Application Note

Using Paragraf graphene Hall sensors to measure current flow

Document Number:	DOC-1671
Revision Number:	1.3
Effective Date:	23/06/2023 00:00:00
Document Owner:	Enderle, Matt

Introduction

This application note covers the use of graphene-based Hall effect devices to measure current flow by sensing the field generated by the movement of electrons in a conductor.

Magnetic field sensing is an indirect form of current measurement which removes the sensing element from the circuitry. This is beneficial because locating the element outside the circuit eliminates a point of failure from the system, removes the sensor's potential to affect the circuit's electrical properties and allows for the removal of the sensor without requiring disconnection. The wide dynamic range and high bandwidth of magnetic Hall sensing elements are also well suited to adapt to the ever-increasing range of AC and DC measurement required from single-device sensing.

Graphene as a next-generation sensing element in magnetic field sensors stands out in its ability to provide predictable results in a wide range of environments. Graphene-based sensors boasts a number of features – namely, their high sensitivity, linearity and robustness. They can achieve sensitivities which are competitive with leading existing Hall sensors, while being simpler to integrate and to calibrate. Further, they prove resilient and reliable when subjected to extreme stresses.

Paragraf is the first company to produce graphene-based electronic devices at scale, using standard semiconductor processes. Our Hall devices can sense fields generated by currents ranging from milli Amperes to hundreds of thousands of Amperes, and from cryogenic to high-temperature automotive environments. The combination of these features results in a more accurate non-contact measurement of currents for a wide range of applications while simplifying the sensing element integration.

The following pages will outline the many ways in which our graphene-based sensors are providing superior solutions to magnetic sensing applications. Please read through the document and visit the Contact page on our web site to discuss how we this technology can benefit your business.

Contents

Revision History

Document Title: Current Sensor Application Note-PC1-MARK-04

Document Number: DOC-1671
Revision Number: 1.3
Effective Date: 23/06/2023 00:00:00
Document Review Date: 23/06/2024 08:14:14

Document Owner: Enderle, Matt

Approvals

Appropriate Approval Path (Workflow) on Q-Pulse

Job Title	Name
Quality Manager	Mike Ellis
Level 4 Manager	Roberto Mijat

Revision History

Revision	Summary of changes	Date	Changes made by (Name)
V1.0	Initial issue	07/03/22	Matt Enderle
V1.1	Added revision history and Q-Pulse Overlays	22/06/23	Matt Enderle
V1.2	Amended typos	23/06/23	Matt Enderle
V1.3	Corrected image captions	23/06/23	Matt Enderle

1. Magnetic field measurement for contactless current sensing

Current sensing is fundamental to assessing the health and efficiency of any electrical system. With electrification increasingly replacing less-reliable mechanical alternatives, there is an ongoing drive for more power efficiency. Likewise, there is a shift from fault management to fault prevention. As such, the need for current monitoring is constantly growing, as it forms an integral part of ensuring the reliability of these systems.

The range of magnitudes and frequencies of currents to be monitored is also expanding with the development of electronics components, conductive materials, and ever-more-complex electrical systems. In all cases, any unexpected change to those currents threaten the functionality of electrical systems.

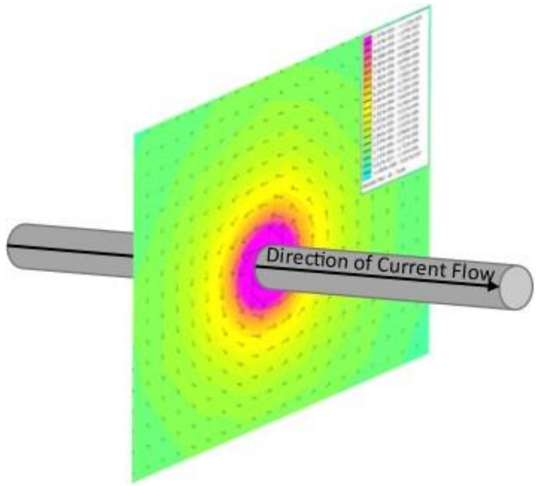

***Figure 1** 3D illustration of magnetic field magnitude in Tesla from a 100mA current flowing in a 2mm wire conductor with no stray field.*

1.1. Non-contact current sensing

Measuring these currents indirectly – i.e., without placing additional components in the current path, also called electrical or Galvanic isolation – is appealing because it is unintrusive to the fundamental electrical system functionality. It does not add a point of failure and does not affect the power efficiency of the system. The conversion from the physical quantity of interest (current) into the physical quantity being sensed (magnetic field) also does not introduce error or lag into the electronics which it monitors. It is these electrically isolated solutions which are the focus of this document.

