PARAGRAF SENSORS

Next Generation Graphene Hall Sensors

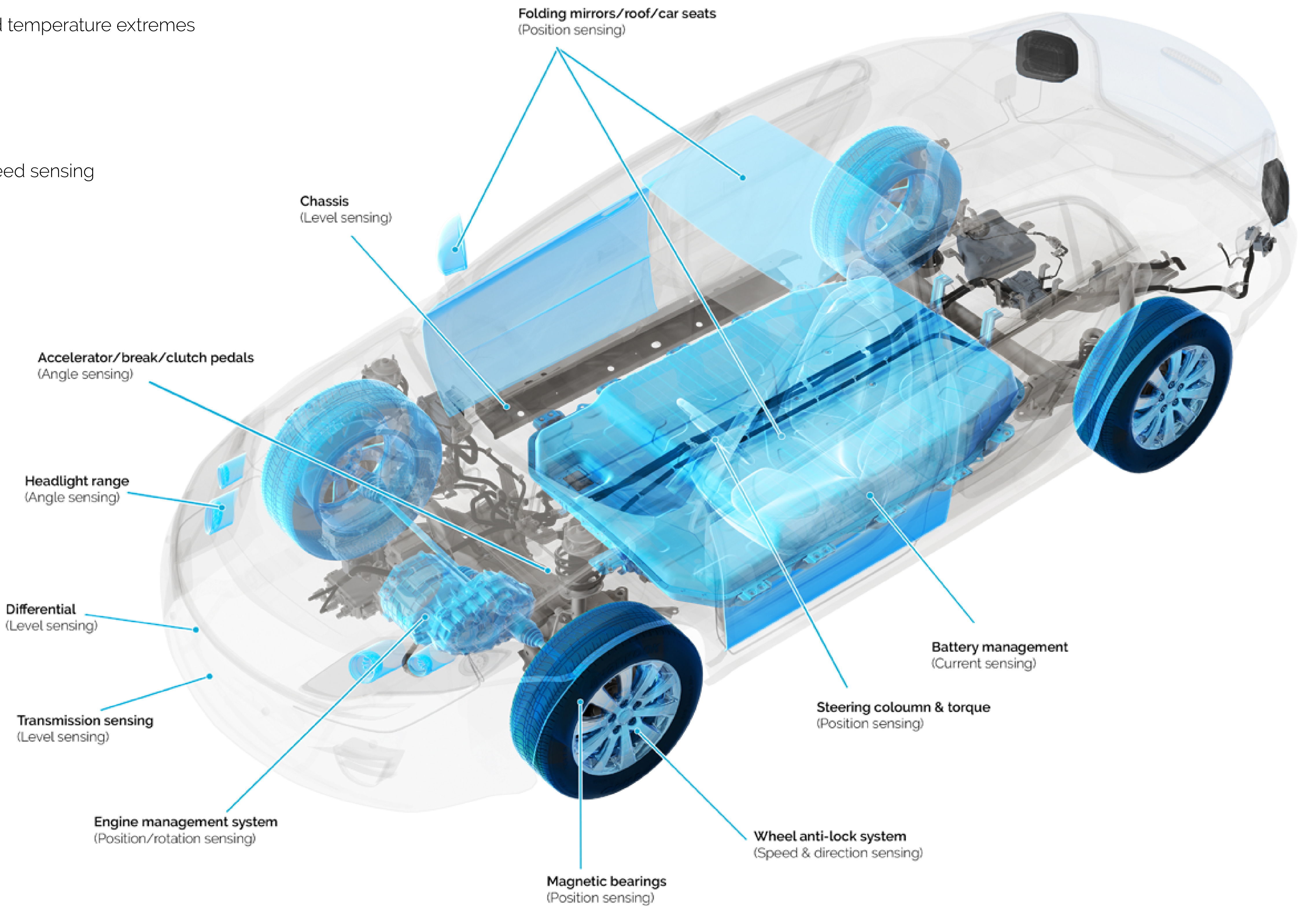
Revolutionising the future

Paragraf® GHS series Hall effect sensors deliver the unique **properties of graphene into magnetic field sensing applications. The sensors give simple yet ultra-high resolution magnetic field measurement under a wide range of operating conditions.**

