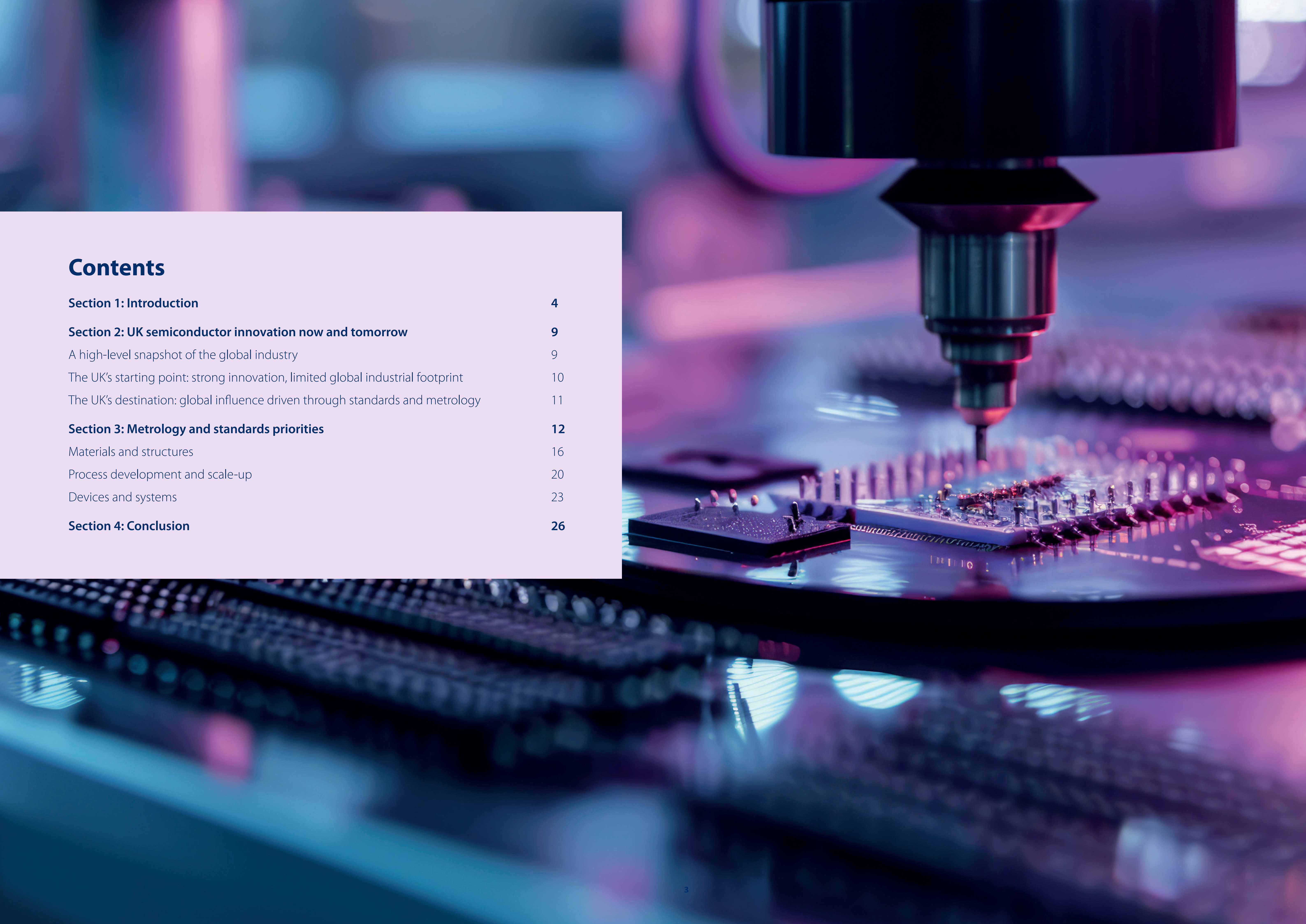
NPL
National Physical Laboratory

UK priorities in semiconductor metrology and standards to drive innovation and growth



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Section 1:
Introduction

The global semiconductor industry is undergoing a period of profound transition. For decades, progress was dominated by relentless miniaturisation. Today, that trajectory is being reshaped by multiple axes of innovation. This is being driven by a convergence of new materials, advanced device concepts, heterogeneous integration (the process of combining different materials or technologies within one system), and demand from transformative technologies such as artificial intelligence (AI), quantum technologies, electrification of transport and clean energy. As the sector diversifies, the basis of competitive advantage is a race for innovation in frontier processes, novel architectures and innovative materials that will form the foundation of emerging semiconductor platforms.

For the UK, this shift presents a significant opportunity. The country has recognised semiconductors as a strategic technology in the UK Science and Technology Framework and the Modern Industrial Strategy. The Government's Digital Technologies Sector Plan sets a clear ambition: by 2035 the UK will be one of the most attractive places in the world to create, invest in, and scale high-growth technology businesses. Achieving this requires more than excellence in basic science. It demands a strategic and joined-up approach to research and development (R&D), and an innovation ecosystem capable of rapid commercialisation, where new semiconductor technologies can move from laboratory prototypes to investable, manufacturable propositions.

This is where metrology and standards become pivotal. As the science of measurement, metrology is the quiet enabler of technological progress. It ensures that materials perform as intended, manufacturing processes are stable, and devices can be qualified, compared and trusted. Standards provide the shared language, test methods and quality frameworks. They are the connective tissue of supply chains, supporting interoperability, and accelerating market adoption. In a sector where fully-onshored supply chains are an impossibility, resilient supply chains will rely on strong international metrology and standards. The nations that determine what those standards are will shape the market.

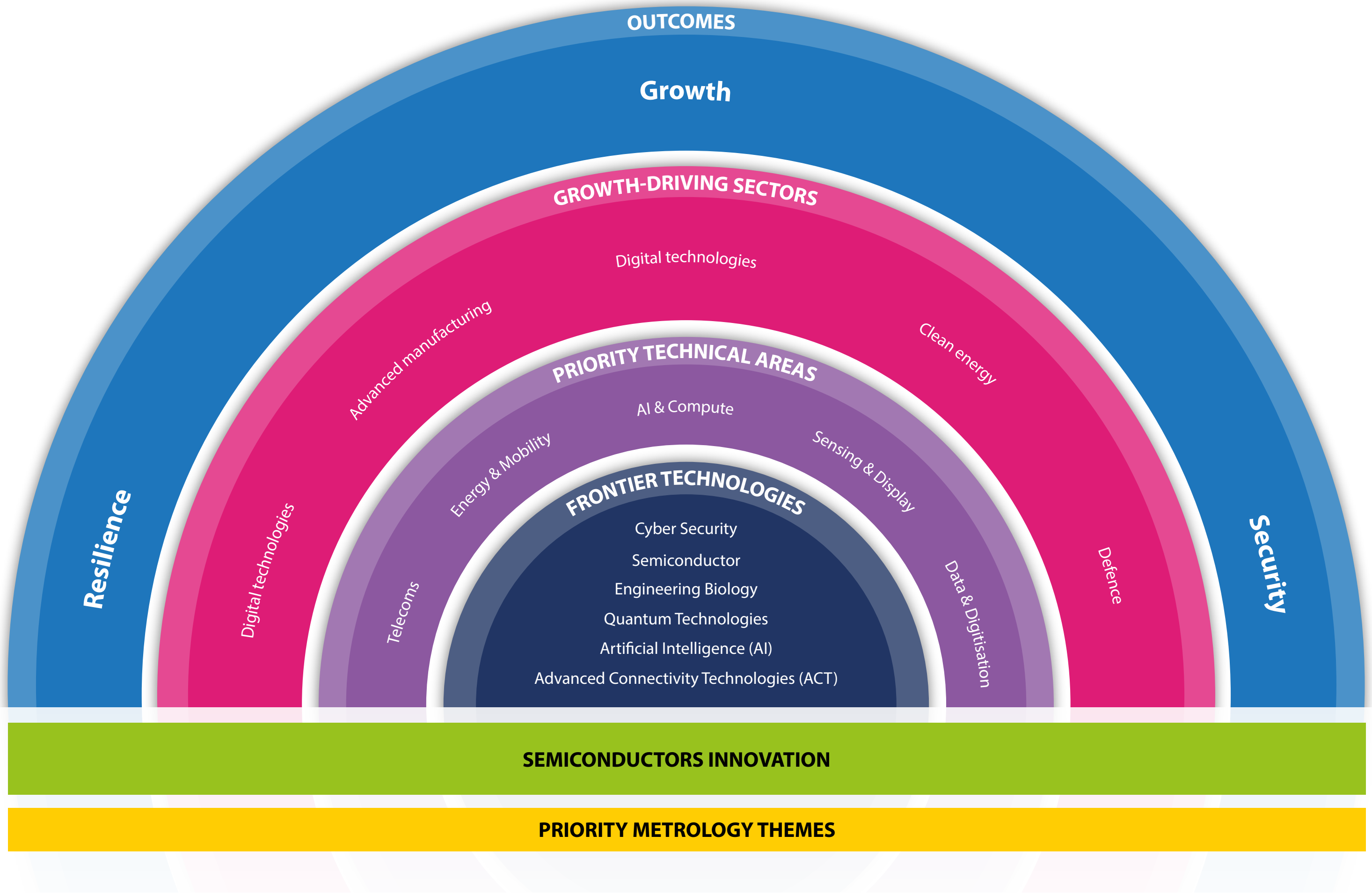


Figure 1: By enabling semiconductor innovation, metrology and standards actively contribute to the major drivers of UK prosperity

The UK's strengths in compound semiconductors (materials that combine two or more elements to achieve performance beyond silicon), advanced materials, photonics, design, modelling, and semiconductor tooling align with many of the essential aspects of semiconductor technology development driving global growth in this industry. Yet these strengths cannot translate into leadership without being connected by a coherent foundation of metrology and standards.