Every electron moving in a conductor has a magnetic signature. In a conductor of known and constant material and shape, any current will have a predictable magnetic field signature. In a simplified case, applying Ampere's law for a sufficiently long wire carrying a current ***I***, the magnetic field ***B***, at a radial distance ***r***, can be approximated as:

$$B = \frac{\mu_0 I}{2\pi r}$$

Equation 1

Where μ_0 is the permeability of free space. This is illustrated in **Figure 1** and **Figure 2** on the next page.

These principles can also be applied in more complex scenarios. Either through simulation or by calibration to a specific conductor, measuring the magnitude of a field signature can yield the value of the current passing through it. In some instances, the current is already known, and the magnetic field is measured to assess the shape, position, or performance of the conductor. Therefore, a magnetic field sensor can be used to measure a current, or to assess the position or performance of a component.

The relationship between the magnitudes of the magnetic field and the current is linear and can be calculated or calibrated to a known value. If the conductor does not change its shape, and the magnetic field sensor does not change its position in relation to the conductor, the conversion factor will stay the same.

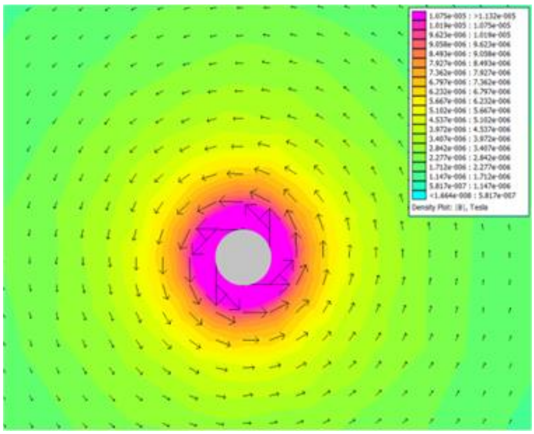

Figure 2 Magnetic field magnitude in Tesla from a 100mA current flowing in a 2mm wire conductor with no stray field.

1.2. Stray field management

In the case of a single conductor in a non-interfering magnetic environment the measurement system can be quite simple. However, in cases where measurements are taking place in a more-complex magnetic field environment there will be a requirement to isolate the magnetic field of interest from its surroundings (e.g., the Earth's field, see **Figure 3**). If the field of interest is larger than interfering fields, placing a magnetic field sensor closer to the source of the field may be sufficient.

If it is not, a magnetic field concentrator can be used to amplify the field response, while reducing potential sources of interference. This works by using magnetically permeable material to concentrate the field generated by the current of interest. A split toroid shaped concentrator is often used for this purpose, since stray fields which are homogeneous over the ring's size will be greatly reduced as the field components acting on each side will cancel one another out (see **Figure 4**). Such magnetic components can, however, introduce saturation and hysteresis issues, and there is no "one size fits all" solution for every application. Saturation in the core should be avoided as it will result in a non-linear response, but even smaller fields will cause some amount of hysteresis.

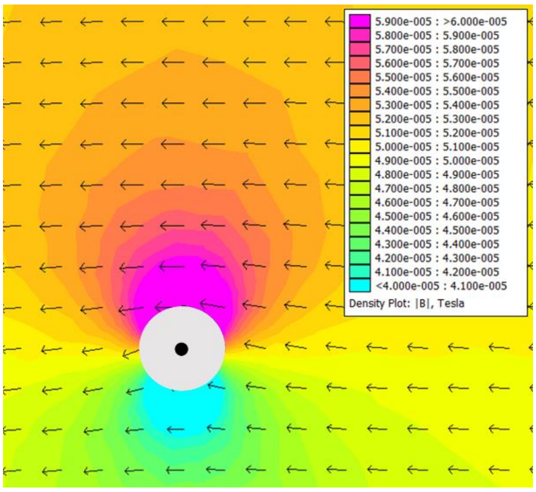

Figure 3 Magnetic field magnitude in Tesla from a 100mA current flowing in a 2mm wire conductor with a 50µT stray field (Earth field)

To counteract this a closed loop system can be adopted, where a coil is added around the concentrator. This secondary coil independently creates a magnetic field, cancelling out the field being measured using feedback from the magnetic current sensor to ensure it remains at equilibrium at zero field. Hence, the current in the secondary loop is proportional to the current flow being measured, and hysteresis is prevented in the concentrator because the field remains low. Of course, this is only one example, and suitable solutions for using flux concentrators will vary from case to case. It is therefore recommended to simulate – and investigate further – any setup intended to include a flux concentrator.