Paragraf's contamination-free direct-to-wafer deposition technology enables high purity graphene to be integrated into sensing technologies. The GHS series of analogue sensors is designed to provide very high-performance measurement, sensing and control for scientific research, battery, healthcare, aerospace, industrial and automotive applications, including:

- Accurate operation under magnetic and temperature extremes
- Precision magnetic field measurement
- Accurate field gradient mapping
- High sensitivity current measurement
- High precision position, rotation and speed sensing
- Continuous ultra-low power operation
- Immunity to in-plane stray fields

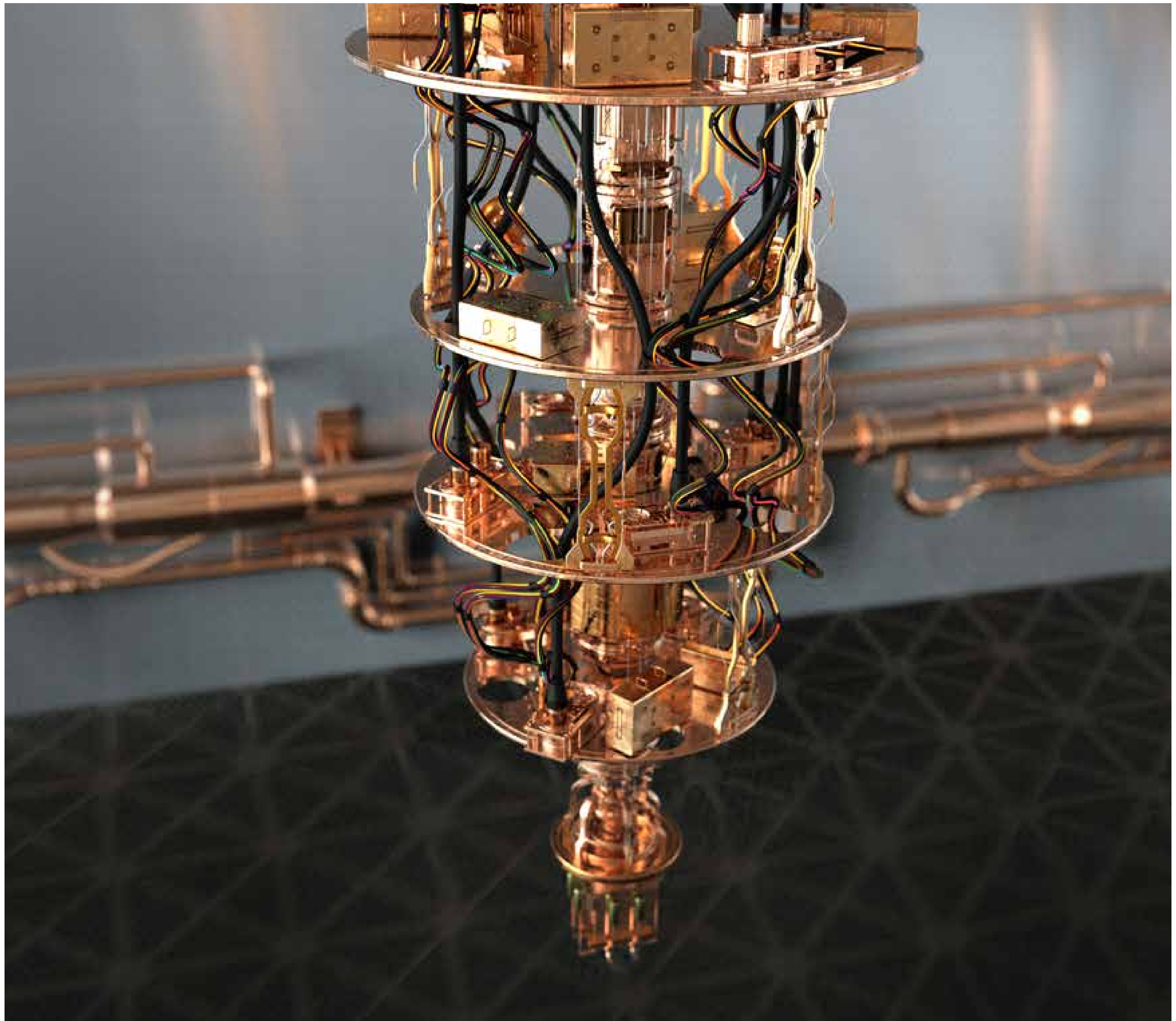
> "The Paragraf graphene Hall sensors are capable of measuring current density distribution within battery cells, accurately and reliably. They have enabled me to reinitiate the research in this domain, which I previously thought could not be achieved."
>
> Dr. Anup Barai – WMG,
> University of Warwick