Like any new technology, emerging semiconductor innovation requires established measurement methods, reference materials and qualification standards (the agreed criteria for testing and approval). Without these, research efforts become difficult to compare, innovative companies face unnecessary technical risk and investors lack confidence. Crucially, the UK cannot restrict its involvement to nationally recognised standards alone. International standards are what enable access to global markets, so the country needs to draw on its unique heritage and strengths in building international consensus in these areas and lead their development for the next generation of semiconductor technology. By leading the definition and dissemination of new internationally recognised standards, the UK can secure influence that endures for decades.

The UK has an opportunity to shape the next generation of semiconductor technologies by innovating in high-demand areas faster than other countries and ensuring that its products can access global markets effectively. Both rely on metrology infrastructure and standardisation activity. This aligns directly with the intent of the Government's Modern Industrial Strategy to strengthen supply-chain resilience, bolster national security and drive economic growth.

The purpose of this report

This report articulates that opportunity and provides practical guidance on the progress in metrology and standards required to realise this ambition. It aims to trigger greater engagement and collaborative action from UK industry, government, academia and national laboratories to make that happen. It also sets the scene for a national dialogue on the semiconductor metrology and standards landscape as it exists today, the future position the UK should aspire to, and the specific metrology priorities that must be addressed to exert international leadership in emerging semiconductor platforms. This is a strategic examination of the metrology and standardisation activity required for positioning the UK to lead in the frontier areas where it already has world-class capability and where global markets are still forming.

By outlining clear, actionable priorities on metrology and standardisation activity, this report aims to support the UK in converting its scientific strengths into industrial advantage, enabling faster scale-up of innovative semiconductor technologies, deepening international collaboration, and reinforcing the UK's position as a trusted and influential partner in the global semiconductor ecosystem.

The findings and recommendations in this report are based on an extensive consultation process involving more than 500 experts in the sector, both in the UK and across key international players. It also considers, and builds upon, numerous studies on the UK semiconductor industry from the past few years, including: UK and Global Standards R&D Needed for Growth and Innovation in Emerging Semiconductors (National Physical Laboratory), UK Semiconductor Workforce Study (Perspective Economics), Semi35: A UK Strategy for Semiconductors (TechWorks), UK Plan for Chips (TechUK), The UK Semiconductor Industry: Current Landscape and Future Opportunities (Manufacturing Technology Centre), Semiconductor Industry in the UK (House of Commons Business and Trade Committee), Strategic Advantage through Science and Technology, and Exploring the UK Semiconductor Innovation System (Royal Academy of Engineering).

How metrology and measurement standards accelerate technology innovation and growth

Innovation across all technology domains depends fundamentally on the ability to measure, compare and trust performance. Whether developing advanced materials, new energy systems, manufacturing processes, medical devices, robotics, or digital technologies, progress stalls when organisations cannot agree on how results are generated or what they mean. Metrology and measurement standards form the common foundation that lets innovators prove their capabilities, allows supply chains to function efficiently, and gives new markets the confidence to emerge.

In many emerging technology fields, breakthroughs begin with a single laboratory creating a novel measurement technique or reporting exceptional performance. Yet without a reproducible way for others to verify these claims the innovation has limited value. Industry needs confidence that results obtained in one organisation can be replicated in another using methods that are transparent, reliable, and traceable. Without that trust, competing measurements between different organisations, or even multiple measurements from a single organisation, cannot be reconciled, performance claims cannot be validated, and risk increases across the ecosystem. This lack of trust is one of the most significant barriers to scaling new technologies.

Measurement standards address this challenge by defining how to measure critical properties and what constitutes meaningful evidence. They ensure that different organisations use comparable approaches, enabling robust evaluation of technologies, clarity for decision making and the ability to benchmark competing solutions.

By transforming bespoke research methods into widely accessible and agreed procedures, standards reduce technical uncertainty, accelerate commercial uptake and help innovators demonstrate their credibility to partners, regulators, investors and customers. They also underpin interoperability and quality assurance across supply chains, ensuring that components, materials, systems and services can work together safely and consistently.

This transformation from a one-off laboratory method to a robust, widely accepted standard requires dedicated measurement science. It involves improving reproducibility, validating test methods, establishing reference data or materials and building consensus among technical experts. Although this work can be complex and time-consuming, it reduces risk at every stage of the innovation pathway and shortens the journey from discovery to deployment.

As technologies become more interconnected and global competition intensifies, countries that lead in metrology and measurement standards gain a strategic advantage. They help shape how emerging technologies are evaluated, define the expectations for performance and safety, and ensure that their innovators can operate on a level playing field in international markets. Strengthening this foundation is essential for translating research excellence into economic impact, enhancing national resilience and enabling the UK to remain a responsible, trusted leader in the development of transformative technologies.

