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INVITED PAPER

Narrow-gap semiconductor magnetic field sensors and applications

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Abstract. Narrow-gap semiconductors have been used for decades in the fabrication of magnetic field sensors, such as magnetoresistors and Hall sensors. Magnetic field sensors are, in turn, used in conjunction with permanent magnets to make contactless potentiometers and rotary encoders. This sensing technology offers the most reliable way to convert a mechanical movement into an electrical signal, and is widespread in automotive applications.

Recent developments in the growth of thin epitaxial layers of InAs and InSb on semi-insulating GaAs or InP substrates have resulted in the development of magnetoresistors with excellent sensitivity and operating temperatures up to 285 °C. Magnetoresistors and Hall sensors require a very thin active semiconductor region, a high carrier density and a high room-temperature mobility. The best materials are narrow-gap III-V compounds. 2DEG layers in InSb and InAs would be ideally suited for these devices. The accumulation layer at the surface of InAs has been used to make magnetoresistors, Hall sensors and magnetotransistors. n-type doped thin InSb films are used to make magnetoresistors that outperform Si-based Hall sensors, even with integrated amplification.

We describe device design criteria, materials requirements and a direct comparison of the three types of galvanomagnetic devices, magnetoresistors, Hall sensors and magnetotransistors, made from the same material. We compare the output of different magnetic field sensing technologies, such as Si and GaAs Hall sensors, and NiFe-based magnetoresistors, with InSb magnetoresistors.

1. Introduction

Magnetic field sensors are used in magnetic recording technology, in metrology, and in position and speed sensors (Weiss 1969, Siemens 1989, Baltes and Popovic 1986, Partin and Heremans 1992). Different applications require very different sensor characteristics. Sensors capable of detecting very small magnetic fields, such as squids and fluxgate sensors, are typically used in magnetic anomaly detection and in laboratory instruments (Lenz 1990). Magnetic recording works with fields that are higher than the earth's magnetic field, but smaller than a few mT. Magnetoresistors made from magnetic metals, such as FeNi alloys in the permalloy range, are often used (Dibbern 1986). They saturate at fields of the order of a few mT. Magnetic fields of the order of 0.01 to 0.3 T are generated in a wide range of position sensors. This paper describes semiconductor magnetometers for the latter field range.

Most applications presently use silicon-based Hall sensors with integrated amplifiers (Allegro Microsystems 1991), though GaAs-based Hall sensors and magnetoresistors made from bulk InSb are also in use. Thin-film InSb-based magnetoresistors promise to offer a better sensitivity, bandwidth and high-temperature performance than the silicon devices. In this paper, we first describe the application of magnetic field sensors in position sensors. We then briefly review the origin of geometrical magnetoresistance effects. We address materials issues, and show that optimal materials are degenerately doped semiconductors with a high density of high-mobility electrons in as thin an active region as possible. Ideally suited would thus be two-dimensional electron gases (2DEGs) in narrow-gap III-V compound semiconductors such as InSb and InAs. We give data on sensors made from epitaxial InSb:Te films, grown by MBE on insulating InP substrates. MOCVD growth and insulating GaAs substrates can also be used. We further report data on InAs-based sensors, where the accumulation layer at the air interface is the active region. We compare the characteristics of different types of sensors made from the same active semiconductor (InAs): Hall sensors, magnetoresistors and magnetotransistors. Finally, we compare the performance of InSb-based magnetoresistors with that of the other magnetic field sensing technologies available, silicon Hall sensors with integrated amplifiers, GaAs-based Hall sensors and magnetoresistors based on magnetic metal films.
2. Magnetic position sensors

Magnetic position sensors can be viewed as contactless potentiometers. They consist of at least a permanent magnet and a magnetic field sensor. The position sensors are designed so that a change in relative position between two pieces of ferromagnetic metal, magnetically biased by the permanent magnet, causes a change in the flux at the location of the magnetic field sensors. Thus a mechanical movement results in an electrical signal. Typical examples of applications are shown in figures 1 and 2. In figure 1, a cogged wheel is rotated with respect to a sensor (here a magnetoresistor) mounted on a permanent magnet. The magnetic field at the level of the sensor varies from $H_{\text{min}}$ (for the alignment shown at the top of the figure) to $H_{\text{max}}$ (for the alignment shown at the bottom of the figure). The corresponding change in the resistance of the magnetoresistor is shown on the right-hand side. This type of system is used in automotive ignition systems. The cogged wheel is a part of the crankshaft. The sensor identifies the angular position of this shaft, and thus of the different positions in the engine. That signal is sent to an electronic control module which determines the timing of the firing of the spark plugs.

