Delivered by
Innovate UK

Driving the Electric Revolution

UK Power Semiconductors Landscape Report

Authored by: Venn Chesterton, Deputy Challenge Director – Driving the Electric Revolution Challenge, Innovate UK and Ben Jackson, Managing Director, BDJ Group

Released: April 2024

Contents

On this contents page, please click the section title text to be taken directly to the specific page you would like to read.

Executive summary

This interim report, commissioned by the UKRI's Driving the Electric Revolution Challenge, delivered by Innovate UK, highlights the UK's capabilities and needs specifically in the area of power semiconductors (power chips).

The work included building up a picture of the UK's power semiconductor supply chain, especially for silicon based MOSFETs and IGBTs and next generation silicon carbide and gallium nitride type devices and the power packaging that such devices go into. A team of independent industry experts was convened to agree areas for deeper investigation and interviews were conducted with a portion of suppliers representing these focus areas.

This interim report also outlines the scope for further work in terms of speaking with more industry partners, specifically in the areas of Gallium Nitride and also legacy, silicon front end manufacturing.

The call is also made for proactive national strategic initiatives to be undertaken to address the specific needs of the power semiconductor supply chain in the UK, either as part of the national strategy or as separate undertakings which can help strengthen the existing national strategy with respect to power semiconductors.

The report details recommendations for strengthening the UK's power semiconductor and power electronics supply chain around four key initiatives:

1. **Putting UK front end activities onto a sustainable footing**
2. **Take a differentiated route in packaging (back end)**
3. **Power chips talent development**
4. **Unlock UK's power electronics and power semiconductor ecosystem**

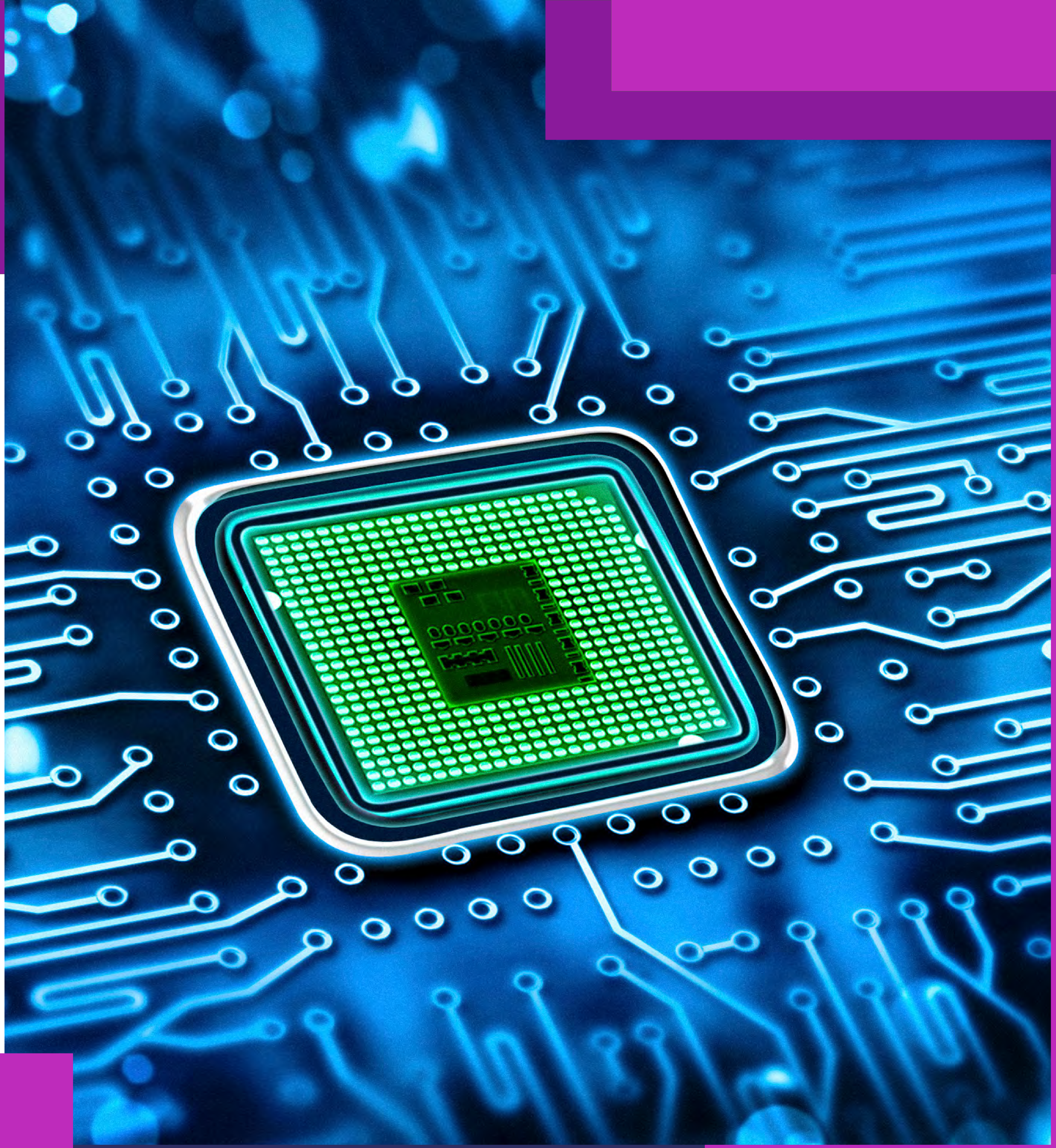
Preface

Given the criticality of semiconductors to national and global industries and our everyday way of life the primary objective of this report is to highlight the needs of the UK power semiconductor supply chain. Given the nuances that will be outlined between all different types of semiconductors, this report will specifically highlight the opportunities, gaps and needs associated with power semiconductors in the UK.

This report forms part of the wider package of work termed the UK Power Semiconductors Landscape project, whose scope, goals and methodology will be outlined in Section 2. While Power Electronics (PE) can cover a wider range of sub components, systems and different levels of integration, the bulk of the work done to date, and the focus of this report is on Power Semiconductors (PS), a sub-group of active components which form the core of the vast majority of power electronics systems.