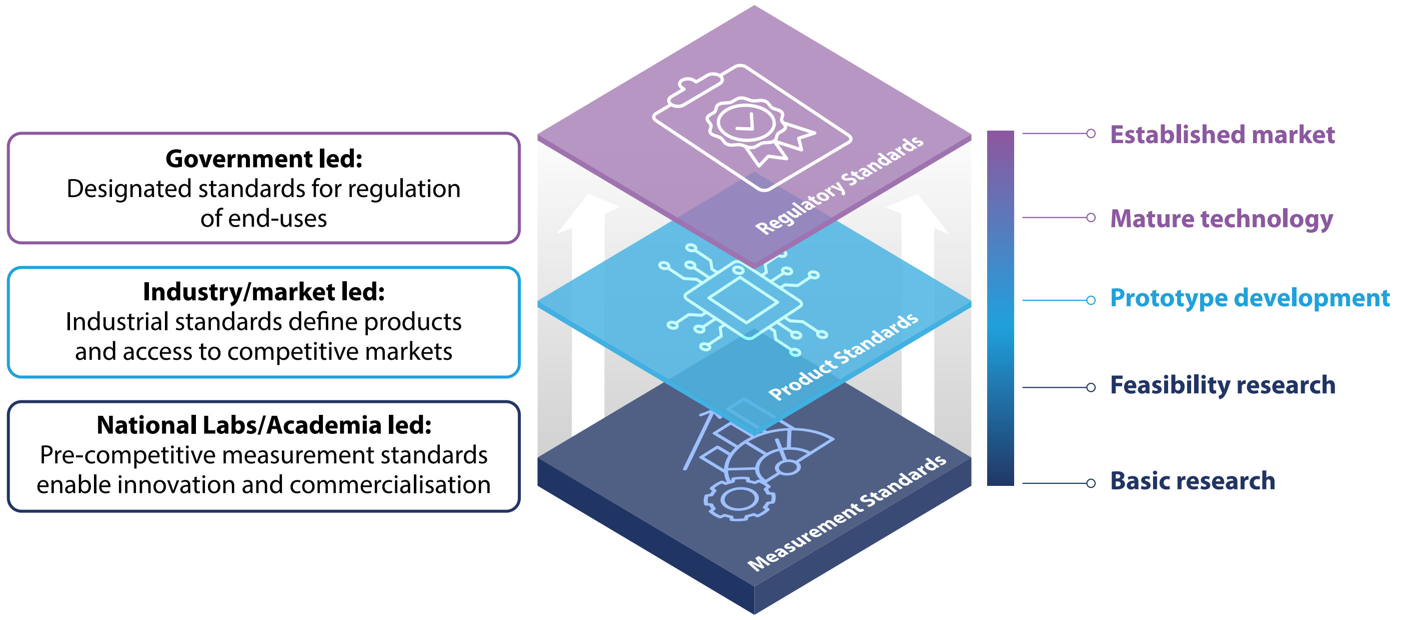
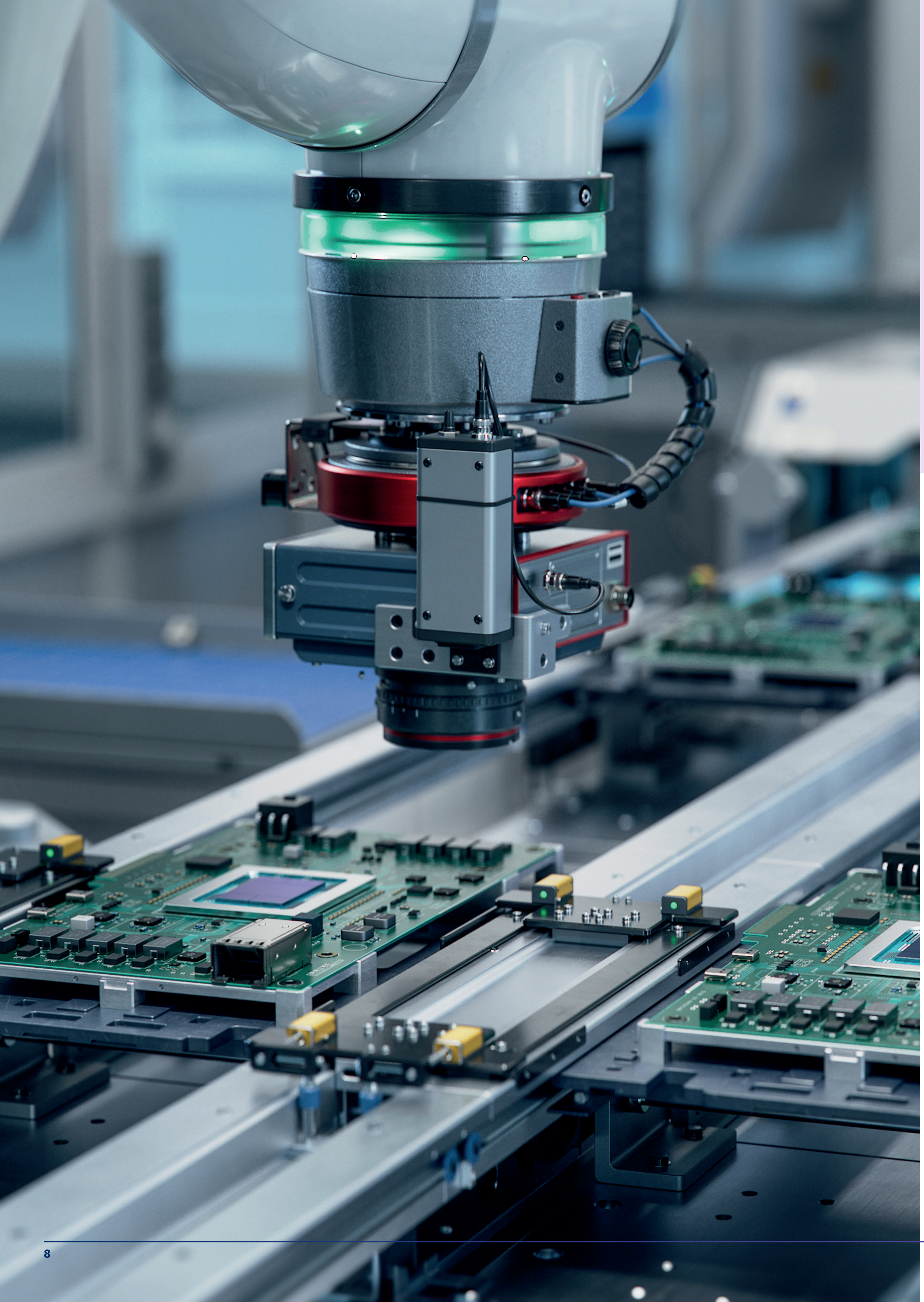


Figure 2: Measurement is the foundation of a system of standards that support semiconductor innovation move from research to products and applications



Section 2:
UK semiconductor innovation now and tomorrow

Understanding the UK's current place in the semiconductor world is a necessary prelude to any attempt at reshaping it. Only by setting out a clear destination can policymakers work out how to move from today's foothold to a stronger future, and what metrology and standardisation activities might speed the journey. The sensible approach is to look first at the global industry and its manufacturing system, then consider where the UK fits into both, and why that should change.

A high-level snapshot of the global industry

Multiple countries with deep industrial roots are active in semiconductor innovation today. Taiwan and South Korea dominate leading-edge silicon manufacturing (although the United States is now gaining significant ground in this area too), with TSMC and Samsung running the most advanced process nodes. Several countries have strengths in chip design, electronic design automation tools, equipment and intellectual property, including the UK, which hosts ARM – one of the leading intellectual property companies in the sector. The United States is also strong here, backed by the CHIPS and Science Act, which is changing investment incentives across research, talent and supply chains. Japan and the Netherlands supply vital materials, speciality chemicals and the lithography tools that make advanced chips possible. Japan is also targeting two-nanometre node silicon as part of its Rapidus initiative. The European Union is carving out a focus on automotive power devices and energy-efficient electronics, and Southeast Asia is well known for its strong activity in assembly, packaging and testing, but sees opportunities to move up the value chain towards the front-end and has been investing significantly in skills development and design. More than half of the world's fabrication facilities are based in China and Taiwan, and while other countries are increasing manufacturing capacity, developing skilled engineers with manufacturing expertise is a challenge. A recent study indicated that more than one million skilled workers are needed globally by 2030. China also dominates the supply chain for raw materials needed for semiconductor manufacture and has been investing heavily in increasing self-sufficiency from research and development (R&D) to equipment manufacture and design. Each region is therefore doubling down on the areas where it can influence emerging markets and strengthen resilience in an increasingly fraught geopolitical climate.

Beneath these interdependent regional pushes lies a mature and carefully choreographed manufacturing process that has advanced incrementally over decades. It begins with bare wafer manufacturing and front-end wafer fabrication, where chips take shape through iterative rounds of lithography, deposition, etch and polishing, each with nanometre precision. It finishes with back-end assembly and packaging, in which dies – individual tiny rectangular pieces cut from a processed silicon wafer, each containing a single integrated circuit – are linked and housed using everything from traditional wire bonding to cutting-edge heterogeneous integration (the process of combining multiple technologies into a single system). This highly standardised, globally integrated workflow remains the backbone of competitiveness for the countries that dominate advanced chip production. It also provides the starting point for emerging technologies, which will impose new requirements on the current system (Figure 3 here). That matters because it is precisely where the UK has an opportunity to engage.

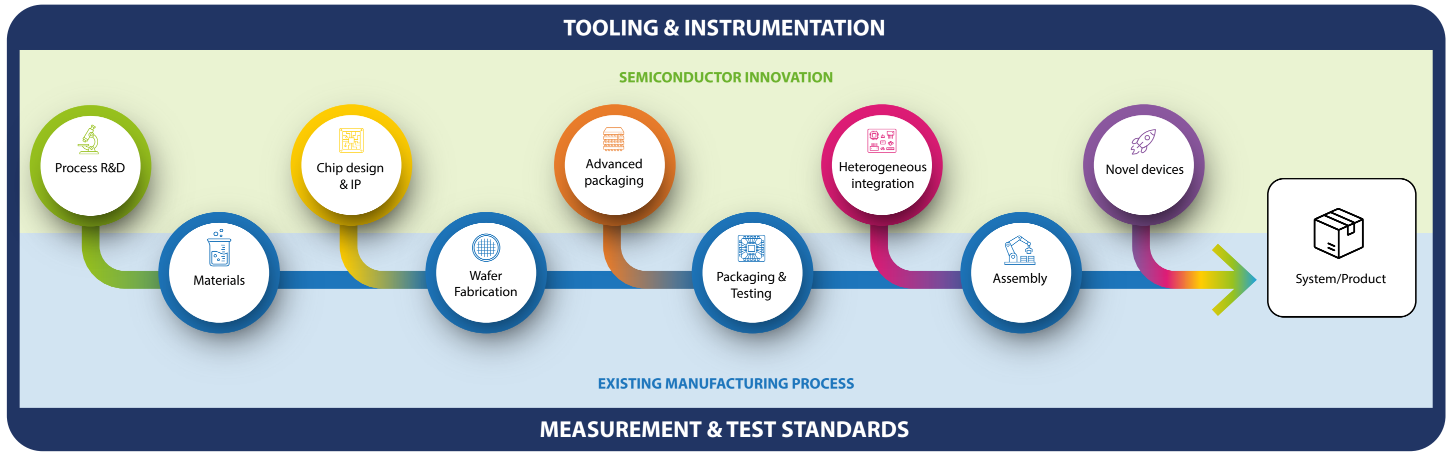


Figure 3: The UK has strengths in areas of semiconductor innovation that can drive value generation throughout the supply chain

The UK's starting point: strong innovation, limited global industrial footprint

In global terms, the United Kingdom is a small player in semiconductors. It boasts a strong heritage in chip design and is home to several end-user industries such as automotive and telecoms that are important for the wider semiconductor sector. But it has no leading-edge manufacturing, only a sliver of the world's wafer fabrication, and a modest packaging base. Its presence in the international standards bodies that shape market access and supply-chain interoperability has become thin, leaving it with limited influence over the rules that govern this critical industry.