Figure 1. Rotary position sensor using a magnetoresistor and a cogged wheel. The flux lines are shown for the two positions of the wheel which result in a maximum ($H_{\text{max}}$) and minimum ($H_{\text{min}}$) value of the magnetic field at the location of the sensor. The inset shows how this results in a variation $\Delta R$ of the sensor resistance.

3. Geometrical magnetoresistance

Consider the case of a slab of semiconductor of length $L$, width $W$ and thickness $t$, as shown in the inset of figure 3. A voltage $V_{\text{app}}$ applied between the two current electrodes forces a current $I$ through the slab. A magnetic induction $B$ is applied normal to the plane of the slab. The current density vector $j$ at each point makes an angle $\theta$ with respect to the electric field $E$. $\theta$ is the Hall angle.

Figure 2. Brushless electrical motor, with a permanent magnet rotor and Hall sensors controlling the current through the stator windings.

stator windings are powered by transistors whose commutation is controlled by Hall sensors activated by the magnetic field induced by the rotor. Such motors have excellent torque, are very reliable, and are acoustically and electromagnetically less noisy than motors with brushes.

Figure 3. Geometrical contribution $(R(B)/R(B = 0)) = 1 + g(W/L) \mu B^2$, assuming $\rho_{xx}(B) = \rho_{xx}(0)$ to the magnetoresistance of a rectangular slab of different length:width aspect ratios for different values of the quantity $\mu B$. 

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The Lorentz force will distort the current lines close to the injecting contacts. Some distance away from the electrodes into the slab, there is an accumulation of charge carriers to one side of the slab. This results in the generation of a transverse voltage, the Hall voltage. If the slab is long enough, the transverse, or Hall, electric field balances the Lorentz force, and the current lines become parallel to the side of the sample. In an infinitely long slab, the current density is \( j = \frac{I}{W L} \). This geometry is commonly used to make resistivity and Hall effect measurements on materials. The resistivity is then

\[
\rho_{xx} = \frac{E_x}{j} = \left( \frac{V_{xx}}{I} \right) \frac{W L}{I}
\]

and the Hall coefficient \( R_H \) and Hall angle \( \theta \) are given by

\[
R_H = \frac{\rho_{xy}}{B} = \frac{E_y}{j B} = \left( \frac{V_{xy}}{I} \right) \frac{1}{B}
\]

\[
\tan \theta = \frac{\rho_{xy}}{\rho_{xx}}.
\]

In the particular case of a homogeneous, non-magnetic material, with a single type of charge carrier

\[
R_H = \pm \frac{1}{n e}, \quad \rho_{xx} = \frac{1}{n e m_v}, \quad \tan \theta = \mu B.
\]

If, furthermore, the carrier's Fermi surface is isotropic, the resistivity \( \rho_{xx} \) is independent of \( B \). In practice, all the conditions needed for this are almost never met, and most materials have a dependence of \( \rho_{xx} \) on \( B \), a magnetoresistance, which contains information about the physics of the electrical transport in that material. This is the intrinsic magnetoresistance and has a different origin from the geometrical magnetoresistance used in sensors.