The project was commissioned by the UKRI's Driving the Electric Revolution Challenge, delivered by Innovate UK, and conducted by independent consultant Ben Jackson from BDJ Group Ltd who has over 15 years' experience managing power semiconductor product lines at leading global semiconductor companies. In the course of work the project was supported by a team of independent UK experts and interviews were also conducted with select industrial partners, details of all participants can be found in Appendix 1.

The authors would like to thank all who participated in providing inputs to this report, for sharing their experience, insights and time. Gaining real-world feedback has been invaluable to validate the work that has been produced and ensuring that recommendations are as specific and tangible as possible.



" This report highlights the opportunities, gaps and needs associated with power semiconductors in the UK."

Venn Chesterton, Deputy Challenge Director – Driving the Electric Revolution Challenge, Innovate UK

Section 1: Introduction

Semiconductors are devices that have been the focus of much attention in recent years, notably around the disruption caused in their supply chains by the responses to manage the global COVID-19 Pandemic. Despite the shortage of these devices having a massive impact on numerous industries and end customers, semiconductors remain a complex area to navigate by those outside the immediate confines of the industry.

Policymakers both at home and abroad have undertaken activities in the last 18 months to see how stronger semiconductor ecosystems can be strengthened, and notably the US and the EU have committed hundreds of billions of dollars of support. **The UK Government has also announced a support package as part of its National Semiconductor Strategy** which plans to have various focus areas around silicon prototyping and low volume piloting, advanced packaging, compound conductors and access to EDA tools, but no specific focus on power semiconductors.

While there is much activity to stimulate activities in the field of semiconductors the quality of understanding around the importance, scope and specific challenges of the semiconductor industry has advanced only marginally over the same time period. Discussion and debate around semiconductors rarely, if ever, distinguishes between different parts of the semiconductor technology spectrum and how different semiconductors are used in different applications and different markets. Debate and discussion often overlook the fact that there are many different types of semiconductors and not all are 'computer chips'.

The Semiconductor Technology Spectrum

Semiconductor devices range from memory and microprocessor chips used in mobiles, to LEDs in screens and lighting, through to sensors used in mobile devices to power devices that drive motors in electric cars. There is a vast array of different types of semiconductors, used in different applications, in different markets for different reasons, but crucially in the vast majority of electronic systems you need multiple types of semiconductor devices to make a useful function occur. This is demonstrated in Figure 1.

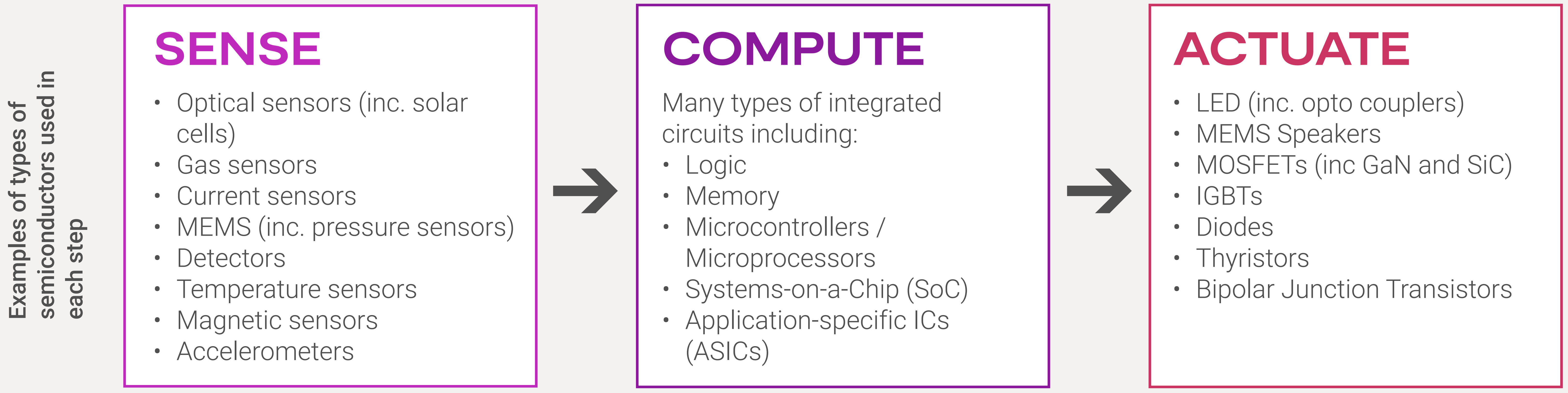


Figure 1. A typical electronic system needs a chain of different semiconductor technologies to perform a useful function.