Operation at Cryogenic Extremes

Paragraf continues to push performance boundaries with its graphene Hall Effect sensors. Oxford Instruments, a leading provider of high technology tools and systems for research and industry, has employed a modified version of the Paragraf GHS-C sensor device to carry out measurements at temperatures and magnetic field strengths far beyond the scope of any other sensing solution.

Tests show accurate operation can be sustained at mK temperature levels while simultaneously exposed to ultra-strong magnetic fields.



> “Conventional Hall sensors can suffer carrier freeze-out at mK temperatures and even if they could still function, their heat dissipation is much too high. Graphene sensors give us and our customers the opportunity, for the first time, to monitor high magnetic fields in-situ in ultra-low temperature experiments.”
>
> Benjamin Bryant, Senior Development Engineer
> Oxford Instruments

High Temperature Operation

Paragraf, together with Rolls-Royce, TT Electronics and the Compound Semiconductor Applications (CSA) Catapult, is helping to realise an industry first by implementing a supply chain for graphene Hall sensors used in high-temperature Power Electronics, Electric Machines and Drives (PEMD) within the aerospace sector.

The aim of the project is to demonstrate an integrated UK supply chain solution for advanced Hall sensing within PEMD, addressing the issues PEMDs experience when switching frequencies across a broad range of temperature conditions.

Hall Effect sensors play a major role in monitoring current levels and magnetic fields in PEMD applications, which is critical to monitoring drive power consumption and machine speed and position. The deployment of conventional silicon Hall sensors is, however, restricted to environments with temperatures below 150°C and frequencies below 100 kHz, which can constrain system level design.

This project aims to demonstrate that graphene-based Hall Effect sensors will operate reliably up to 180°C, and potentially even at temperatures of up to 230°C. This will allow them to be mounted within the machine or power module enclosure, enabling much greater flexibility in the design of new PEMD equipment.

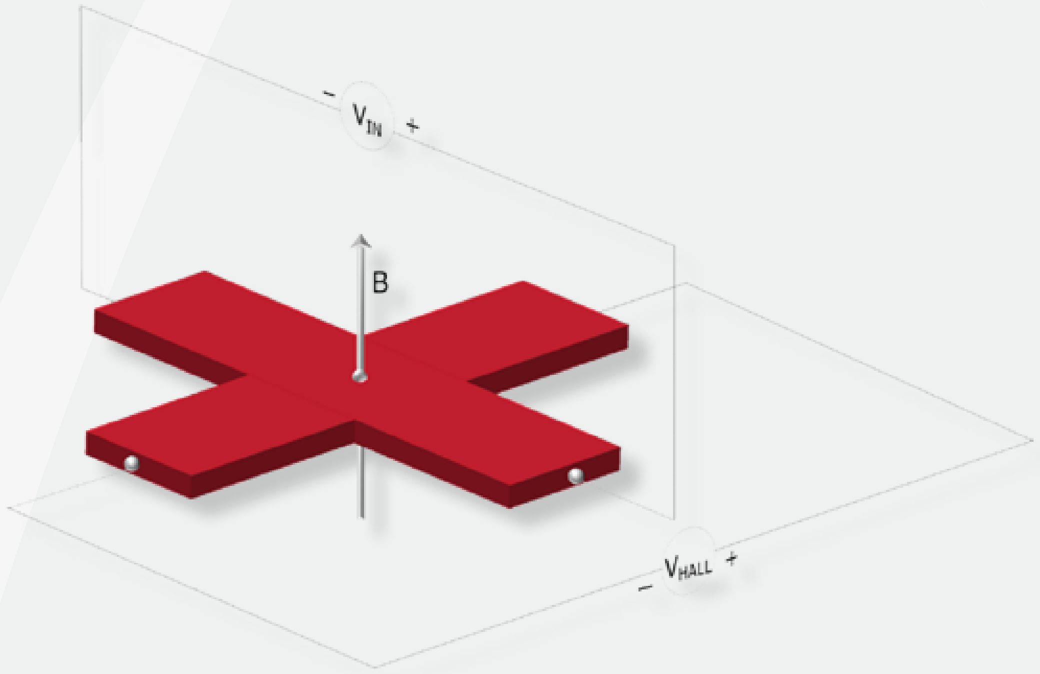
The ability to monitor current levels more accurately and reliably will enable better overall system control, which will in turn reduce size and weight and help design more efficient electric engine systems.