Although a closed loop system is not necessary for stray field cancellation, this is a good example of how a flux concentrator can affect the complexity of integration – e.g., the sensor's overall geometry, and amount of supporting electronics.

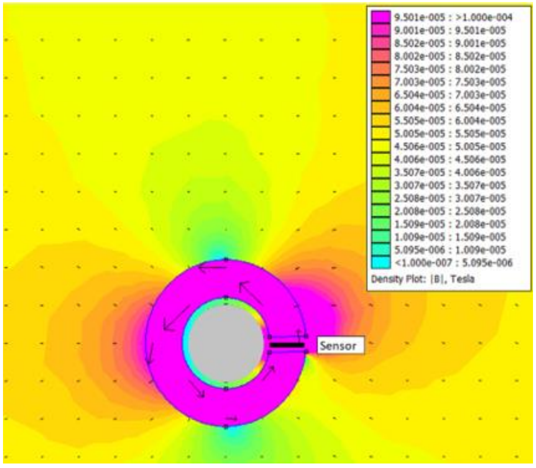

Figure 4 Use of ferrite concentrator to detect the magnetic field generated by a current of 100mA in a 2mm wire conductor in the presence of a 50µT stray field (Earth field).

Alternatively, using multiple sensing elements can enable extraction of only the field of interest. A simple example of this gradiometric measurement is given in **Figure 5**, where a secondary sensor is placed in a position where it will pick up only stray fields and will not measure the current, allowing the stray fields to be directly subtracted from the measurement.

In **Figure 6**, a sensor is placed on each side of the conductor so that the field from the conductor will be positive in one sensor and negative in the other. Assuming each sensor is subject to the same stray fields, they will add to the measured signal for one sensor while in the other they will decrease it. Subtracting one signal from the other will therefore give twice the true signal.

When adding sensors, the impact of each addition must of course be minimised. Factors such as system complexity, cost, performance, power, and size requirements, should be considered to optimise for the specific application or implementation at hand. Like every other measurement method, the complexity of the system will be tightly linked to the complexity of the measuring environment; other environmental factors such as temperature and mechanical stress can also induce non-repeatable behaviour and impact a sensor's ability to function. These factors are mentioned later in this document.

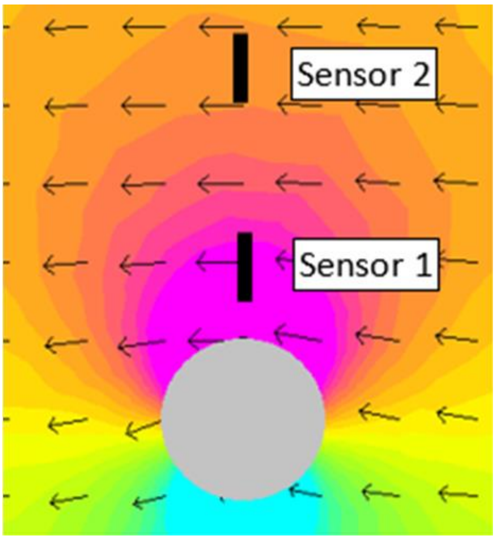

Figure 6 Sensor 1 and 2 in a gradiometric arrangement where:
Sensor 1 - Sensor 2 = most of the field of

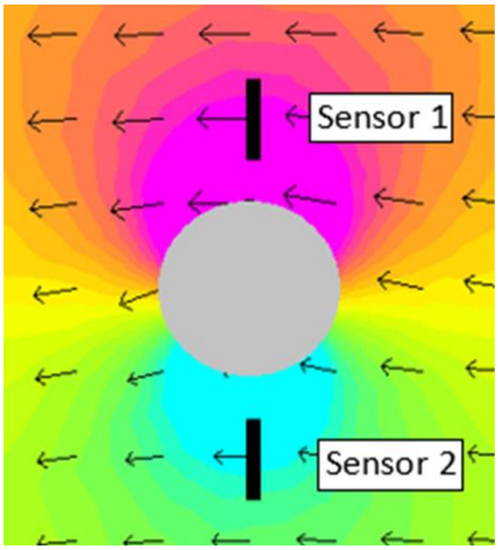

Figure 5 Sensor 1 and 2 in a gradiometric measurement where:
Sensor 1 - Sensor 2 = the field of interest