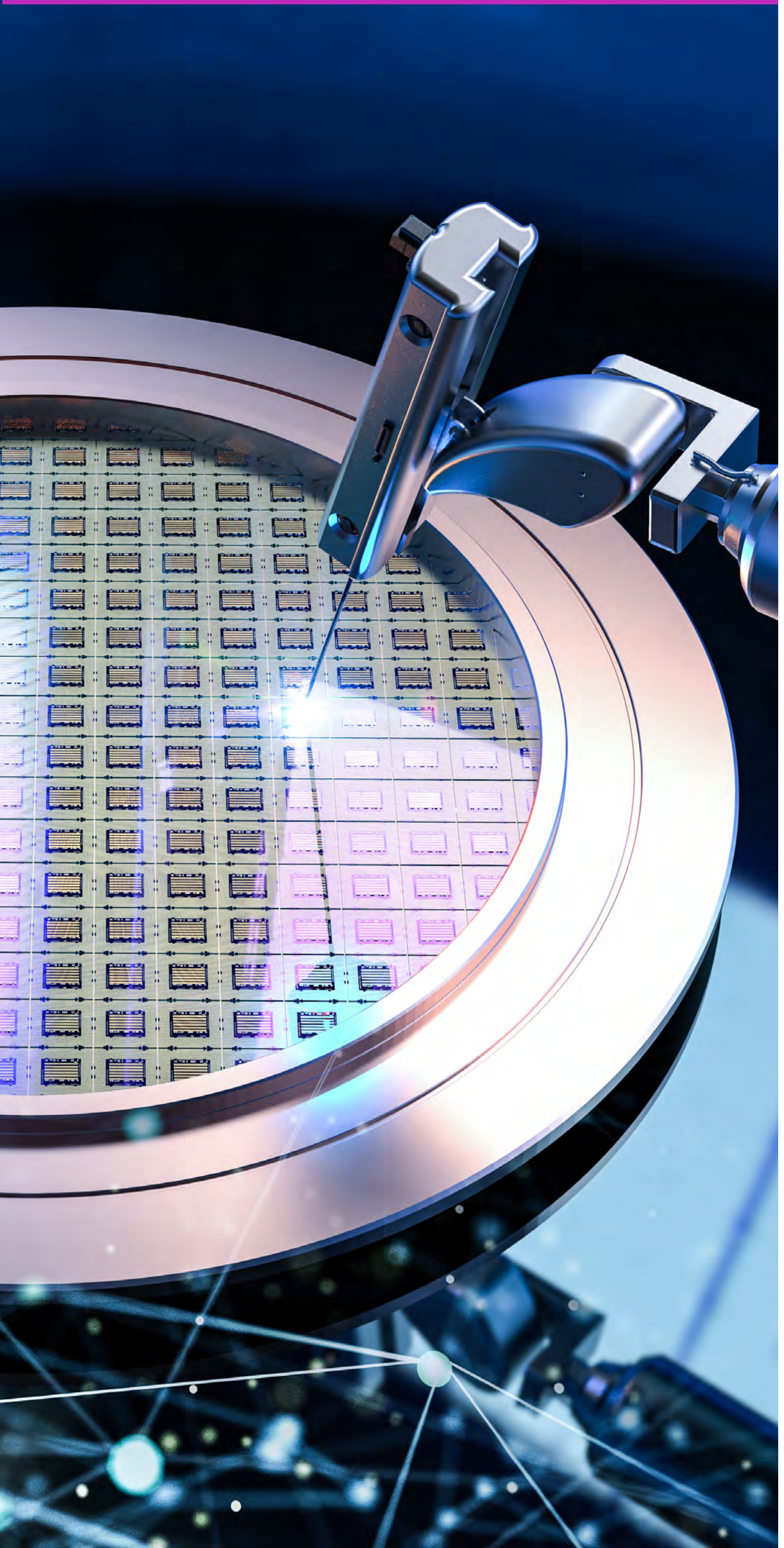
In a typical electronic system, an electric input signal must be generated which represents what is going on in the outside environment. This is called the sense stage and devices used could take the form of microphone, touch, temperature or light sensor all of which are typically based on semiconductor technologies. The signal from these sensors is then processed in the compute stage. Here computer chips or ICs (Integrated circuits) such as microprocessors, logic devices and memory type semiconductors take the input signal and based on the desired function, the system decides what to do before feeding a signal to the last stage, the actuate stage. In the Actuate stage, the electrical signals are harnessed to provide some form of action on the outside world, examples include power semiconductors controlling the flow of electricity to a motor to move an object, through to an LED light or a speaker. All electronic systems follow the **Sense ➔ Compute ➔ Actuate flow** and different types of semiconductors are needed at each stage for the overall desired functionality to occur.

Value beyond node size and mask count

While different types of semiconductors bring different features and value to electronic systems, there are important nuances when it comes to the maturity and value of different technologies. Often broad generalisations about 'advanced' and 'mature' technologies will be made to indicate that only certain 'node sizes' (how large or small the individual features that can be created in a given semiconductor technology) or types of semiconductors are of value. While node size is a useful indicator of technological advancement in some types of semiconductors (e.g. microprocessors or other ICs) it is of very limited importance when evaluating other, equally critical devices, for example, power semiconductors or sensors.

Another metric that is often used to compare the advancement of technologies is the mask or layer count – namely how many layers a given semiconductor technology has.

In ICs, adding multiple layers enables more complex circuits to be produced in a given area, allowing higher levels of computation and resulting in superior functionality. It is not uncommon for advanced ICs to have upwards of 50 layers. By contrast, each layer adds considerable cost (regardless of semiconductor technology) and in the field of power and sensor semiconductors, the goal is to create the best device performance with as few layers as possible, with the most advanced devices having a mask count typically below ten layers. It should also be noted that in the area of power semiconductors, although using a fewer number of layers in front end fabrication, there are very specific needs around epitaxy and substrates that are often integral for high performing power semiconductors to be created using relatively low layer counts.



In reality, the level of innovation and value of any semiconductor technology can't solely be summed up by its node size or mask count and a more nuanced assessment must be made in the context of which part of the semiconductor technology spectrum is being considered when evaluating the technology in question. Similarly, as semiconductors are often associated with consumer electronics goods which have short product life cycles and frequent functional upgrades, there is a common misapprehension that only the 'new' semiconductors are of value. Just as modern skyscrapers with advanced glazing rely on longstanding concrete and steel technologies for their construction, the most advanced electronic systems also rely on legacy semiconductor technologies to function just as much as they need to the latest microprocessor on the smallest possible node size.

Modern systems are a serial chain of technologies, that need each other to work as a whole. Without doubt, there are parts of the semiconductor supply chain which are more established and commoditized versus others, but linking these attributes to value and importance can't be easily done in the semiconductor world. Therefore the attribution of strategic value is a hugely complex task and requires a detailed and specific approach to be taken.

Overcoming barriers to entry

The barrier to entry to develop new semiconductor technologies is very high. Investment in a single front end factory (wafer fab) can be in the low single digit billion pound range. Construction times can take between two and five years depending on where the factory is being sited (e.g. part of an existing semiconductor fabrication facility or a virgin site requiring new infrastructure and licenses) or the tooling and equipment needed to fill the clean room. Once a wafer fab has been built, front end technology processes need to be either transferred in from an existing wafer fab, a task that can take around one year, or developed a new front-end process from scratch. Developing new front-end technologies from scratch is a process that will cost in the order of low double digit million range for power and sensor type devices, well into many tens of millions of pounds for a new IC or microprocessor platform. Development times to create these technologies can also be lengthy ranging from 2-5 years or longer depending on the type of technology node being pursued.