High Radiation Tolerance

Radiation testing has shown that the GHS graphene Hall sensors perform well when exposed to high levels of gamma and neutron radiation. This demonstrates that expensive radiation protection is not required for the operation of GHS sensors and has opened up a host of new applications in space technology, such as satellites and other machinery operating in space.

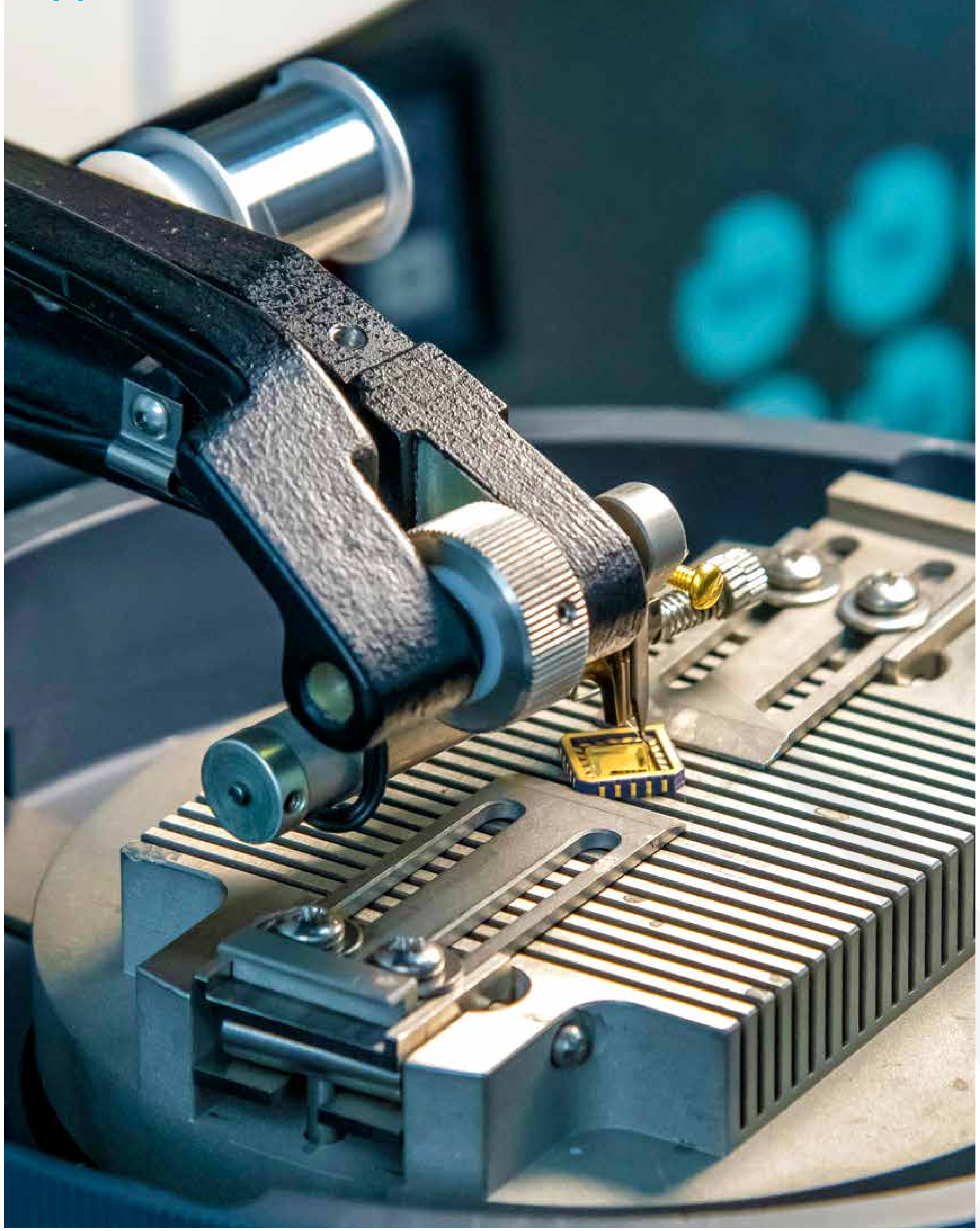
Lack of Planar Hall Effect

Graphene is well suited as a magnetic sensor due to its high carrier mobility and two dimensional nature, operating on the basis of the Hall effect (Hall sensors).