The UK does, however, have two assets that offer a genuine opening for its semiconductor ambitions. The first is a research and development capability that consistently outperforms its size. Universities and laboratories excel in compound semiconductors (materials that combine two or more elements to achieve performance beyond silicon), materials science, quantum technologies, telecommunications, photonics and power electronics. This strength creates fertile ground for start-ups and spin-outs, where the UK has demonstrated remarkable proficiency, but it struggles to support them to scale and grow. Much of the country's expertise sits upstream of manufacturing and outside the standards forums and groups that determine how technologies enter global supply chains. As a result, the UK's technologies will struggle to secure adoption, investment, or export traction without tighter links between early innovation and industrial capability.

The second is the country's capability in compound semiconductor development, where the UK has built a quietly formidable position. Anchored by CSconnected in South Wales, generating £500 million in annual sales and thousands of skilled jobs, the UK commands end-to-end capabilities across power electronics, photonics and high-frequency RF, rooted in decades of academic leadership. The country's clusters in Wales, Scotland and the Southwest now host pioneering firms and research centres working with materials from gallium nitride (GaN) and gallium arsenide (GaAs) to silicon carbide (SiC) and indium phosphide (InP), giving the UK a rare depth across the supply chain. This spans epitaxy, a process that lets engineers create ultra-pure, precisely engineered semiconductor layers with tailored electrical or optical properties, to device design, advanced packaging and integration. This ecosystem, supported by national facilities, has positioned the UK as a global hub for emerging technologies that are essential for the growth of 5G, AI hardware, electric vehicles, and next-generation photonics.

Both these assets will benefit considerably from the UK's longstanding authority in metrology and standards. National laboratories have spent more than a century providing trusted measurement science, reference data and calibration services across sectors from aerospace to telecoms and quantum systems. The UK has also helped shape the International System of Units and holds influential roles in international standards committees, giving it a reputation for technical rigour and scientific excellence. This heritage offers the UK a way to convert its experience into global leadership if it chooses to deploy it strategically.

It is an important time to be able to do exactly that because new semiconductor technologies are advancing far faster than the standards that govern how they are made, tested and integrated. Mature silicon platforms rest on decades of recognised practice and widely adopted specifications.

Novel materials and device architectures, by contrast, often arrive without agreed performance metrics, standard test methods, or even consistent terminology. Countries that participate early and actively in developing the metrology and standards to fill this gap can anchor their technologies in emerging markets, shape the vocabulary, and develop the test methods and performance metrics through which their accelerated innovation and growth are recognised. Those that do not risk being sidelined, regardless of how strong their underlying science may be. The UK has a chance to place itself firmly in the first group and stand with the countries that define these standards, not the ones that must adapt to them.

The UK's destination: global influence driven through standards and metrology

The UK Government's Digital and Technologies Sector Plan provides a vision of the desired destination for the UK's role in semiconductor innovation. It calls for a strategic and joined-up approach to R&D, enhanced commercialisation pathways and a focus on technologies with high-growth potential and cross-sector application. It highlights the need to strengthen semiconductor supply-chain resilience, support national security priorities and collaborate internationally as a reliable, trusted partner in the global semiconductor ecosystem.

This vision aligns directly with, and relies significantly upon, a metrology- and standards-led approach. As global markets expand to incorporate a broader range of semiconductor technologies, countries that can provide authoritative measurement science, pre-standards research and leadership in the development of international standards will have the ability to shape new markets rather than merely participate in them.

The UK is therefore at a pivotal moment. While it is no longer a manufacturing superpower, it has distinct scientific strengths and an ambition to lead in emerging technology domains. Realising this ambition requires a deliberate, coordinated approach to metrology, standardisation and capability development that positions the UK as an indispensable contributor to the next generation of semiconductor innovation.

The remainder of this report outlines the metrology priorities required to enable this transition and identifies the actions needed to move the UK from its current starting point towards a position of influence and leadership in global semiconductor standards and innovation.

Section 3:
Metrology priorities

The following section sets out twelve metrology and standards priorities that have been identified through consultation with the UK semiconductor community. These are critical enablers for realising the UK's opportunity to play a leadership role in next-generation semiconductors. Each priority highlights a distinct metrology or standards capability gap that must be addressed. The structure mirrors the lifecycle of semiconductor innovation:

- **Materials and structures**
- **Process development and scale-up**
- **Devices and systems performance**

It outlines why each capability matters, the research required to deliver it and the feasibility of doing so. Taken together, these priorities form a practical guide for coordinated action across industry, academia and national laboratories, ensuring that the UK can secure influence in the evolving global semiconductor landscape.

MATERIALS AND STRUCTURE		
PRIORITY	**OVERVIEW**	**RECOMMENDATIONS**
Material property measurement	Emerging semiconductor and process materials lack reliable, traceable data for key physical, chemical and structural properties, creating uncertainty in design, simulation and fabrication and limiting the confidence needed to scale novel materials into manufacturable devices.	Develop authoritative, traceable measurement methods, reference materials and shared datasets, coordinating universities, national laboratories and industry to translate research techniques into pre-standards and internationally recognised standards that support consistent modelling, qualification and supply chain integration.
Material quality metrics	New materials entering high-value manufacturing require agreed definitions of quality, including uniformity, defect density and interface integrity, yet these metrics remain inconsistent, hindering supplier comparison, slowing adoption and weakening the UK's early advantage in advanced material supply chains.	Establish common quality metrics, good-practice guides and standards through whole supply-chain engagement, supported by interlaboratory studies, training and dissemination, so material performance can be benchmarked consistently and scaled confidently into global markets.
Defect metrology and classification	Material and structural defects increasingly determine device yield and reliability, but novel materials introduce unfamiliar defect types that lack standardised detection, classification and performance relevance, limiting manufacturers' ability to prioritise improvements and control processes effectively.	Develop non-destructive, wafer-scale inspection tools, standard defect taxonomies and shared algorithms, integrating multimodal techniques to relate defects to device outcomes and enabling consistent comparison across laboratories and production lines.
Metrology for complex 3D structures	Three-dimensional and non-planar device architectures require measurement of buried features and complex geometries that cannot be characterised using conventional planar techniques, creating uncertainty in process control and limiting confidence in performance and reliability.	Create high-resolution, non-destructive subsurface metrology, supported by modelling, advanced sensing and environmental control, and develop pre-competitive standards and reference structures that link 3D properties directly to device functionality.

PROCESS DEVELOPMENT AND SCALE UP		
PRIORITY	OVERVIEW	RECOMMENDATIONS
Defining manufacturing sustainability metrics	Semiconductor production consumes significant energy, water and critical materials, yet the industry lacks consistent, traceable metrics to quantify environmental impact across manufacturing, use and end of life, making sustainability targets difficult to measure or compare.	Define lifecycle metrics and measurement standards, establish validated test beds and digital tracking approaches, and coordinate policy, standards bodies and industry to enable benchmarking, reporting and adoption of lower-impact processes and circular-economy practices.
Process metrology and in-line inspection	Increasingly complex processes demand faster, more sensitive in-line measurements to control variability and maintain yield, but inconsistent methods and limited traceability reduce confidence in production data and restrict effective real-time decision-making.	Define standard process-control metrics, expand in-line sensing and modelling capability, transfer best practice from mature manufacturing sectors and provide training to embed statistically robust, traceable measurement throughout fabrication and assembly.
Confidence in complex data flows and AI analysis	Advanced inspection generates vast data volumes increasingly analysed using AI, yet inconsistent calibration, formats and uncertainty frameworks undermine trust in results and limit the reliability of digital twins and automated process optimisation.	Establish traceability, interoperable data standards and uncertainty models, enabling consistent data fusion and validation so AI-driven insights and predictive tools can be confidently deployed in production environments.
Heterogeneous integration standards	Chiplets and multi-material assemblies depend on reliable interfaces, bonding and interconnects, but the absence of agreed compatibility metrics and measurement approaches constrains manufacturability and risks fragmentation of emerging packaging ecosystems.	Define shared interface metrics, develop non-destructive characterisation of buried structures and create early standards through international collaboration, supported by reference materials and interlaboratory comparisons to enable scalable heterogeneous integration.