Given this high barrier to entry in developing new front-end technologies, and the very high upfront capital expenditure, it is essential that devices can be produced in high volumes to maximise the return on investment. They must also be produced over a long time – it is not uncommon to find front end technologies still in high volume production, and remaining profitable after two decades. But the factors influencing the sustainability of a given technology over time will depend on what type of semiconductor technology it is, and which market it is being sold into.

Regardless of the type of semiconductor technology or product being produced, a cornerstone for all semiconductor companies to be viable is to have access to economies of scale for production. To achieve such economies of scale, semiconductor companies need to operate in a region with a stable, long term industrial ecosystem that gives confidence for very large upfront capital investments to be made and volume production and employee resourcing to be sustained over the long term (20+ years).

Section 2: Summary of work completed

This report represents an interim read out at the midpoint of the work being undertaken as part of the UK Power Semiconductors Landscape Project. This work has several phases as outlined in Figure 2.

The work done has ranged from identifying and outlining the key power semiconductor manufacturing capabilities regarded as benchmark internationally through to mapping the presence of UK power semiconductor players, to interviewing a select number of companies to verify the work done to date as well as confirming industry capabilities, opportunities and challenges. It should be noted that the report's authors are still keen to interview further companies involved with power semiconductors before moving to the final stage of compiling a proposed strategy to support the UK power semiconductor industry.

PHASE ONE

Confirm focus areas for investigation

- Greatest **strengths** in UK power semiconductor supply chain.
- Greatest **weaknesses** in UK power semiconductor supply chain.
- **Areas** of power semiconductor supply chain that are likely going to be **important/or high relevance for success in the future.**

→

PHASE TWO

Verify UK PE capabilities

- **Interviews with key industry stakeholders** relevant to the topics identified in Phase 1.
- **Confirm strengths.**
- **Confirm size of gaps.**
- Evaluate **difficulty to fill gaps.**

↑ Output of this report

→

PHASE THREE

UK power semiconductor strategy

- Strategy that covers **where the UK power semiconductor industry needs to go to have future success** covering: **market, application, product and technology families and manufacturing capabilities.**
- Estimate of **funding needed** to execute strategy.

↑ Planned next steps

Figure 2. Overview of landscape project work.

Section 3: UK power electronics and semiconductor supply chain overview

The initial focus of the work undertaken was to compile an overview of the range of companies working in different areas of the power semiconductor industry. To structure the work done in this report, a simple template grid outlining the classical tier 2 semiconductor manufacturing flow is shown in Figure 3 with areas of high and low UK activity marked in respective positions on the grid. A populated version of Figure 3 can be found later in the report. At times, based on publicly available information it was not possible to establish precisely which capabilities companies had and there may well be capabilities in the UK beyond those represented here. Nonetheless, there are some notable gaps outside of the focus areas.

It should be noted that the scope of the work undertaken here was strictly looking at IGBT, MOSFET (LV and HV), Gallium Nitride (GaN) and Silicon Carbide (SiC) devices in bare die, discrete and module package formats. There are many 'adjacent' capabilities in the UK in other areas which are not in the scope of this report.