2. Introduction to magnetic sensing technologies

System complexity is a key factor in determining the practicality of implementing a solution. Therefore, the features which affect ease of integration – sensor size, geometry, and additional necessary circuitry – are key, as well. When a sensor and/or its supporting electronics are too expensive, too large, or too power-hungry, it may be impossible to use for the intended application. For sensors that meet the above requirements, the linearity of the sensor over the intended dynamic range becomes the main concern. A single sensor which can natively measure across the desired range of field magnitudes, frequencies, directions, and so on – with sufficient linearity – will drastically reduce the need for additional sensors or other supporting electronics.

2.1. Single-chip solutions

Available non-contact current sensing solutions can be divided into two broad denominations: simple-to-implement, lower-cost, single-chip solutions, which include Hall and magnetoresistive (MR) sensors; and higher-complexity, higher-cost solutions which extend beyond a single-chip, such as fluxgate magnetometers and Rogowski coils. The high-cost domain provides advantages for specialist cases; however, their footprint, complexity, and expense of implementation make it difficult to usefully apply a single summary to a variety of cases. Solutions in the former category, though, are often largely comparable. As such, they can be implemented similarly in a wide variety of applications, and it is these generalised applications that we seek to summarise here.

These applications cover a broad range of currents, varying in both magnitude and frequency, ranging from the nano Amperes to tens of kilo Amperes, and from DC to hundreds of kilo Hertz. For an appropriately sized copper conductor in what we will assume to be free space, we can recall Ampere's law – Equation 1 on page 5 – to determine the magnetic field 5mm away from the wire, which will be between 0.1nT (1µG) to hundreds of milli Tesla (or a few kilo Gauss) for currents from 2.5µA to 10kA respectively.

In addition to requirements on the dynamic range, the frequency of current can vary from direct current (DC) to hundreds of kilo Hertz for most applications, and up to few mega Hertz for safety switching applications. For a single-chip sensor to encompass this range it must of course be able to distinguish bi-directional currents, and to have sufficient bandwidth to measure at the frequency of interest without significant signal degradation. Preferably this can be achieved without requiring the use of multiple sensing elements – again to reduce complexity.

2.2. Hall sensing elements

The two main technologies of single-chip magnetic current sensors are Hall and MR sensors.

MR sensors function by measuring the change in resistance within a magnetic material, or a combination of magnetic and other materials, due to an external field. MR sensors typically have a dynamic range of a few tens of mT, limiting their utility at high fields. Nonlinear behaviour can also occur in the magnetic material at high fields – this is a hysteresis behaviour, as mentioned in the description of the use of flux concentrators.

A Hall sensor is based on its namesake Hall effect; the deflection of electrons in a thin conductive layer which is proportionate to the strength of a magnetic field applied perpendicularly to their travel. This causes a measurable voltage without any magnetic materials, and the deflection retains its proportional relationship over a broad range of field strengths (for more information refer to Paragraf's GHS Technical Note).

The nature of the Hall effect comes with the added benefit of being inherently bi-directional – i.e., reversal of the current (and therefore the magnetic field) also causes the deflection of the electrons to reverse – a property that is not inherent to MR sensors, which are typically sensitive to the magnitude of field. As such, there is no requirement for multiple sensing elements or other supporting circuitry if bi-directional sensing is required.

The differences in the physical principles underpinning these types of sensors not only change properties such as dynamic ranges, sensitivities, etc.; they also affect how such a device can be physically located. In a Hall sensor, the sensed field will ideally be at a right angle to the conducting plane through which the sensor is powered. Conversely, for an MR sensor, the sensed field must be parallel to the flow of current through the sensor.

Even for sensors of comparable size, then, their practicality can vary significantly in scenarios where physical dimensions are constrained. For instance, when sensing a current path along a printed circuit board, a Hall sensor would be best positioned immediately next to the current path and flat to the board, while an MR sensor in the same position would need to stand vertically or, if horizontal, cross over the current path perpendicularly. Another area where physical orientation might become a concern is when sensing a current in a wire with the aid of a split toroid concentrator, mentioned earlier in this document. The amplification provided by such a concentrator is closely linked to the width of the split in the toroid, with a wider gap reducing the magnetic field strength within. Hence, to maximise sensed field, it is important that a sensor's size along the sensing axis be as small as possible, to minimise the gap.

