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Recent advances in Hall magnetometers

A subtle revolution is taking place in magnetometry, with innovative Hall instruments enabling the investigation of magnetic fields in ways that were previously unthinkable

Traditional Hall sensors measure only one component of the magnetic field vector (Figure 1). Measuring the complete vector requires three such sensors, mounted at right angles. Not only are such three-axis sensor assemblies expensive to manufacture, they are also relatively large, typically up to 10mm in diameter. This limits their use in small gaps, especially when the field strength varies significantly over small distances – which is exactly the sort of situation of interest today, such as, for example in high-efficiency motors and generators.

Key to the solution is the vertical Hall sensor, which measures field components parallel to the substrate (Figure 2). It is now possible to combine a classic planar sensor with two vertical sensors to build a three-axis assembly on a single CMOS integrated circuit (Figure 3). The total assembly is 200µm in diameter – more than an order of magnitude smaller than a traditional assembly.

Magnetometer on a chip

A Hall magnetometer is much more than a sensor: it also requires a current source to bias the sensor, amplifiers for the Hall signal output, and a set of switches to change measurement range. There is no reason these functions cannot be integrated onto the same IC as the three-axis sensor, resulting in a complete three-axis magnetometer on a chip.

However, the device shown in Figure 3 does even more: it implements a clever technique called spinning current to minimize the sensor's zero offset, that is a non-zero measurement in a zero field.[3] This error is ubiquitous with Hall sensors, and is troublesome mostly because the offset is strongly dependent on temperature. As illustrated in Figure 4, much of the offset changes sign if the voltage and current connections are exchanged. Since the Hall voltage is independent of the

Figure 1: **The classic Hall sensor is a rectangular plate of semiconductor material with four terminals. The Lorentz force caused by a magnetic field B, normal to the plate, tries to deflect the current I. This process induces an opposing electrostatic force that manifests itself as the Hall voltage, V_{Hall}**

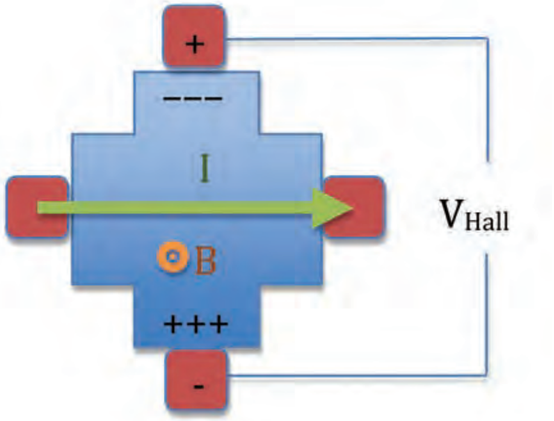
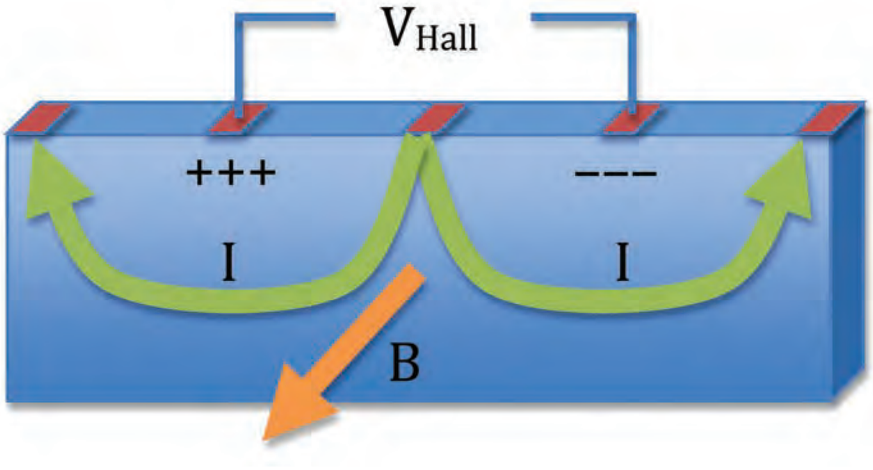


Figure 2: **In a vertical Hall sensor, the current in the two halves of the device flows in opposite directions, causing the Lorentz forces to act in opposite directions. Consequently, a voltage is measured at the output terminals[1]**