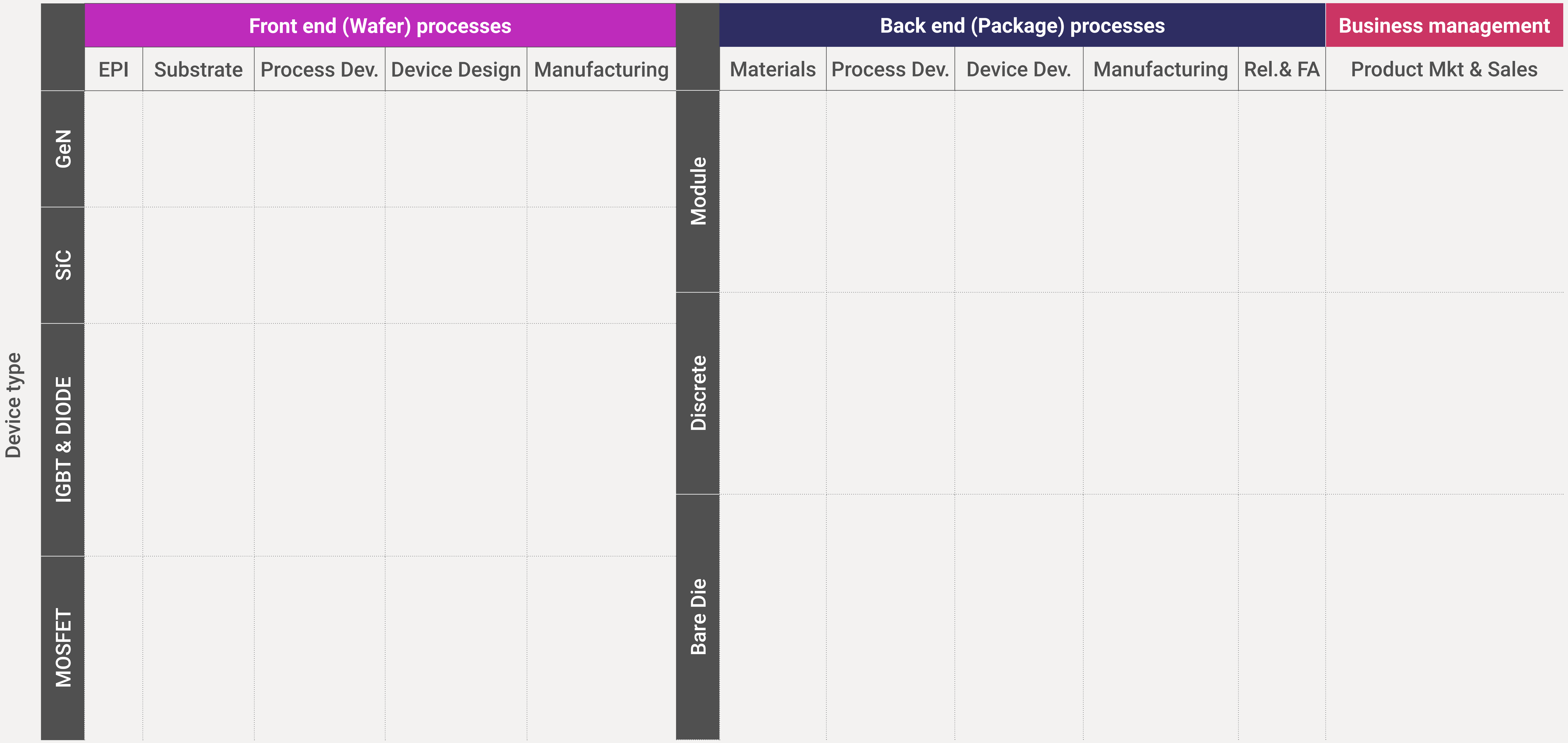


Figure 3. Scope of work and areas of high UK activity in the power semiconductor supply chain. A populated version of this template grid can be found later in this report.

Section 4: Power semiconductor cornerstones

In the last decade, the global megatrend of decarbonisation and the move to net zero has shifted the activities around different products and solutions in the semiconductor industry. In the 1990s and early 2000s as computing and mobile applications grew there was massive momentum behind advancements in signal processing and digital semiconductors, particularly in the area of microprocessors. In this time frame, the focus of the industry was very much in advancing the capabilities of the 'compute' stage of electronic systems. Now to reduce carbon emissions, the need to electrify and automate an ever-increasing range of systems, attention is increasing on the sense and actuate stage type semiconductors. This is not to say that advancements in semiconductors falling into the compute stage will stall, or become less relevant, but rather that activities in sensors and power semiconductors are having to ramp up dramatically to unlock the pathway to a more electric, lower carbon future.

Furthermore, the pace of innovation in the area of power semiconductors is getting quicker with reducing time between major innovation cycles and successive technology generations. The pressure to innovate quicker is in large part driven by power semiconductors being one of the key technologies in enabling net zero and their importance is arguably independent of some major technological choices on the path to net zero. For example, in the automotive industry there are ongoing debates as to the future prospects of battery electric versus hydrogen powered cars. While the outcome of this technology battle will have massive implications for both the battery and hydrogen industries, regardless of which dominates long term, the impact on power semiconductor needs will be largely unchanged – both types of vehicles will need a vastly greater quantity of power semiconductors than a traditional, ICE based car today.

Based on extensive industry experience at leading power semiconductor companies, the author has noted a number of key 'cornerstones' items which are generally either 'must haves' or 'increasingly desired' for any supplier who wishes to be successful in high volume consumer, industrial or automotive markets with IGBT, MOSFET (LV and HV), SiC and GaN devices. The topics are outlined in Figure 4 along with an assessment of likely UK capabilities for each. It must be stressed that the topics identified here are by no means an exhaustive list but designed to cover the main points to differentiate between UK suppliers and help identify gaps versus international competition. Not all items are needed for success, but this list represents the typical capabilities of the leading suppliers in the market today.

The rationale for each cornerstone is explained, along with a score indicating the likely presence of the capability in the UK today based on the research completed. This analysis was conducted by interviewing a number of industry partners to validate findings, however in some cases only publicly available information could be used. It is therefore possible that there might be individual cases where a capability exists that is not referenced in this analysis.

It should be noted, that to be marked as fully present, the capability must be qualified and in high volume production. This relatively tough bar is by no means accidental – there is a distinct difference in the semiconductor industry between having a capability in an R&D form and having the same capability ramped up and proven in high volume production; the two are not equal.

Figure 4 part 1: Power semiconductor cornerstones (front end).

	Cornerstone	Rationale	UK Power Semiconductor Capabilities	
Front end (Wafer) processes	Multiple substrate and epi sources	Help secure security of supply chain	Well equipped for compound (WBG) materials, but mainly for non-power type devices	L
	200mm wafer diameter capabilities at minimum	Standard requirement for any meaningful/best cost competitive mass production Si capability today. Next step for WBG	Some 200mm production lines for Si. Majority of Si power semiconductor production is 150mm and all compound lines are on wafer diameters of 150mm or less.	M/H
	300mm wafer diameter capabilities for silicon (not WBG) technologies	Fast becoming the next generation standard, even for ultra-thin technologies – will offer better economies of scale	No 300mm wafter manufacturing capabilities identified in the UK for power semiconductors	L
	Advanced TCAD simulation	Set device performance expectations. Considerably quicker than running physical lots in wafer fab	Good capabilities likely to exist across all front end sites	H
	Ability to easily run fast turn around / trial lots with multiple splits (variants)	Improve rate of learning and quality of innovation		H
	Ultra-thin (<70µm) wafer processing capabilities (including back side laser anneal)	Essential technology for cutting edge IGBT and MOSFET technologies	Production level capability understood to exist at one UK site	H
	Sinterable and solderable front side metallization schemes	Supports next generation, bond-wireless/double sided cooled packages (improved reliability and cooling/efficiency)	Production level capability understood to exist at several sites	H
	Automated optical inspection	Identify die with physical defects – important step in pursuit of 0ppm		H
	Wafer map in mass production	Important for use cases where many die need to be paralleled or grouped in back end e.g. in large modules		H

H Ramped in full production **M/H** R&D capability/pending production ramp **L** Little or no capability

Figure 4 part 2: Power semiconductor cornerstones (front end).

	Cornerstone	Rationale	UK Power Semiconductor Capabilities	
Front end (Wafer) processes	Wafer map in mass production	Important for use cases where many die need to be paralleled or grouped in back end e.g. in large modules	Understood to exist at the larger UK production sites	H
	High current (>100A) wafer probe (automated)	Remove bad die before they are packaged ➔ pursuit of 0ppm and substantial opportunity to reduce cost of yield loss in back end	Production capability likely not existing	M
	Dynamic test at wafer probe (automated)	Replicate switching conditions in application, reduces cost of yield loss in AE and at customer	Understood to exist at the larger UK production sites	
	Automated hot and cold wafer probe	Effective at removing outliers or 'walking wounded' die ➔ pursuit of 0ppm	Many sites potentially have equipment that is capable of doing hot or cold wafer probe test but likely not in mass production	
	Industry 4.0 levels of automation	Reduce cost, improve fab utilisation and efficiency, improve quality	Understand no such capabilities exist in UK at a whole wafer fab level	L

H Ramped in full production **M** R&D capability/pending production ramp **L** Little or no capability

Figure 4 part 3: Power semiconductor cornerstones (back end).