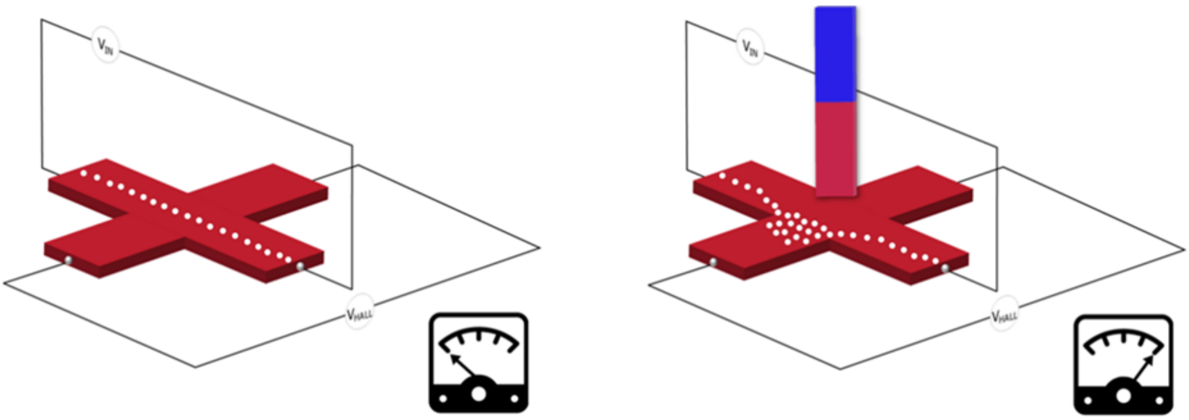

Figure 7 Operating principle of the Hall sensor

3. Benefits of Graphene Hall Sensors for current sensing – the GHS package

3.1. Demands of modern sensing environments

There is a broad range of currents which a sensor may be required to measure, and the environment in which it is required to function in can also vary in the extreme. In particular, temperature and mechanical stress concerns affect many Hall and MR technologies in the market today. This is especially true in environments with high-temperature and mechanical variations, such as in automotive applications. Robustness to stresses, temperature fluctuations, and in-plane stray fields is therefore an essential metric in assessing the suitability of a sensor.

Regarding uncontrolled environmental conditions, a sensor's robustness can largely be assessed by considering two coefficients – sensitivity and offset. The importance of repeatable, linear, and small sensitivity changes is fairly evident. Repeatability is essential to reduce uncertainty in the measurement and allow for accurate compensation. Linearity is important as it allows for much more simplified correction and calibration, reducing the cost and time spent on system calibration. Finally, a small magnitude of sensitivity change due to environmental factors ensures that, if sensitivity drops, it can still detect the desired levels of field and, if it rises, it does not produce so much signal that amplification electronics saturate.

The offset coefficient is the degree to which the offset – the zero-error, a set signal measured without external magnetic field – varies with environmental effects. Repeatability, linearity, and magnitude of change are again key, but in this case especially the latter. This is because the magnitude of the offset is often much greater than that of the signal. To combat this, in most cases, it is a simple matter of applying an equal and opposing voltage to bring the voltage signal at zero field close to a true zero. This must be implemented before signal amplification in order to optimise the signal-to-noise ratio. If the correction is not done dynamically, changes by even a few percent due to temperature or stress can be significant since the offset is much larger than the true signal, and will lead to amplifier saturation, limiting the dynamic range of the system.

If one or both of these coefficients are non-linear, or otherwise difficult to compensate for, it can limit the range of measurement or reduce precision. A sensor which cannot provide a predictable response under different temperatures or stresses, even with best-case corrections, will of course ultimately be of limited use.

3.2. Hall sensor technology landscape

The current technological landscape of Hall sensing falls into two broad categories. Silicon sensors are accurate, affordable, and widely available. They are fairly robust to temperature – i.e., with a repeatably small, linear response – and in some cases can have bandwidths in the MHz. However, low sensitivity limits sensor positioning and potentially requires field concentration, if indeed they can be used at all. Heavy metal (III-V) compound semiconductor sensors, in contrast, have high sensitivity but are more complicated to manufacture and are less robust to their environment (having non-linear temperature offset and sensitivity dependence).