DEVICES AND SYSTEMS		
PRIORITY	OVERVIEW	RECOMMENDATIONS
Hardware security standards	As semiconductor supply chains globalise, assurance of device authenticity and protection against tampering becomes critical, yet there are few standardised, measurable methods to verify provenance, integrity or resilience to physical and functional attacks.	Develop test methods, secure identifiers and conformity assessment infrastructure, combining design analysis and physical inspection, and ensure nationally accessible facilities so robust security standards can be applied across companies of all sizes.
Next generation device performance testing	Devices operating at extreme voltages, temperatures, frequencies and spectral ranges require new performance metrics and test methods, as existing standards do not adequately characterise behaviour in demanding applications such as power, photonic or quantum systems.	Build national measurement capability, calibrated sources and traceable procedures for these regimes, working with industry to define relevant metrics and develop standards that enable reliable qualification and comparison of next-generation devices.
Package performance testing	Advanced packaging strongly influences thermal, electrical and mechanical performance, yet suitable measurement methods for stresses, parasitics and environmental effects in complex assemblies remain limited, constraining reliable qualification of novel system-level designs.	Develop non-destructive test methods, models and reference datasets that reflect real operating conditions, enabling consistent evaluation of packaging performance and supporting early standards for advanced integration technologies.
Device reliability standards	Reliability is critical across all applications, especially safety-critical systems, but wide-bandgap and high-performance devices exhibit new failure mechanisms not addressed by legacy silicon tests, creating uncertainty in lifetime prediction and qualification.	Develop accelerated ageing methods and internationally aligned reliability standards focused on packaged-device behaviour, coordinating UK laboratories, Catapults and industry to generate evidence, shape consensus and support confident adoption of compound semiconductors.

Materials and structures

1. Material property measurements

The semiconductor industry depends on an accurate understanding of material properties. As the sector moves beyond conventional silicon, a growing range of new materials is entering device design and manufacturing, including two-dimensional materials, compound semiconductors, organic and hybrid systems, and dielectrics. Across all these material classes, progress depends on the ability to measure their fundamental properties, including optical constants, electrical and thermal conductivity, mechanical properties, chemical composition and crystal structure. For advanced materials, these characteristics are difficult to measure reliably, yet they form essential inputs into design and simulation tools, which are now central to process development and yield optimisation. Today, many of these properties are poorly known and measurement approaches are inconsistent.

A specific area of need is emerging semiconductor materials with complex compositions, for example where the implantation, distribution, and activation of various dopants creates a very large parameter space for physical property measurements. The resulting uncertainty undermines modelling accuracy, limits reproducibility and increases risk when scaling from laboratory research to manufacturing. Establishing authoritative, traceable measurement methods for material properties across emerging semiconductor and process materials would therefore provide direct support for innovation across the UK ecosystem.

This challenge aligns closely with the UK's strengths in materials research and applied metrology. In many cases the underlying science is well understood. However, new materials demand adaptation of existing methods, development of new approaches and the establishment of standard reference samples.

By enabling close collaboration between universities, national laboratories and industry in pre-standards research to define priority parameters and translate them into formal standards, as well as creating an open-access database of reference values, the UK can reduce uncertainty at the earliest stages of semiconductor innovation and strengthen the foundations of its future manufacturing capability.

2. Material quality metrics

Material property measurements alone are not sufficient. As advanced materials move from laboratory research to application, the lack of agreed metrics for material quality for those applications, standardised internationally, threatens to slow commercial progress. Several of these materials are already entering UK supply chains, giving the UK a narrow window in which to define the quality-control frameworks that will shape emerging global markets before competitors in the United States and Asia consolidate their positions.

Doing so requires authoritative standards for issues such as layer uniformity, defect density and interface properties. These must be supported by robust measurement methods that can be applied consistently across suppliers and customers. Industry demands range from single-layer characterisation to the development of reliable electrical contacts and the ability to assess interfaces. Progress will depend on closer involvement from the full supply chain, including a detailed understanding of how material parameters relate to end-use demands.

The UK needs to start by identifying the most critical end uses and then work backwards to determine where each supply chain demands quality metrics. These can then be translated into good-practice guides, community standards and formal international standards. Some uses are close to market, others remain speculative. But by moving early, the UK can shape the measurement standards that sit at the heart of emerging semiconductor materials.

Example of impact:

Standards enable confidence and commercialisation in 2D materials

Two-dimensional (2D) materials such as graphene and molybdenum disulfide (MoS_2) offer significant potential for next-generation electronics, sensing and energy storage. However, early industrial adoption was hindered by inconsistent terminology and a lack of agreed, non-destructive methods for assessing material quality. Variations in defect density, layer thickness and flake size made results difficult to compare, increasing technical risk for manufacturers and investors.

NPL addressed this gap through pre-standards research with the University of Manchester and industry partners, developing reproducible measurement protocols and quality metrics for real-world 2D materials. This work underpinned the first ISO standards for graphene terminology and characterisation, alongside practical guidance and measurement services that enabled consistent benchmarking across the supply chain.

Building on this foundation, NPL established methods to quantify defects in MoS_2, providing a rapid, non-destructive method for monitoring material quality during the very early stages of semiconductor manufacturing. Several UK companies have now adopted these approaches to optimise growth processes, validate product quality and support commercial sales.

By providing trusted, standards-based measurement, this work has reduced uncertainty, strengthened supply-chain confidence and accelerated investment and commercialisation in the UK's emerging 2D materials sector.

3. Defect metrology and classification

New materials introduce new types of defects that require robust characterisation, classification and metrology. It is not sufficient simply to detect these defects; their relative impact on device performance must be understood, as not all defects are equally critical. The silicon industry has established defect taxonomies and inspection methods. But novel materials, engineered wafers and heterogeneously integrated structures introduce new defect types that are not captured by existing classifications and lack suitable measurement techniques. There are already tools widely used in production to help address this, but they need to be adapted, and new ones developed, to meet the sensitivity, throughput and compatibility needs of new materials.

Addressing this will require fundamental advances in non-destructive analysis for advanced semiconductor materials, including optical, electrical, and X-ray techniques, along with standardised measurement protocols and consistent standards for data processing and defect classification. Multimodal and hybrid metrology, alongside better understanding of instrument-sample interactions, are also important routes to progress.

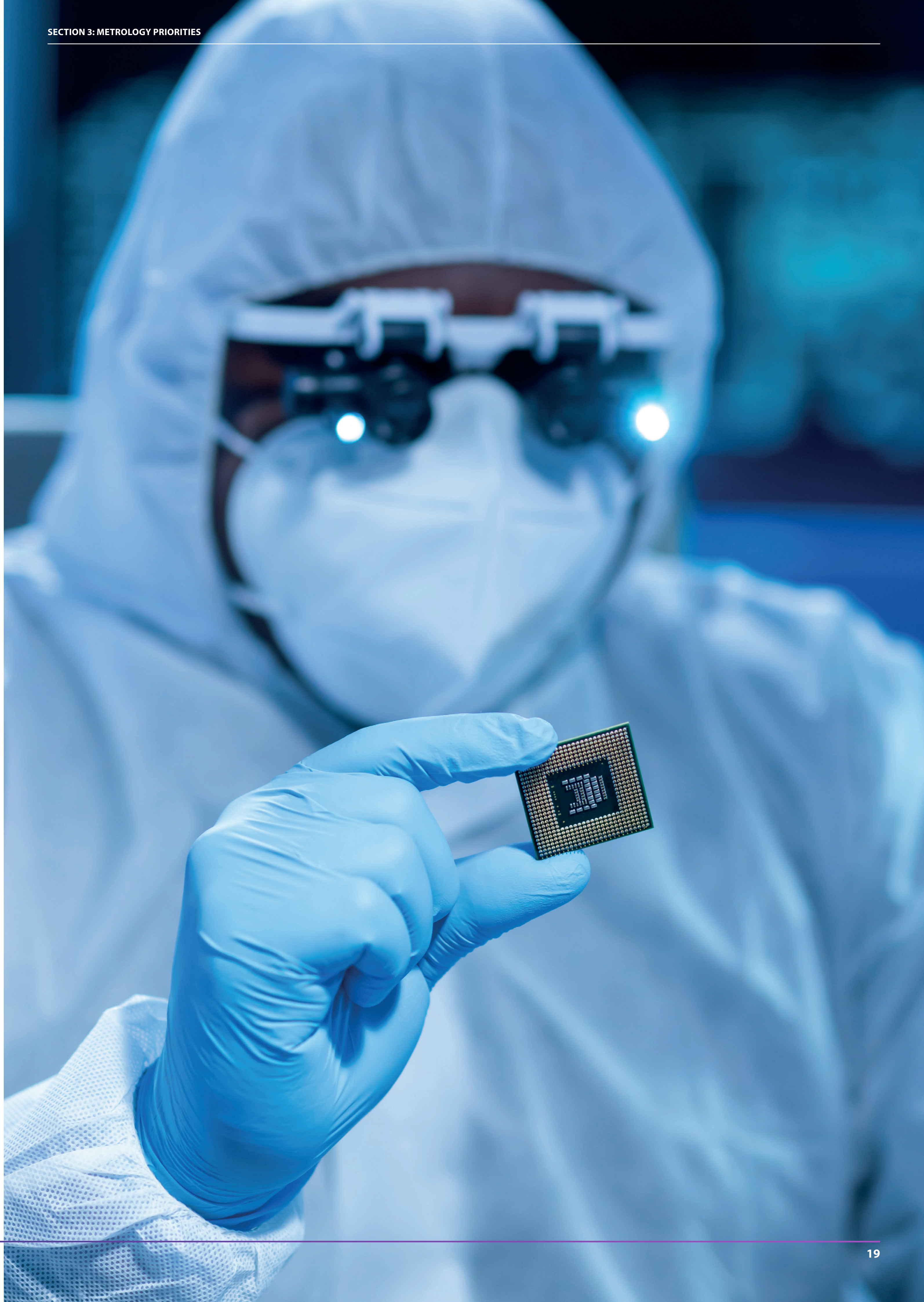
Creating entirely new wafer-scale capability is ambitious, but even incremental progress would yield substantial benefits, including improved process control and more efficient integration of existing inspection technologies. If the UK can combine the experience and knowledge of equipment makers, fabricators and research institutions, alongside smaller innovators, it will be able to build a coherent roadmap and drive the development of common standards and algorithms for defect identification, classification and analysis. Getting this right would put the UK in a stronger position to understand and manage defects in next-generation materials, which will be an essential component of competitive innovation for future semiconductor manufacturing.