In high-mobility semiconductors, the Hall angle can become large even in moderate magnetic fields. In a rectangularly shaped slab of semiconductor with \( L \leq W \), there is not much length available for the current lines to become parallel to the \( x \) axis. Conformal mapping techniques are used to calculate these lines (Lippmann and Kuhrt 1958a,b). Over most of the rectangle, they are inclined at an angle \( \theta \) with respect to the direction normal to the current electrodes. The current path in such a short, wide sample is longer than in the same sample at zero magnetic field. This leads to a large increase in resistance. It is the geometrical magnetoresistance effect (Weiss 1969). The Hall voltage is not fully developed and does not counteract the Lorentz force effectively. The magnetoresistance of rectangular elements is

\[
R(B) = R(B = 0) \left[ 1 + g(W/L) \frac{\mu^2 B^2}{\rho_{xx}(B)} \left( \frac{\rho_{xx}(B)}{\rho_{xx}(0)} \right) \right]
\]

or, under the conditions under which (4) holds, and for \( \theta < \pi/8 \)

\[
R(B) = R(B = 0) \left[ 1 + g(W/L) \mu^2 B^2 \left( \frac{\rho_{xx}(B)}{\rho_{xx}(0)} \right) \right].
\]

In these equations, the factor \( \rho_{xx}(B)/\rho_{xx}(0) \) accounts for the intrinsic magnetoresistance, while the factor \( 1 + g(W/L) \mu^2 B^2 \) accounts for the geometrical influence of the width-to-length ratio, and is shown in figure 3. \( g(W/L) \) is given by Lippmann and Kuhrt (1958a).

Practical magnetoresistors have to have a reasonably large resistance, of the order of 100 to 3000 \( \Omega \), in order to limit the current consumption and local heating effects. The geometry of each element, \( L \leq W \), is not favourable. Devices are therefore made with multiple rectangular elements, connected in series as shown in the inset of figure 4.

4. Materials

The sensitivity of magnetoresistors is an almost quadratic function of the mobility of the semiconductor. The materials with the highest room-temperature mobilities are n-type InSb or InAs. These are also narrow-gap semiconductors, in which the intrinsic carrier density is a strong function of temperature at room temperature. To compensate for this, manufacturers dope the semiconductors n-type. This technique has two disadvantages: in most semiconductors, the mobility decreases as the doping level is increased, because of scattering of electrons by ionized impurities, and when both the electron density and the electron mobility are high, the electrical conductivity is also high. A high device resistance is desirable, but the \( L:W \) ratio is not a free parameter, since it is related to sensitivity. A high resistance is obtained by using very thin slabs or films of semiconductor, ideally \( \leq 5 \mu \text{m} \).

Hall generators are often made in the geometry shown in figure 3 but with four contacts instead of two. The Hall resistance for an infinitely long slab is \( R_{xy} = V_{xy}/B = \rho_{xy}/\mu \), and for a material for which (4) holds, it is \( R_{xy} = B/\mu n e t \). Thus, the output of a Hall generator is linear in the applied magnetic field, and the most sensitive devices are made from thin, lightly doped slabs of material. On the other hand, temperature stability is obtained by degenerate doping of the active region, so that the only free design parameter is again the thickness of the active region. A four-terminal device analysis (Endsley et al 1961) of a Hall device further shows that the ratio of the power output \( (V_{xy} I_{\text{out}}) \) to the power input \( (V_{xx} I) \) is almost proportional to the mobility of the
contacts define a large number of rectangular elements in figure... mobility decreases. The mobility in the magnetoresistance appears. Devices are made from the temperatures of almost 300... room-temperature electron density of $6.4 \times 10^{14}$ cm$^{-3}$ and mobility of $\mu \approx 45$ 300 cm$^2$ V$^{-1}$ s$^{-1}$ grown on insulating InP by molecular beam epitaxy. A current path was then etched as a mesa in the film. Evaporated contacts define a large number of rectangular elements with large $W:L$ ratio, connected in series. The resistance of this device as a function of applied magnetic field at different temperatures is shown in figure 4. In figure 5 (Partin et al. 1992b), we show the effect of varying the Te doping level on the zero-field resistance and the magnetoresistance. The performance of the InAs-based magnetoresistor described below is also indicated in figure 5.

Magneto resistors made from bulk InSb are also available commercially from Siemens. These devices are made from InSb boules that contain needlelike precipitates of metallic NiSb. The metallic needles serve the same purpose as the lateral contact stripes in the device shown in figure 4: they short out the Hall voltage, so that a large magnetoresistance is apparent. Devices are made from the boules by slicing wafers, and lapping them to the desired thickness (Weiss 1969).