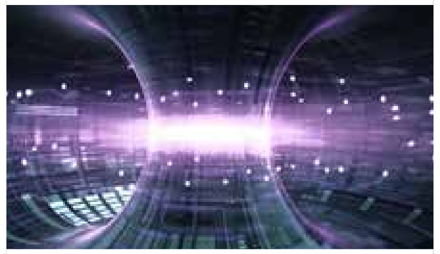
Benefit	Feature
High sensitivity	Low carrier concentration
Wide field measurement range	High sensitivity (amplification not required) Free of ferromagnetic materials (no hysteresis)
Robustness	Strength and resistance to thermal and electrical shock Radiation tolerance
Low noise	High carrier mobility
Low power consumption	High sensitivity/low drive current
Impervious to stray fields	Truly 2D sensing element (immunity to in-plane stray fields)
Ease of calibration	Repeatable linearity and temperature coefficient Simple polynomial fit for non-linearities

Industrial Applications



Position, rotation & torque sensing

Simplify sensing in magnetically complex environments, utilising the immunity to in-plane stray fields.



Fusion

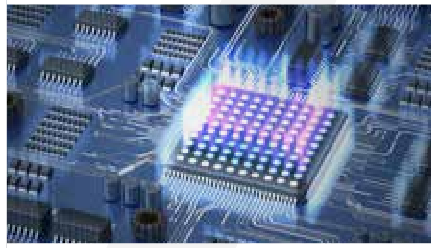
Measure and map fields (<30 T) and field gradients of high field superconducting magnets, used for plasma confinement.

Medical accelerators

Provide high resolution field strength feedback to magnet control circuits for in-line beam tuning.

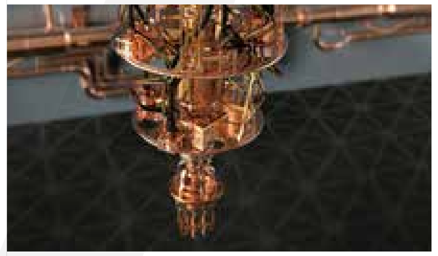
EV battery development

Non-destructively measure aging via current density mapping across battery cells. Perform non-contact/isolated current measurements at cell tabs and busbars to provide powerful insights into battery performance relative to design, age and condition.



Quantum computing

Measure field strength and vibration frequencies directly in the superconducting qubit space, to obtain better qubit stability and control.



Ultra-low temperature equipment & research

Measure exact field at cold finger/mK temperatures without introducing heat. Accurately measure field at research sample position whilst maintaining precise alignment to field vectors.

High energy physics labs

Map and calibrate accelerator magnets including cryogenic undulators and wigglers, to high resolution with no planar Hall effect.

Magnet manufacturing

Accurately calibrate electromagnet field strength vs current input. Map and shim electromagnets more efficiently using GHS maps instead of NMR mapping stages. Quickly characterise and sort/grade permanent magnets.

GHS-A Ambient Range

Advanced graphene Hall effect sensors ideal for magnetic field and current measurement in emerging industrial, battery, consumer, electric machines and e-mobility applications.

The graphene GHS-A Hall effect sensor is optimised for use in relatively low field environments and normal ambient temperatures.

Bringing the magnetic field measurement resolution towards that of more complex magnetic sensors, yet with the small size and ease of use of a Hall sensor, the 1D analogue GHS-A magnetic sensor can address monitoring tasks which conventional technologies simply cannot provide an effective solution for.