4. Metrology for complex 3D structures

As semiconductor architectures continue to miniaturise, smaller silicon nodes require stacked and highly intricate three-dimensional structures. While the UK has no manufacturing capability in advanced silicon nodes, many of the same considerations apply in areas of compound semiconductor innovation in this country. Confidence in device performance increasingly hinges on understanding subsurface features, non-planar interfaces and multi-parameter variations that influence behaviour. These structures demand non-destructive testing methods at nanometre resolution, novel sensing approaches and data-handling techniques capable of linking three-dimensional physical properties directly to optical, thermal and electrical performance.

The UK already has many of the building blocks for this across academia, national laboratories and industry. Our strengths in chip design, multi-scale modelling and advanced sensing mean we can assemble multidisciplinary teams needed to close the gaps. There is also a significant production volume of power-electronic and optoelectronic devices that rely on complex 3D structures, making them a natural focus for UK capability. In addition, the UK has a strong base of tool and instrumentation companies whose equipment is used in advanced fabrication facilities worldwide, and whose growth depends on access to leading-edge metrology.

Together, these strengths mean the UK can play a meaningful role in developing pre-competitive metrology and standards for 3D structures, even without domestic leading-edge CMOS fabrication. Progress will require research into new metrologies, including (but not limited to) advanced optical methods, ion and electron beam microscopy, scanning probe measurements, environmental control for ultra-sensitive measurements and modelling tools to interpret physical testing. There is a significant opportunity for the UK to define the measurement specifications and coordinate early-stage standards work, while commercial organisations develop and deploy the technologies themselves.



Process development and scale-up

5. Defining manufacturing sustainability metrics

As energy use, raw material scarcity, and chemical-intensive processing climb the agenda, the semiconductor industry is under mounting pressure to account for its environmental footprint. This pressure comes not only from political or cultural shifts, but also from cost and regulation, particularly given the high energy and water consumption of semiconductor manufacturing.

Although the industry is exploring PFAS (per- and polyfluoroalkyl substances) alternatives and methods of reducing water consumption, the absence of consistent metrics makes it difficult for firms to benchmark performance or understand the true impact of their devices, from manufacturing to end of life.

Establishing credible measurement standards for manufacturing sustainability would allow companies to compare processes, trace critical materials, validate emissions data, and demonstrate progress to regulators and investors.

This requires validated test beds and traceable provenance for both materials and components used in manufacturing processes. If the UK moves early to define these metrics and build associated inspection and data-validation tools, it could export solutions overseas as demand for transparent sustainability reporting increases. The European Union's expected legislation to control market access based on sustainability will only increase this demand.

Delivering this work calls for research in data analytics, re-tooled testing environments and new processes and materials designed with sustainability in mind. This relies on ensuring that emerging sustainability metrics are robustly validated and internationally recognised. With consistent policy support and international collaboration, this work can help steer the industry towards a more sustainable, and eventually net-zero, future, enhancing profitability and stimulating UK growth.

6. Process metrology and in-line inspection

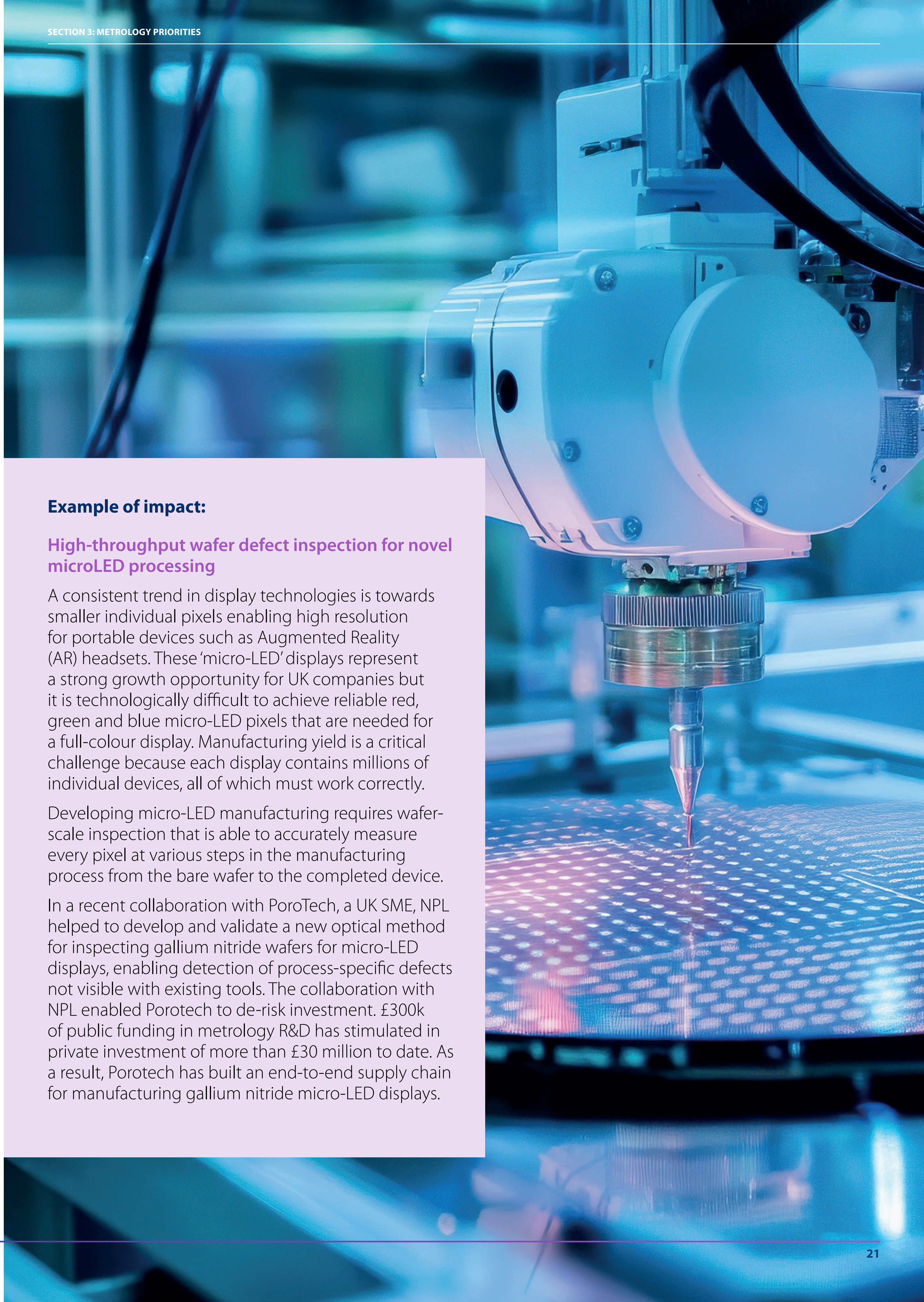
As semiconductor manufacturing grows more complex, the industry's ability to assess and control processes in real time has become crucial. Advanced lithography, etching, deposition, implantation and heterogeneous integration processes now demand faster, more sensitive in-line measurements, coupled with rigorous modelling and simulation, to maintain yield while improving device performance. The long-term goal is to create new metrology tools that offer reliable and traceable data and can be used within the manufacturing process.

This is important because process window excursions can be expensive, so quickly detecting them and identifying the cause is essential. Inspection tools exist in the semiconductor industry today, but new ones need to be developed to extend this capability into new materials and processes as both become more prevalent in the sector.

The UK can draw on its strong experience in other sectors with similar quality-control cultures, such as aerospace or pharmaceuticals, translating what it knows from these industries into applications in semiconductor process environments.

Research is needed on chiplet-level characterisation, identification of variability sources, multi-scale modelling, and new in-line methods compatible with advanced production flows. Industry will also need ways to monitor new tools used for these purposes to deliver successful outcomes.

Delivering the above requires insight into the metrology demands of any new manufacturing processes and ensuring standards and training keep pace with industry needs. Even incremental improvements in process control can deliver economic benefits through higher yields and longer tool lifetimes, so this is a considerable opportunity to exploit.