	Cornerstone	Rationale	UK Power Semiconductor Capabilities	
Back end (Package) processes	Materials expertise and good, ongoing working relationships with all major material vendors	New processes (e.g. sintering) are rarely 'plug and play', have to work with vendors to get the process to work on specific technology	Understand well established relationships exist, possibly some variation in depth of relationships when considering access to very new materials from overseas vendors	H
Back end (Package) processes	Quick turn pilot line with all major steps (equipment types) in one place	Allows quick learning and concept development for new processes and products	Several package prototype lines existing in industry with good capabilities. Also, have industry accessible resources e.g. Driving the Electric Revolution Industrialisation Centre – North East	H
Back end (Package) processes	Advanced thermal modelling	Key for power semiconductors to enable design trade-offs to be evaluated at a device level, and working with customers the impact of device level trade-offs can be modelled at a system level, greatly improving product fit (better cost/performance ratio)	Generally expect a good capability to exist with some variation of specific modelling capabilities between industrial sites both in industry and academia.	H
Back end (Package) processes	Advanced electrical modelling (RCL)	Key for power semiconductors to enable design trade-offs to be evaluated at a device level, and working with customers the impact of device level trade-offs can be modelled at a system level, greatly improving product fit (better cost/performance ratio)	Generally expect a good capability to exist with some variation of specific modelling capabilities between industrial sites both in industry and academia.	H
Back end (Package) processes	Sintering die attach	More reliable/lower thermal resistance interconnect technologies.	Exists at several sites, with some variation between sites in terms of production readiness	M
Back end (Package) processes	Ultra low void solder die attach processes	Improve overall cost/performance of product for a given level of reliability.	In volume production at several sites	H
Back end (Package) processes	Heavy gauge wire, ribbon and copper clip based interconnect technologies	Lower inductance, lower resistance packaging ➔ get maximum value especially out of wide band-gap die	In volume production at several sites with some variation on precise technology mix	H
Back end (Package) processes	Transfer moulding	Well established in discrete and increasingly becoming the standard assembly technology for power modules	Exists at several sites, with some variation between sites in terms of production readiness and exact technology capabilities	M
Back end (Package) processes	Automated dynamic final test	Replicate switching conditions in application, reduces cost of yield loss in BE and at customer	Not understood to exist in mass production	M
Back end (Package) processes	Highly experienced reliability and failure analysis lab	Essential for innovative process development and, resolving issues for customer both during design-in and mass production	Multiple sites having some in-house capability, quite heavy reliance on external or even overseas labs for more advanced testing and analysis	H

H Ramped in full production **M** R&D capability/pending production ramp **L** Little or no capability

Section 5: Summary of findings

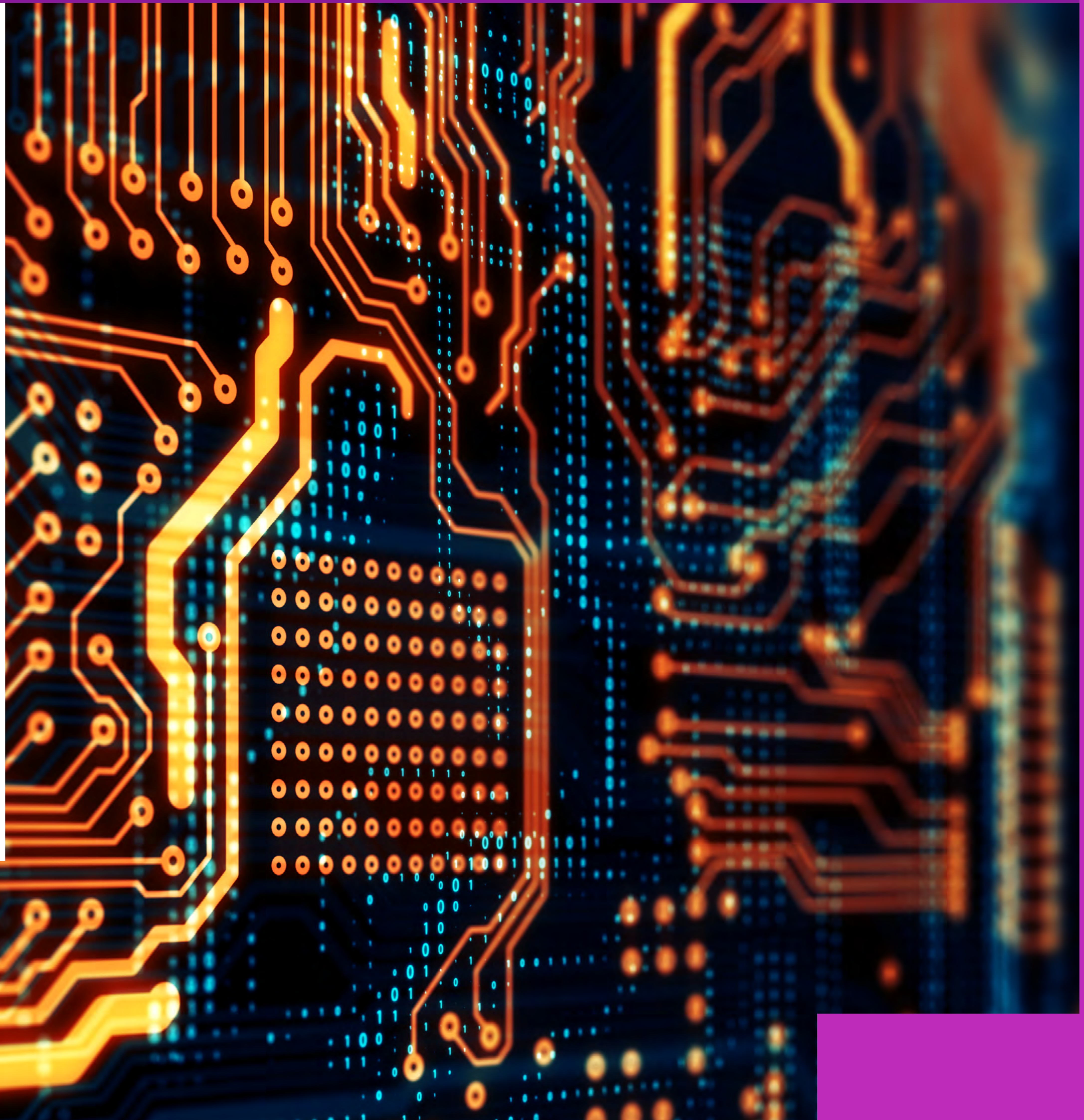
The industry overview and cornerstones were reviewed by a panel of independent industry experts (see Appendix 1) to identify areas of possible strength and weakness in the UK power semiconductor supply chain.