The GHS-A offers:

- High sensitivity
- Low noise
- Ultra-low power operation
- Immunity to in-plane stray fields
- No hysteresis & no saturation in output
- All-round robustness

Typical applications:

- Drive-by-wire sensing and feedback in e-mobility applications
- Battery R&D, production, reuse/recycling and battery management system (BMS)
- Electric motors and magnetic bearings feedback, control and development
- Industrial and medical robotics

Performing tasks such as:

- Position, rotation, speed and torque sensing
- Current sensing
- Current density mapping
- Magnetic field mapping and cross-calibration

The GHS-A is available with a number of accessories including a PCB accessory, socket, probe assemblies and the GHS Array Starter Kit. A datasheet is available on request.

> The electric revolution is underway and with it comes more demanding magnetic and current sensing challenges, to which the GHS-A can respond.

GHS-C Cryogenic Range

High resolution magnetic field measurements under operational extremes, far beyond the scope of any other sensing solution:

- Increase manufacturing throughput by quicker magnet mapping, replacing existing NMR probe mapping stages.
- Measure directly in cold bore – room temperature inserts not needed, allowing quicker collection of quality data.

Utilising the inherently high sensitivity of this two-dimensional material, the GHS-C range achieves outstanding resolution at cryogenic extremes, with the technology previously proven at mK, and verified for measurement up to 30T, with unique properties such as a negligible planar Hall effect and all-round robustness.

> Achieve high resolution over extremely large magnetic field ranges, in a small low-power package capable of operating at cryogenic temperatures.

More accurate characterisation of material properties at the extremes of temperature and magnetic fields.

- Achievement of the lowest possible base temperatures – the power consumption of the GHS-C is extremely low, keeping heat load at cold finger to a minimum.
- Small form factor when compared to standard fluxgates and NMR probes.
- The lack of planar Hall effect will also aid experiments where either vector fields are used or the sample must be rotated in the field to understand material properties. Lower noise allows cleaner high resolution data.

Applications include quantum computing, high energy physics labs, cryogenic cooling equipment, fusion, medical accelerators, ultra-low temperature research, and magnet manufacturing.

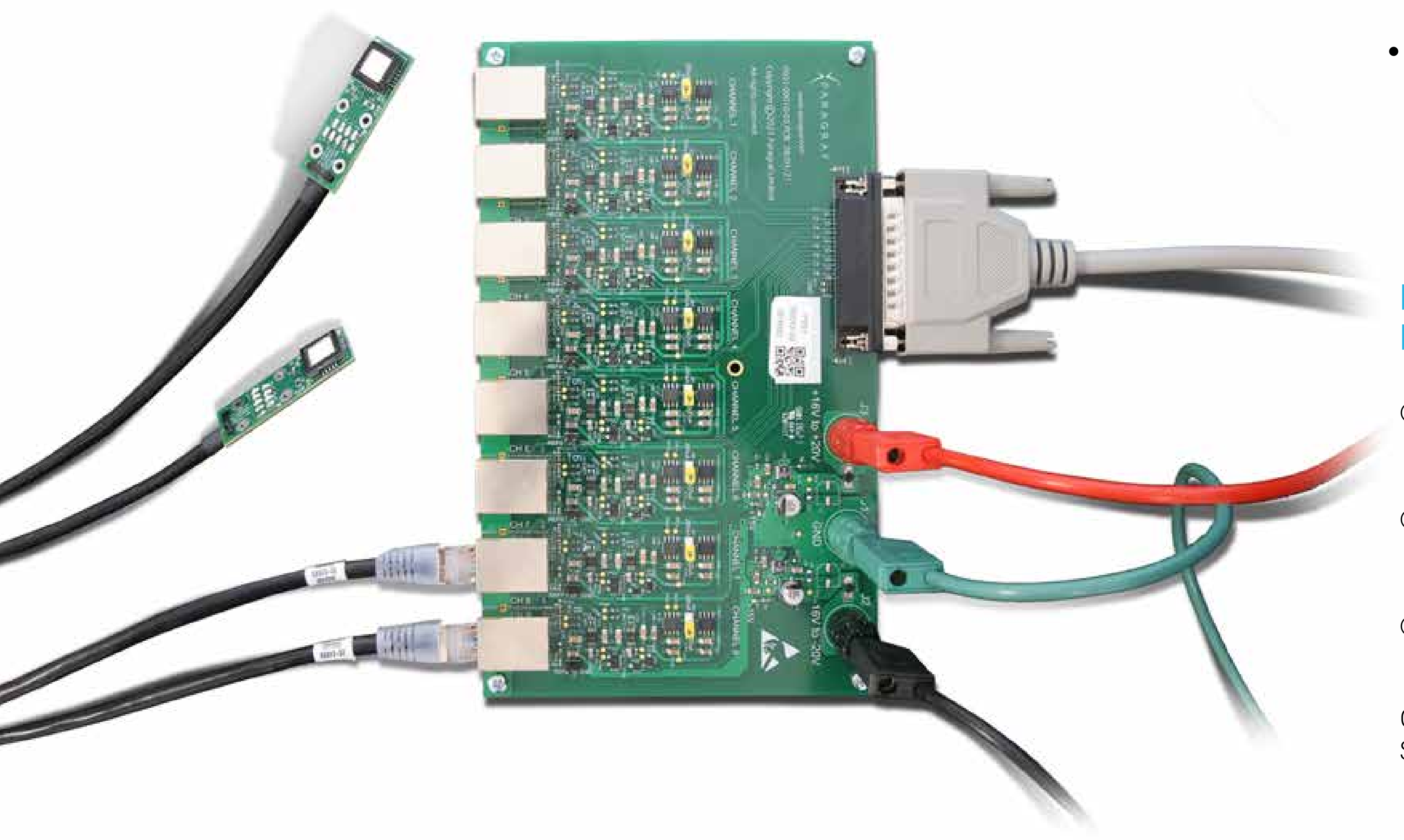
The GHS-C comes as standard with a cryogenic-rated socket for ease of implementation.