The recent use of almost two-dimensional electron gases in magnetoresistors has made it possible to achieve the best compromise between high electron density and high mobility, while maintaining a reasonably large resistance per device (Heremans et al. 1990). Devices based on nearly two-dimensional electron gases have so far been limited to InAs, and work is under way to extend this to InSb-based magnetoresistors. InAs devices are less sensitive than InSb devices (figure 5), because the mobility of InAs is lower, but they work up to maximum operating temperatures of almost 300 °C. The sensors described here are made from 2 µm thick InAs film, grown by MOCVD on an InP substrate (Partin et al. 1992b), and not intentionally doped. A profiling study of the resistivity and of the Hall coefficient at 0.3 T gives the thickness dependence of the areal carrier density $N_A$ and electron mobility $\mu$ (figure 6) in that film. $N_A$ remains nearly constant, which indicates that an accumulation layer of electrons dominates the transport. The mobility decreases as the film gets thinner, which is consistent with a picture in which the electrons in the accumulation layer are pushed back closer and closer to the InAs/InP interface, which has a high dislocation density. From this, the...
Heremans et al authors conclude that the strong accumulation layer of electrons, which is known to exist at the air interface (Noguchi et al 1991, Reisinger et al 1981, Washburn et al 1979, Wieder 1974), dominates the transport in this particular film. From the slope of the thickness dependence of $N_s$, the contribution of the bulk carriers to the Hall coefficient is estimated to be of the order of 30%. The accumulation layer on InAs surfaces can contain size-quantized sublevels (Tsui 1975). In our film, the accumulation layer is approximately 300 Å thick. The equivalent volume density in the potential well is more than $2 \times 10^{18}$ cm$^{-3}$. Ionized impurity scattering limits the mobility of a bulk-doped layer at that density to about 10 000 cm$^2$ V$^{-1}$ s$^{-1}$, while this film has a mobility of 20 000 cm$^2$ V$^{-1}$ s$^{-1}$. Theoretically, this results in an improvement in sensitivity for magnetoresistors by about a factor of four. The output of a magnetoresistor made from this film is shown in figures 7 and 5.

5. Comparison of sensor concepts

We now compare the outputs of magnetoresistors, Hall sensors and magnetotransistors made from the same material, namely the InAs film described in figure 6. Magnetoresistors are two-terminal devices, and are therefore not sensitive to the polarity of the field. Hall sensors, having four contacts, and magnetotransistors, having three, are polarity sensitive. The output of the magnetoresistor is shown in figure 7. Hall sensors are most often made from simple square slabs, with contacts in each corner. The current is then passed across one diagonal of the square, the Hall voltage measured across the other. Sometimes, the current contacts are evaporated along one complete side of the sample, and the Hall contacts are narrow, and located in the middle of the non-metallized edges. Narrow-gap semiconductors are most often used in applications where a substantial current is desired from the Hall contacts. An efficient geometry is then the one shown in figure 8, where we also report the output Hall resistance $R_{xy}/I$ and the input resistance $R_s = V_{xy}/I$ of such a sensor at different field values and temperatures.

Magnetotransistors have been made in silicon using CMOS technology (Baltes and Popovic 1986), and in 2DEGS in GaAs/AlGaAs (Nathan et al 1990). We concentrate here on a sensor with FET-like geometry (named MAGFET) shown in figure 9. Silicon MAGFETS proved to be rather insensitive to the magnetic field. We fabricated an InAs MAGFET and show its characteristics in figure 9. A constant biasing current $I$ is passed through each of the two drains D1 and D2. The output voltage as a function of field, $V_{xy}$, is measured between D1 and D2, and the quantity $V_{xy}/I$ is shown in figure 9 (top). The input impedance of the device is the average voltage between the source and each of the drains, and shown in figure 9 (bottom). A current $2 \times I$ has to be dissipated in the device to get an output voltage comparable to that of the Hall sensor. The conclusion is that a MAGFET is a less efficient device than a Hall sensor.