In each area possible target companies were identified, with a view to interview them and verify the outcomes of the expert panel review. The interviews were conducted from late 2022 into spring 2023. Companies were usually visited in person and results of the industry overview and panel outcomes were presented to participating companies to gather their feedback and adjustments were made to the findings accordingly. The companies visited also took time to show the report team their production lines so that the best possible understanding of their capabilities, opportunities and challenges in the UK power semiconductor supply chain could be developed. The companies which chose to engage were open and keen to participate and the report team sincerely thanked them for their contributions. In compiling this report, every effort has been made to identify commonalities and synergies between interview feedback whilst making the observations as specific as possible.

While many individual companies, and sub sectors of the UK power electronics supply chain will have individual and specific areas of strength and weakness, the Figures 5 and 6 summarise the main strengths and weaknesses identified across the UK power semiconductor supply chain in the course of this work to date.

UK power semiconductor strengths

The UK has a long heritage not only in semiconductors, but specifically in power semiconductors and wider power electronics and systems. Some further background on the strengths identified are set out in Figure 5.



Existing front end production

It is a common misperception that the UK has limited front end (wafer fab) manufacturing capabilities for semiconductors. Indeed, the UK fabrication landscape is not as advanced as the manufacturing footprints overseas that are producing advanced digital processors on very large wafter diameters and with the latest very small node sizes. However, in power semiconductors nodes size is far less of a consideration for how advanced and valuable a technology is. The advanced power semiconductor devices needed for additional electric net zero applications such as electric cars do not need to be produced in fabs capable of the smallest node sizes. The UK has multiple fabs running silicon devices in high volume with fabs in Manchester, Lincoln, Newport, Bedford and Greenock being some of the most well established. Just one of these sites is capable of producing over one billion power semiconductors a year[1].

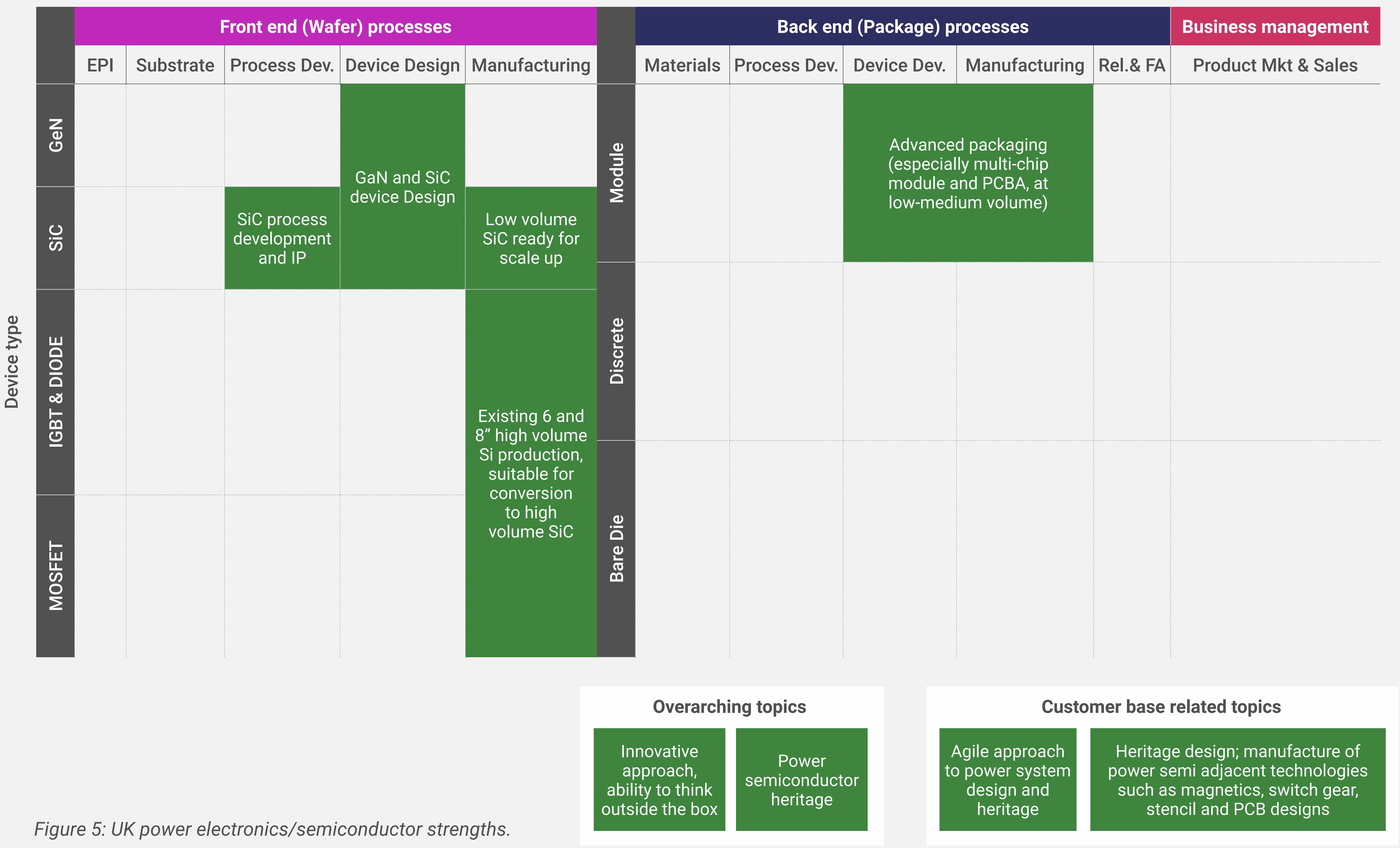


Figure 5: UK power electronics/semiconductor strengths.