A compact board

enabling simultaneous measurements to be taken from up to eight GHS sensors

The GHS Array Starter Kit is a compact board, enabling simultaneous measurements to be taken from up to eight GHS sensors. Each sensor is attached to a probe with a 1.5 m serial interface cable and is accompanied by its own temperature sensor for simultaneous temperature monitoring and temperature correction of the magnetic measurement data.

This hardware is simple to integrate into existing data acquisition systems. It will help manufacturers through the initial stages, before they look to implement larger scale test rigs featuring greater numbers of GHS-A or GHS-C devices.



Battery analysis applications:

- **Real time current density mapping** – observe localised variations across the cell, over time, and during charge/discharge etc.
- **Failure mode analysis** – correlate hot spots to local changes in current density.
- **Mapping current flow direction** through a cell.
- **Monitoring leakage currents & fringe fields** at the current tabs.
- **Simultaneous localised monitoring of current tabs** during charge/discharge cycling.
- **Simultaneous monitoring of current flowing into individual cells** within a multi-cell pack.

Other applications:

- **Magnetic materials research** – multi-axis magnetic materials characterisation during stress testing.
- **Magnet sorting** – quick multi-axis characterisation and sorting of different magnet grades.
- **Electromagnet mapping** – real time field imaging and field gradient mapping of electromagnets.
- **Electric motors/bearings** – map and monitor rotor and stator fields, check for defects e.g. pinholes in winding insulation.
- **Non-destructive testing** – distributed measurements of metallic and magnetic parts for defect identification.

Product Range	Product Code	Description
GHS-C	AGHSCE1001	Cryogenic Extreme-Range 1D Graphene Hall Sensor
GHS-C	AGHSCM1001	Cryogenic Mid-Range 1D Graphene Hall Sensor
GHS-A	AGHSAM1101	Ambient Mid-Range 1D Graphene Hall Sensor
GHS Array Starter Kit	AGHSXXA001	GHS Array Starter Kit: interface PCB supporting simultaneous data collection up to 8 probes (not included)

About Us

Paragraf was formed in 2017, as a spin-out from the Department of Materials Science at Cambridge University.

At our custom R&D and production facility, we develop and deliver game-changing, commercial-quality, graphene electronic devices using contamination-free technology that is both scalable and compatible with existing electronic device manufacturing production processes.

With far-ranging applications including the semiconductor, green energy and sensor markets, we strive to revolutionise electronics by delivering graphene technologies to the world, creating a brighter, better future for everyone.

Paragraf currently employs more than 90 people, with representatives in Japan, South Korea, Taiwan and USA.

PARAGRAF
LEADING THE WAY
IN GRAPHENE ELECTRONICS

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