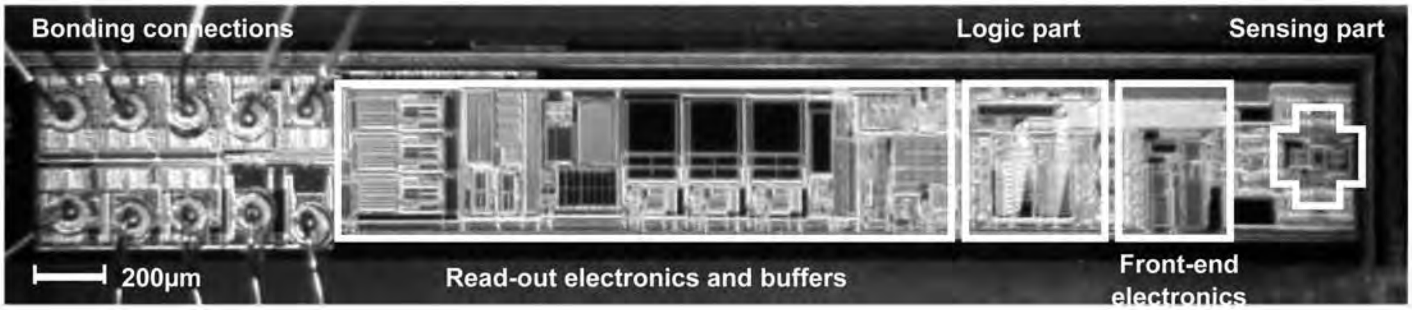


Figure 3: **The chip dimensions are 4,300 x 500µm[7] on this integrated three-axis Hall probe[2]**

direction of current flow, one can cancel the offset by periodically switching the current and voltage terminals and averaging the readings.

In fact, spinning current does more than reduce sensor offset. Choosing the switching frequency high enough will minimize the effect of the 1/f noise found in all resistors. Last but not least, spinning current also suppresses the planar Hall effect, a spurious signal caused by magnetoresistance, strongest when the field vector is in the sensor plane and at 45° to the current. Rotating the current direction by 90° flips the sign of the planar Hall effect, just as it does for the offset.

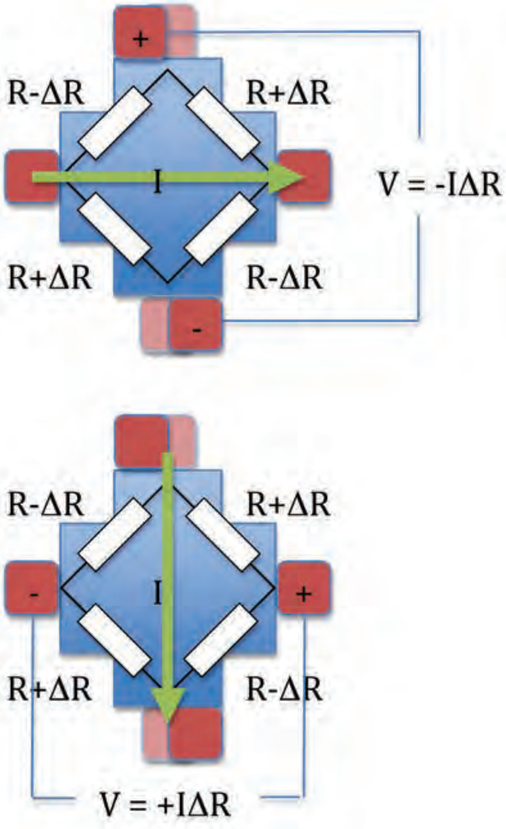


Figure 4: **The principle of the spinning current technique is illustrated using a resistor bridge to model a common cause of offset, terminal misalignment. In this example, such an arrangement results in a negative offset if the current flows left to right (above), but a positive offset when the current flows top to bottom (below)**

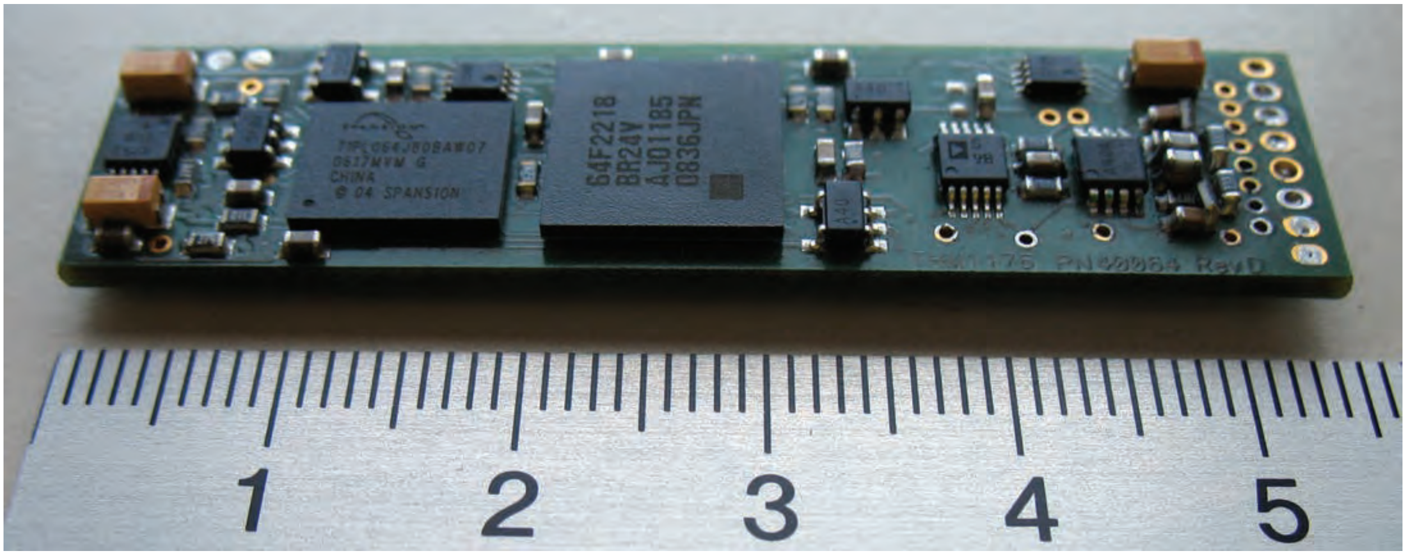
Spinning current requires a large number of fast, low-resistance switches, and is optimally implemented in an integrated circuit. It more than makes up for the fact that silicon is not the optimal material for a Hall sensor, due to its relatively low mobility.[4] The end result is a complete, high-precision magnetometer on a chip.

