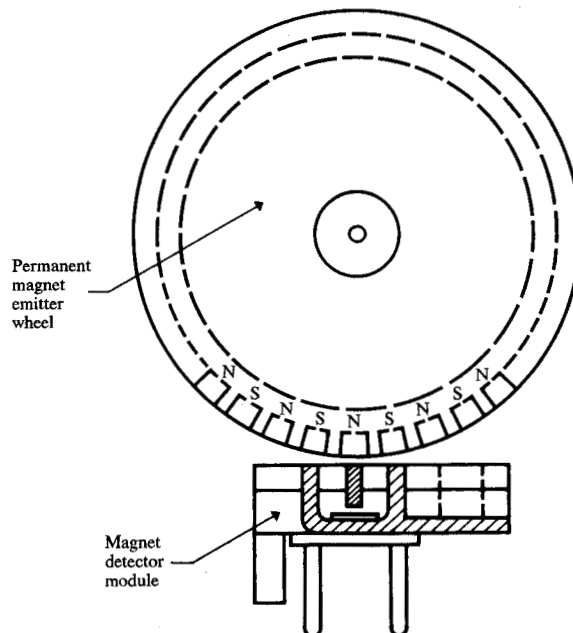
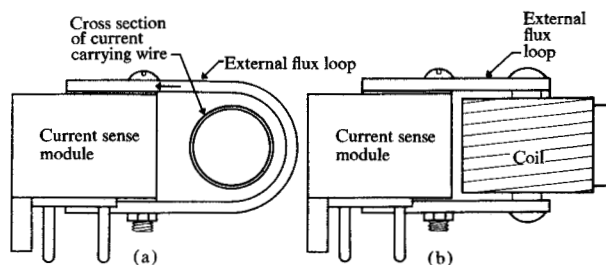


Figure 9 Magnet detector used to detect rotation or to measure the rotational speed of an emitter wheel.

undercurrent protection) can be adjusted with an external resistor in the control electrode circuit.

The switching hysteresis can be chosen and is determined by component values and interconnections on the chip, or it can be externally adjusted via a separate pin. For special applications, the hysteresis can be increased to a value causing latching; that is, the hysteresis can be made so large that even at zero current through the loop the circuit does not switch back after it has been triggered by an overcurrent. A pulse applied to the external threshold adjustment circuit or to any externally accessible control electrode can be used for resetting. Similarly, the threshold adjustment feature or a separate control electrode can be used for functional or diagnostic testing of the current sensor and its associated circuitry within a

Figure 10 Current sensor module: (a) single-turn; (b) multi-turn.



complete system. Instead of injecting an actual overcurrent into the monitored line the switching threshold is temporarily changed to a value lower than the nominal line current or to zero, causing switching as if an overcurrent had occurred.

Mounting and electrical connections for the current sensor are identical to those described for the mini-switch. On the other hand, the current sensor can be mounted directly on the current carrying wire by way of its external flux loop, with a floating electrical connection to the pins.

Summary

Combining a controllable Hall cell integrated on a master-slice circuit chip with a flux concentrator package produces a versatile, low cost magnetic sensor module. Equipped with various attachments, it can cover a large range of transducer applications, from mechanically operated switches to proximity sensors and current sensors.

The Hall cell control feature is provided by control electrodes, diffused at various locations into the Hall cell. Depending on their locations, these control electrodes have a predictable effect on the voltage on the Hall electrodes in the form of an offset voltage that is directly proportional to the control electrode current. This control feature permits compensation for the inherent zero-offset voltage of the Hall cell or the adjustment of the switching threshold over a large range. It also permits simulating the effect of a magnetic field for test purposes. The control current (ranging in value from a few μA to about 1 mA) makes possible feedback schemes for switching hysteresis, analog sensing, and automatic bias compensation.

In current sensing particularly, the improved transfer efficiency and the well defined air gap length provided by the prepackaged flux concentrator module present a major advantage. Equally important in achieving versatility at low cost is the simple threshold or gain adjustability for digital or analog current sensing, which is made possible by the control electrodes. Finally, the regulation of the Hall cell current, adjustable switching hysteresis up to a latching provision with external reset, and diagnostic checkout possibility within an active system provide increased accuracy, flexibility, and utility to magnetic current sensing.

There are some limitations associated with the Hall transducers described herein. Temperature dependence of the epitaxial silicon Hall cell resistance remains a problem, even with supply current regulation. Stress sensitivity of the Hall cell is another drawback, especial-

ly in connection with temperature-induced stresses in a back-bonded chip. The inherent zero-offset voltage also remains a problem; its compensation requires measurement and individual adjustment that is worthwhile only in cases requiring special accuracy.

The elimination of some or all of these limitations may eventually lie in replacing the epitaxial Hall cell with a superior sensing element. An MOS Hall cell [8] may provide improvements. That device is compatible with the improvements described in this paper, including the use of control electrodes. A magneto-resistor bridge configuration is another alternative. Practically all of the improvements could be obtained with only minor modifications. The same would be true for more sophisticated devices such as active, self-amplifying, semiconductor sensing structures of the type discussed in [9]. In addition to the electrical and magnetic improvements described in this paper, much in terms of accuracy, reliability, and cost of such a device does, of course, depend on the physical design and manufacturing, and there is ample room for improvement in these areas.

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