Example of impact:

High-throughput wafer defect inspection for novel microLED processing

A consistent trend in display technologies is towards smaller individual pixels enabling high resolution for portable devices such as Augmented Reality (AR) headsets. These 'micro-LED' displays represent a strong growth opportunity for UK companies but it is technologically difficult to achieve reliable red, green and blue micro-LED pixels that are needed for a full-colour display. Manufacturing yield is a critical challenge because each display contains millions of individual devices, all of which must work correctly.

Developing micro-LED manufacturing requires wafer-scale inspection that is able to accurately measure every pixel at various steps in the manufacturing process from the bare wafer to the completed device.

In a recent collaboration with PoroTech, a UK SME, NPL helped to develop and validate a new optical method for inspecting gallium nitride wafers for micro-LED displays, enabling detection of process-specific defects not visible with existing tools. The collaboration with NPL enabled Porotech to de-risk investment. £300k of public funding in metrology R&D has stimulated in private investment of more than £30 million to date. As a result, Porotech has built an end-to-end supply chain for manufacturing gallium nitride micro-LED displays.

7. Confidence in complex data flows and AI analysis

The in-line inspection and real-time process monitoring described above generates large amounts of data that can be used to improve process control and enable earlier detection of material and process defects. AI has an important role to play in processing this data to produce actionable insights, yet the value of these insights depends entirely on trust. Without agreed methods for analysing the data and confidence in the systems acquiring and processing it, manufacturers cannot make meaningful comparisons between different tools, materials, process outcomes, or suppliers.

The long-term ambition is high-speed, nanometre-resolution in-line analysis supported by the introduction of virtual metrology and digital twins, where the manufacturing process is simulated and provides live monitoring of tool conditions and overall process performance. Achieving this ambition will require agreement across the community on ensuring traceability, calibration, and data accuracy.

Progress depends on advances in multi-scale and multimodal modelling. This must consider the quality of the data sources that feed those models and how uncertainty is propagated throughout. The UK should be using its heritage in both metrology and tool and instrument manufacturing to promote progress on the standardisation of data formats for interoperable tools, laying the groundwork for future international standards in this area. To move at scale, coordinated industry-academic funding is essential, along with a clear business case that links early defect insight to yield gains and supply-chain confidence.

8. Heterogeneous integration standards

As semiconductor architectures advance from monolithic scaling to the assembly of chiplets, stacked dies, and multi-material device platforms, the industry is beginning to outpace its existing metrology playbook. Heterogeneous integration depends on tightly controlled interfaces between dissimilar materials, yet today there are few agreed metrics for interface compatibility, bonding quality, or operational reliability for these complex assemblies. This gap is becoming a strategic bottleneck, constraining industrial capability because of the lack of validated methods for characterising interfaces, stresses and failure modes across these assemblies.

The metrology need is therefore twofold:

- to define common interface metrics that allow designers, fabricators and packaging houses to understand whether materials are compatible
- to develop high-resolution, non-destructive measurement methods capable of interrogating complex heterogeneously integrated structures, including buried interfaces, thin interlayers, vias and micro-bump interconnects

The UK has world-class expertise in compound semiconductors, photonic integration and advanced device modelling, but without standards that articulate interface requirements and define acceptable process windows, this innovation cannot translate into manufacturable systems at scale. The UK risks missing the opportunity to project its technology leadership, from both established enterprises and small and medium enterprises, onto international markets. Realising this opportunity will require coordination to establish the best solutions for heterogeneous integration and to standardise them.

Although the technical challenges are significant, the underlying scientific capabilities already exist within national laboratories and leading universities. Realising this potential will require UK companies to work collectively with them to develop shared standards, recognising that achieving international consensus may be more difficult. Heterogeneous integration is likely to be a contested area, with different regions promoting their own approaches. Early engagement through pre-standardisation international collaborations will therefore be essential to build alignment and avoid fragmentation.

Devices and systems

9. Hardware security standards

As semiconductor supply chains become more dispersed, verifying that devices are authentic, unaltered and free from accidental or engineered-in vulnerabilities in the original design is becoming a significant technical challenge. Hardware security depends on the ability to detect counterfeits, identify malicious modifications and confirm that chips continue to behave as intended under stress or attack. The growing use of third-party intellectual property and chiplets increases this risk. Industry needs measurement approaches that can reveal unauthorised changes, identify weak points in designs and provide confidence that components come from trusted sources.

The UK is well positioned to contribute. It has recognised expertise in chip design, embedded-system security and forensic analysis, and is already active in the development of global standards in this area.

There is also scope to strengthen physical examination techniques, including high-resolution imaging, electrical and thermal signature analysis, and the use of unique identifiers such as physically unclonable functions and material-level tagging to support authentication and provenance.

As with other emerging areas of standards, progress depends not only on defining technical requirements but on ensuring that conformity-assessment capability exists to support adoption. If security requirements are too costly or complex to demonstrate, they risk limiting participation across the supply chain. Providing nationally available, affordable testing and certification infrastructure will therefore be essential if hardware security standards are to strengthen resilience while remaining accessible to innovators of all sizes.

10. Next-generation device performance testing

From neuromorphic devices to single-photon emitters and detectors, a new wave of semiconductor devices is emerging for applications that operate far beyond the limits of conventional electronics. The expansion of space as an operational domain is driving demand for devices that can function reliably in harsh radiation and thermal environments, while quantum technologies require semiconductors to perform effectively at cryogenic temperatures. At the same time, new power devices must tolerate increasingly higher voltages and temperatures, high-frequency components are being pushed into the multi-gigahertz range, sensors are required to detect weaker signals, and photonic and quantum devices increasingly depend on ultra-pure emission spectra.

As these technologies improve and expand their capabilities, existing test methods are no longer adequate. Manufacturers need guidance on how to undertake measurements that can credibly assess responsivity, stability, frequency response, spectral purity, lifetime reliability and behaviour under thermal and electrical stress.

The UK has much of the photonics and materials supply chain already in place, giving it a realistic chance to lead in this area despite the complexity. Success will require advances in calibrated light sources and measurement methods across ultraviolet, near-infrared, and short-wave infrared bands, ultra-low-current metrology, and new standards for high-frequency, high-temperature, and cryogenic testing.

The UK has the capability to build measurement capability and traceability, and translate emerging test techniques into repeatable standards, gradually broadening engagement with international bodies. This capability is currently fragmented across industry, academia and national laboratories, and needs to be more centralised and accessible if the UK is to build confidence in the quality of measurement outcomes.

11. Package performance testing

This metrology priority is connected to the need for packaging performance testing, particularly for next-generation devices. As semiconductor devices begin to operate at higher voltages, temperatures and frequencies, and more optoelectronic devices enter the market (which require optical windows and precise alignment of components), packaging has become a primary determinant of performance rather than simply a finishing step. Thermal pathways, parasitic reactance and environmental robustness now shape reliability as much as the underlying device. Yet novel materials and packaging architectures lack agreed metrics for assessing these behaviours.

The industry need is clear. Manufacturers require standardised methods to measure, model, and simulate heat flow, electrical parasitics, mechanical stress and degradation in increasingly complex three-dimensional structures. They also need test capabilities that can accommodate higher-frequency and higher-power operation, many of which do not yet exist. In addition, non-destructive techniques are required to probe fine-scale interconnects, novel joining materials, and encapsulation schemes that fall outside traditional silicon packaging norms.

Without these metrology capabilities and standards, UK innovation in compound semiconductors, photonics and power devices may struggle to transition into manufacturable, qualifiable systems. Meeting this demand will require coordinated development of thermal and electrical test methods, reference datasets, and early standards that reflect real packaging conditions.

12. Device reliability standards

Reliability is a critical requirement for all semiconductor devices, particularly in safety-critical applications where failure can have severe consequences. As performance is pushed to higher voltages, temperatures, frequencies, and power densities, reliability increasingly becomes a limiting factor, with gains in capability often traded off against long-term stability. This tension is especially evident as power devices move beyond silicon to advanced materials such as silicon carbide (SiC) and gallium nitride (GaN), where operating conditions differ significantly from those assumed by existing standards.

These materials enable operation at higher voltages, higher temperatures and faster switching speeds, and their failure mechanisms differ markedly from those of conventional silicon devices. Existing reliability tests therefore provide only partial insight into lifetime behaviour, even as demand accelerates for compound semiconductor power devices, driven not only by decarbonisation goals but also by system-level performance benefits. In electric vehicles, for example, SiC devices enable higher operating voltages and reduced cooling requirements, which in turn allow thinner cabling, smaller thermal-management systems, lighter platforms and increased driving range. As a result, sectors moving rapidly to adopt these technologies may do so before suitable reliability standards are in place, leaving manufacturers and end users to manage uncertainty.

This creates an opportunity for the UK. New metrology capabilities are needed to characterise emerging failure mechanisms, develop accelerated test methods grounded in physical models, and evaluate the next generation of packaging, bonding and encapsulation materials that will support high-voltage, high-temperature operation over the coming decade.