3.3. GHS: Sensitivity & robustness

Graphene is an emerging, transformative electronics material – the first so-called "wonder" material which can now be mass manufactured and used in real devices. Its two-dimensional, highly conductive nature provides excellent performance as a Hall sensor. The key determining factor of sensitivity of a Hall sensor is the mobility of charge carriers, how easily the current is deflected by a magnetic field passing through the Hall plate, and this is especially high in graphene. This mobility rivals common compound semiconductor sensor materials such as gallium arsenide (GaAs) and promises to reach the levels even of specialist, extremely high sensitivity sensor materials such as indium antimonide (InSb). This provides a variety of benefits to current sensing, such as enabling more precise measurements with existing electronics and increasing flexibility of sensor placement (as the greater sensitivity allows equivalent signal over a greater attenuating distance). It can also lead to reduced power consumption; since greater current flow through the Hall element increases the available charge which can be deflected by the sensed field, and hence increases the signal. A higher-sensitivity device can therefore achieve the same signal at lower current. These three benefits, of course, are not entirely mutually exclusive – a design can optimise towards a single benefit, or a balanced combination of two or all three factors, depending on what is desired.

Graphene's chemical and thermal stability and high strength combine to make a sensor which is robust to temperature and mechanical shock. The variation of offset with temperature displayed by graphene Hall sensors is low and linear compared to compound semiconductor Hall sensors; closer, in fact, to the reliability of silicon sensors. Their bandwidth, too, is more like that of silicon sensors; the response time of GHS is on the order of hundreds of kilo Hertz, and up to 1.6MHz in low-resistance sensors, before signal drops to 70% of its DC signal value.

Even at forces close to the destructive limit of the graphene device's substrate – a force equivalent to a few kg – Paragraf sensors display no long-term change in sensitivity, offset, or noise. This linearity in response to temperature as well as field reduces the need for complex electronic calibration before and during use. As such the improved conductivity of graphene can be fully leveraged while also maintaining ease and versatility of application, providing consistent current measurement in a variety of environments.

3.4. GHS: Integration compatibility, a greener solution

The ability to produce graphene-based electronic devices at scale, using standard semiconductor processes, means that graphene sensors can be used flexibly, and often interchangeably with their heavy-metal Hall counterparts. They have comparable resistances (on the order of kΩ), component footprints, and pin arrangements, and use the same standard methods for Hall signal conditioning (for more information refer to our GHS Technical Note). They are also flexible in terms of power supply, taking a range of currents or voltages, and tolerant to electrostatic discharge. This allows the integration of graphene sensors into existing or upcoming designs and manufacturing processes without increasing system complexity, and without changes to the supply chain or design.

Graphene Hall sensors also consist mainly of carbon and aluminium oxide, meaning a high level of performance is provided using non-polluting materials, in a format which is safe to handle. Similar levels of performance in other sensors typically involve a compound semiconductor sensor which is rich in heavy metals such as gallium, arsenic, and antimony. The manufacturing and materials of silicon Hall sensors are typically less hazardous but, as touched upon previously, their sensitivity is also lower.

Similar considerations also permeate beyond what is present in the final product – while the manufacturing process for graphene Hall sensors uses the same technology, the materials involved differ significantly. The primary material requirement for graphene manufacture is nitrogen, while materials for compound semiconductor sensors are often toxic, pyrophoric, or both, among other undesirable features. This leads to graphene's environmental footprint being more akin to that of silicon devices at the manufacture, use and repurposing phase, while providing the performance of heavy metal sensors.

4. Conclusion

As the requirement for streamlined, but accurate, current sensing solutions increases, the need for a robust and versatile technology is critical. In particular, the environments in which the sensing elements are used is increasing in complexity, with more-demanding restrictions on size, temperature span, increased mechanical stresses, and more challenging stray magnetic fields.

Affordable single-chip sensors which can provide galvanically isolated current sensing across a broad dynamic range provide a low-power, no resistance and non-invasive method of addressing this issue. In harnessing graphene to make mass-produced hall effect sensing elements available, Paragraf has demonstrated the potential of this “wonder” material. Graphene hall sensors achieve the sensitivity of compound semi-conductors, the ease of integration and ease of calibration of silicone silicon devices, whilst providing resilient and predictable outputs when subjected to extreme stresses. Combining these merits permits a more accurate non-contact measurement of currents for a wide range of applications without adding complexity to the sensing element integration.

Contact us:

www.paragraf.com

enquiries@paragraf.com