To summarize our comparison of device sensitivities, we note that magnetoresistors have an output proportional to $B^2$, while Hall sensors and MAGFETS have outputs proportional to $B$. Therefore at low fields, Hall sensors are more sensitive. But in position-sensor applications,
the field usually varies between two non-zero values, $B_{\text{min}}$ and $B_{\text{max}}$, and the sensitivity must be calculated at a non-zero average field

$$B_{\text{av}} = \frac{(B_{\text{min}} + B_{\text{max}})}{2}. \quad (7)$$

Device sensitivity is defined as

$$S = \frac{1}{1/I}(dV_{\text{out}}/dB) \quad \text{at } B = B_{\text{av}}. \quad (8)$$

With $B_{\text{av}} \approx 0.1$ T, the values for $S$ at 20°C are, from figures 7, 8 and 9, $S = 2460 \, \Omega^{-1}$, $103 \, \Omega^{-1}$ and $83 \, \Omega^{-1}$ respectively for the magnetoresistor, the Hall plate and the MAGET made from the same semiconductor.

6. Comparison with other solid state sensors

The sensitivity of different solid state sensors is shown in figure 10 as a function of applied magnetic field at 20°C. These sensors are the thin-film InSb-based magnetoresistor shown in figure 4, a thin-film NiFe-based magnetoresistor (Nippon Resistor 076100-0202), an ion-implanted GaAs Hall generator (Siemens KSY-10) and a Si-based Hall generator with integrated on-chip amplification (Allegro 3501). The outputs of the sensors in figure 10 are very different in nature. In order to make a meaningful comparison, the sensitivity of each sensor in figure 10 is defined by equations (7) and (8), but with $B_{\text{av}} = 0$ T. At the lowest fields, magnetoresistors based on NiFe are most sensitive, but their sensitivity saturates at fields around $5 \times 10^{-5}$ T. Hall sensors are always more sensitive than magnetoresistors at low fields. The cross-over field depends on the technology used: unamplified InSb-based magnetoresistors are more sensitive than the Si-based Hall generator even with integrated amplifier above 0.03 T. The latter sensor has a cut-off frequency (3 dB) of 25 kHz, because of the large-gain amplifier used on the chip. The amplifier gain is further limited by the available power supply's dynamic range. Amplifiers could be integrated on the GaAs or InP substrates used in the InSb- or InAs-based sensors too, but in general there is no need for them: the output voltage of magnetoresistors can simply be further increased by increasing the device resistance. Many other ways of conditioning the output signal can be integrated with any of the above sensors, such as trigger circuits, latching circuits, or circuits that linearize the output and compensate for temperature over a limited range.

7. Summary

Solid state sensors, such as magnetoresistors, Hall generators, magnetodiodes (Cristoloveanu et al. 1983) and magnetotransistors have the great advantage of being integrable with amplification and signal processing.
circuits, resulting in very cost-competitive systems. The magnetic field range to be detected determines the choice of sensor. The relative sensitivity of the sensor in a specified field range is of primary concern, but other factors are the operating temperature range, the power consumption, the size, the linearity of the sensor, and sensitivity to the polarity of the field.

Narrow-gap III–V semiconductors are the materials of choice to fabricate magnetometers for magnetic position sensing, because these applications require a good sensitivity around 0.1 T. Degenerate doping is required to obtain sufficient stability of the carrier density as a function of temperature. The use of very thin active regions, preferably ZDEGS, results in improved performance. Within the same material system, the sensors with better sensitivity around 0.1 T are at present magnetoresistors. When comparing InSb or InAs technologies with other solid state magnetic sensors, we can generate the following very crude guidelines. NiFe-based magnetoresistors are preferred for sensing magnetic fields below about 0.005 T, typical in magnetic read-out applications. Si Hall sensors with integrated amplification are useful in low-frequency applications in the field range between 0.005 and 0.03 T. InSb-based magnetoresistors are most suitable in field ranges above 0.03 T, work up to 200 °C, but are not sensitive to the polarity of the field.

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