The aim is to develop credible, internationally aligned reliability standards that support the safe and confident adoption of compound semiconductor devices. Much of the standardisation activity in this area is already underway internationally, yet UK engagement remains limited.

This gap needs to be addressed, particularly given the demanding end-use environments now being targeted, including very high-voltage power electronics, cryogenic operation for quantum and space applications, and emerging photovoltaic materials. These are areas where the UK has relevant expertise and the potential to help shape future standards.

Research efforts should therefore focus on reliability testing at the level of the final packaged device, where many critical failure mechanisms arise and where UK capability is well established. Strong expertise in lifetime prediction and device physics means it is feasible for the UK to take a more active leadership role, provided efforts are coordinated across national laboratories, Catapults, universities, and industry partners.

Example of impact:

Standards de-risk investment in novel photovoltaic technologies

The UK has developed a strong research capability in emerging photovoltaic materials, particularly organic–inorganic hybrid perovskites. During the 2010s, rapid growth in research activity and subsequent publications of associated academic papers, exposed a critical weakness: inconsistent measurement practices produced unrepeatable results, limiting comparability between laboratories and increasing uncertainty about true device performance.

To address this, leading groups established consensus test procedures based on the academic-led ISOS protocols, creating a shared and widely adopted framework for evaluating stability and efficiency. These informal standards improved reproducibility, enabled credible benchmarking and reduced technical risk across the field.

This has supported commercial translation. Oxford Photovoltaics, a UK spin-out from the perovskite research community, has used standardised methods and internationally recognised ISO and IEC testing to independently verify high-performance devices, including a 26.9% efficient silicon-perovskite tandem solar module. Access to independent, standards-based validation has strengthened confidence in the technology's reliability and durability, helping to de-risk investment and contributing to approximately $150 million raised to date.

This case illustrates how early alignment with agreed measurement standards can accelerate the progression of novel energy technologies from laboratory research to investable, scalable products.

Conclusion

The global semiconductor industry is moving into a phase where progress is defined less by traditional CMOS scaling alone and more by the ability to integrate new materials, device architectures and system level innovations.

This shift is visible in the growing importance of compound semiconductors, heterogeneous integration, advanced packaging, high-frequency and high-power devices and growth in semiconductors for strategic domains such as energy, transport, communications, space and quantum technologies. These changes are creating new markets, but they are also placing unprecedented strain on the measurement systems and standards frameworks that underpin industrial confidence.

Throughout this report, a consistent theme has emerged. Innovation in semiconductors cannot be separated from the ability to measure, compare and trust performance. As technologies diversify, the lack of agreed metrics, test methods and qualification pathways is becoming a limiting factor. Where standards lag behind innovation, risk increases, investment slows, and promising technologies struggle to move from laboratory success to industrial adoption. Conversely, where metrology and standards are developed early and aligned with emerging needs, they act as accelerators, reducing uncertainty, enabling interoperability and opening routes to global markets.

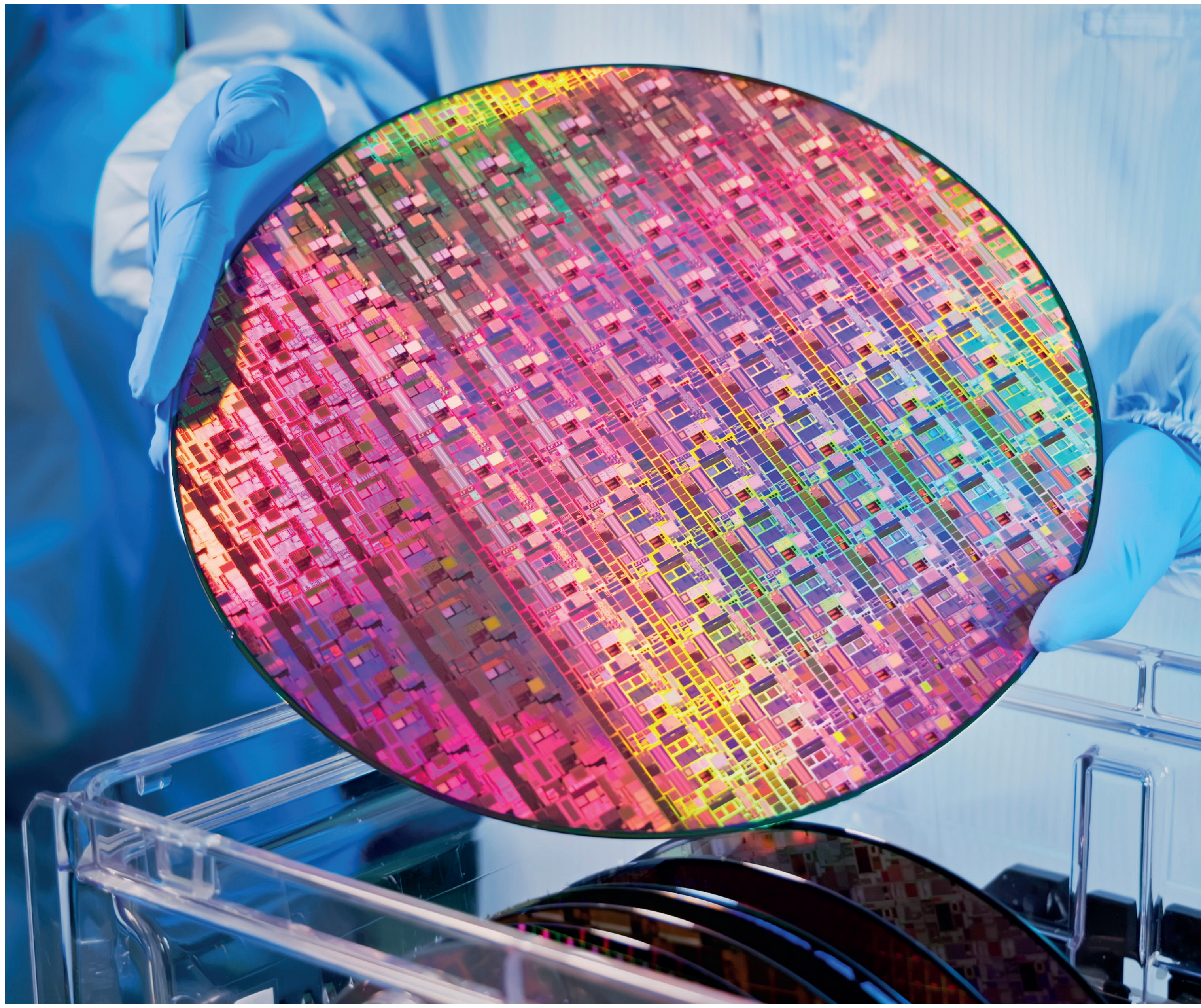
For the UK, this moment presents both a challenge and an opportunity. The country is not, and is unlikely to become, a leader in large-scale advanced silicon manufacturing. But it possesses strengths that are highly relevant to the direction in which the industry is moving. These include world-class capability in compound semiconductors, materials science, photonics, power electronics, device modelling, semiconductor tooling and applied measurement science. The UK also has a long-standing reputation for rigour and trust in metrology and standardisation, and an established role in shaping international consensus through standards bodies.

The twelve metrology priorities set out in this report translate these strengths into a practical agenda for action. They span the full lifecycle of semiconductor innovation, from materials and structures, through process development and scale-up, to device and system performance. Individually, each priority addresses a specific capability gap. Taken together, they define a coherent strategy for enabling the UK to exert influence where global markets are still forming, rather than competing where they are already mature.

Delivering this agenda will require coordination. No single organisation, sector or discipline can address these challenges alone. Industry must engage earlier and more consistently in pre-competitive metrology and standards activity, recognising it as an investment in market access and long-term competitiveness rather than a downstream compliance exercise. Academia must align fundamental research more closely with the measurement and qualification needs that shape industrial adoption. National laboratories must continue to act as convenors, providing trusted reference capability, translating research into standards and ensuring international alignment.

Government has a critical enabling role. Clear policy signals, sustained support for metrology infrastructure, and recognition of standards as strategic assets will be essential. Targeted funding for pre-standards research, support for UK participation in international standards forums, and mechanisms that lower barriers for SMEs to access measurement and conformity assessment capability will all strengthen the ecosystem. Above all, metrology and standardisation must be treated as integral components of the UK's semiconductor strategy, not as peripheral technical concerns. This will have a desirable knock-on effect, as support for semiconductor innovation will enable the growth of other frontier technologies in the UK, such as AI, quantum and advanced communication technologies.

If these actions are taken, the UK can move decisively from its current starting point towards a position of durable influence. By shaping how emerging semiconductor technologies are measured, qualified and trusted, the UK can help define the rules of future markets, support resilient supply chains and convert scientific excellence into sustained economic and strategic advantage. The opportunity is real and the direction is clear. This report argues that what we need now is to invest in extending our foundational metrology capability and standardisation activities that will unlock the innovative potential in the UK's semiconductor industry.



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