Goodbye lab bench, hello real world

The integrated sensor has dramatically reduced the complexity of a Hall magnetometer. Using low-power, highly integrated components that have become common with battery-powered embedded systems such as mobile phones, the electronics that once required a shoebox now fits in something slightly larger than a USB memory stick (Figure 5). The entire system consumes less than 0.5W, and can easily be powered by a battery. As a result, the magnetometer has just been promoted from the laboratory to real fieldwork.

It's important to note, however, that there's no need to sacrifice functionality for small size. The system shown is a full-featured instrument, competitive with classic bench-top magnetometers: manual or automatic range control; selectable trigger modes; temperature, non-linearity, and angle correction; standardized computer interface; and even online help, should the engineer need it.

The only feature completely lacking on such a compact magnetometer is a front panel. Consequently, a computer is now an integral part of the system, to display the results and change the settings. Fortunately, computers have also



shrunk, and a laptop, netbook, or PDA offers a portable and user-friendly alternative to the standard instrument front panel. Moreover, the increased emphasis on software, coupled with the advent of high-level programming tools such as LabVIEW (very popular in the instrumentation world), encourages adding powerful analysis tools such as spectral analysis (Figure 6).

Magnetometers of the future

To summarize the current state-of-the-art technology: three-axis field measurements provide accurate results regardless of the angle between probe and field. A sensor assembly 200µm in diameter gives access to small gaps and accurate measurements in inhomogeneous fields. Digital post-processing accurately corrects for temperature, non-linearity, and angular errors. A software front panel provides full control, as well as advanced features such as spectral analysis and alarms – and all this in a compact, battery-powered package.

But what does the future hold? One continued thrust is to reduce the level of noise and improve the resolution of integrated three-axis Hall sensors, which is currently around 0.1mT. This will increase their measurement range even further, making them suitable for applications currently covered by other probe technologies, such as Hall sensors with integrated magnetic flux concentrators.[3]

Other developments are predictable extrapolations of what we have already seen: sensor ICs with even greater levels of integration, even more compact packaging, interfaces to new portable computers such as tablets, and software with even more application-specific analysis features. However, not all Hall magnetometers will follow this development path: instruments for specialty applications, such as very high-precision magnetic field measurements, or measurements at cryogenic temperatures, follow their own evolutionary logic.

Figure 5: **An ultra-compact instrument composed of a multiplexer, an ADC, a microcontroller, a USB computer interface, and precision voltage regulators. The computer interface relies on standardized protocols such as USB Test and Measurement Class and Standard Commands for Programmable Instruments**

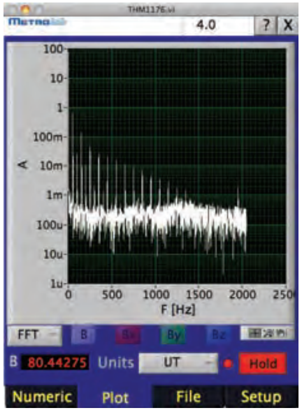


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Figure 6: **The new front panel's software interface. A sample screenshot, showing spectrum of the magnetic field surrounding a switching power supply**

Calibration makes the difference

Even the humble single-axis gaussmeter, far from extinct, is actually enjoying a renaissance, powered by inexpensive industrial Hall sensors.

The majority of such inexpensive instruments and do-it-yourself projects, however, suffer from one major deficiency: they lack proper calibration. All instruments require calibration, but Hall instruments are notoriously finicky, with errors arising from variations in the Hall coefficient, offset, noise, non-linearity, angular error, temperature dependencies, and planar Hall effect and another, poorly understood effect called the 3D Hall effect.[6] Moreover, these parameters are not stable[7] and the calibration needs to be repeated periodically. In the end, calibration – as much as sensors or hardware or software – distinguishes hobby-grade from industrial-grade magnetometers.

Microscale, three-axis sensors, wide measurement range, portability, sophisticated analysis features, accurate calibration: for the magnetics professional, all these developments mean increased accuracy and flexibility – and the ability to make measurements that previously were simply impossible. ■

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