1. Advanced Propulsion Centre UK, Strategic UK opportunities in passenger car electrification (June 2020)

Between them these factories have a rich heritage of designing and developing silicon-based power semiconductors. They have advanced technologies such as ultra-thin wafer processing, solderable and sinterable front metallization and high current wafer probe all of which are key technological cornerstones needed to support more electric technologies for net zero.

Moreover, it is important to stress that there is a distinct difference in the semiconductor industry between developing a novel technology in a prototype fab, and actually ramping it up into high volume production with a high yield. The ramp into high volume production is essential for the economies of scale to make any semiconductor product viable. Importantly these UK sites have extensive high volume production experience, having shipped hundreds of billions of devices over many decades into some of the world's most demanding markets such as automotive.

Finally, it is likely that many of the tool sets which are in the UK legacy silicon fabs, have the capability to be repurposed to produce new compound semiconductors such as SiC and GaN on silicon. Indeed, some of these sites already have long standing experience of running compound semiconductor devices. Being able to supply volumes of these types of semiconductors into the global market, at a time when the compound semiconductor production ramp continues and the supply chain remains constrained and should be seen as a strong opportunity for the UK.

Despite the strengths of the legacy UK front end manufacturing base, currently the report authors judge this sector to be at risk with current approach being pursued by government. Extra steps need to be taken to position this part of the industry for sustainable success and these will be outlined later in the report.

Opportunity for compound scale up

In addition to a strong existing silicon manufacturing footprint, the UK has good footing in the world of wide band gap, or compound semiconductors such as Gallium Nitride (GaN) and Silicon Carbide (SiC). These next generation compound or Wide Band Gap semiconductors are set to replace many legacy silicon power technologies over the rest of the decade and offer greatly improved efficiency over silicon devices. Although these types of technology have been in production for many decades in some cases, in the power semiconductor arena, adoption has been fairly limited in terms of volumes of product produced until recently. This picture started to change rapidly in 2017 with very high volumes and quality demands of the automotive industry getting behind SiC in particular with the launch of the Tesla Model 3, which in part had a SiC drivetrain. Since then, many other Original Equipment Manufacturers (OEM) have followed suit, and global demand for SiC has grown substantially becoming a $0.9 billion market by 2021 growing with a CAGR of 37%[2] with the improved efficiency that compound semiconductors offer being of value particularly in electric vehicle architectures. There are a range of views on how much SiC will displace legacy silicon devices over the next decade. In the specific case of using SiC on the main inverter of electric vehicles (one the largest markets for SiC globally), estimates vary from around 50-80% of drivetrains switching to SiC over the next decade.

2. *Advanced Propulsion Centre UK, Q4 2022 Automotive industry demand forecast, March 2023*

The UK has a long heritage in SiC in particular both in university R&D and industry. Since 2014, located in Lochgelly, the UK has had one of the very first dedicated SiC foundries globally. Furthermore, it is important to note that compound semiconductors can't just be 'dropped into' systems to replace silicon devices, but the application must be adapted to get the most from the improved performance that the compound semiconductors offer. To help in this respect the Compound Semiconductor Applications Catapult was founded in Newport, and this also forms part of the wider CSconnected cluster in South Wales linking up 13 partners with the goal to form a global centre of excellence in compound semiconductor technologies. As part of this cluster the UK has one of the largest producers of compound semiconductor substrates, although it is understood the focus of production here is more on materials for RF and photonic type semiconductor devices rather than power devices.

The research undertaken in this report identified the deep process development and device design know-how and associated IP that UK entities have in compound semiconductors. Combined with the possible potential to ramp up compound technologies in legacy Si sites, and with the CSconnected cluster, the UK could play a greater role in the global power semiconductor market by leveraging opportunities around compound type devices.

It should be noted however, that while the UK has many strong and unique qualities in the area of compound semiconductors, today the most advanced and best performing SiC devices in production are developed and produced outside of the UK. Wolfspeed, ST and Infineon being market leaders both in terms of investment, fabrication facilities, volume shipped and device performance for SiC. Nonetheless, when the UK capabilities on SiC, combined with the activities of UK based startups developing novel GaN devices are considered in the global context the picture is more positive. The UK approach to compound device development of more of a fast and agile approach compared to overseas competitors. Furthermore, the global rush to net zero technologies will put immense pressure on the associated supply chains. There has been a huge amount of focus and worry about the limits that battery, raw material and electric motor production, may put on reaching these goals, but ironically very little to no focus on the equally likely limiting affects that semiconductor production will impose, despite the pandemic highlighting the particular challenges and sensitivities in the global semiconductor supply chains. This potential disconnect between net zero policy and reality of the power semiconductor supply chain is clearly illustrated in the field of electric vehicles; in 2022, 12% of passenger cars and vans produced in the UK were battery electric or plug in hybrid – but by 2030 their share is forecast to increase to 88% of production[3], a 7x increase in share. The growth picture is equally dramatic overseas with a ~5x and ~4x increase in xEV share in European and global markets respectively over the 2022 to 2030 timeframe[3] which will be very hard to meet.

Assuming total vehicle production stays flat, the author estimates the switch from ICE to xEVs alone will likely result in a 4x increase in power semiconductor volumes between now and the end of the decade. If non-xEV specific demand for power semiconductors were to stay flat over this timeframe, a similar increase in wafer fab production capacity will be needed globally in the next seven years.

3. Goldman Sachs, Equity Research, The Green Technology Cycle SiC June 2022

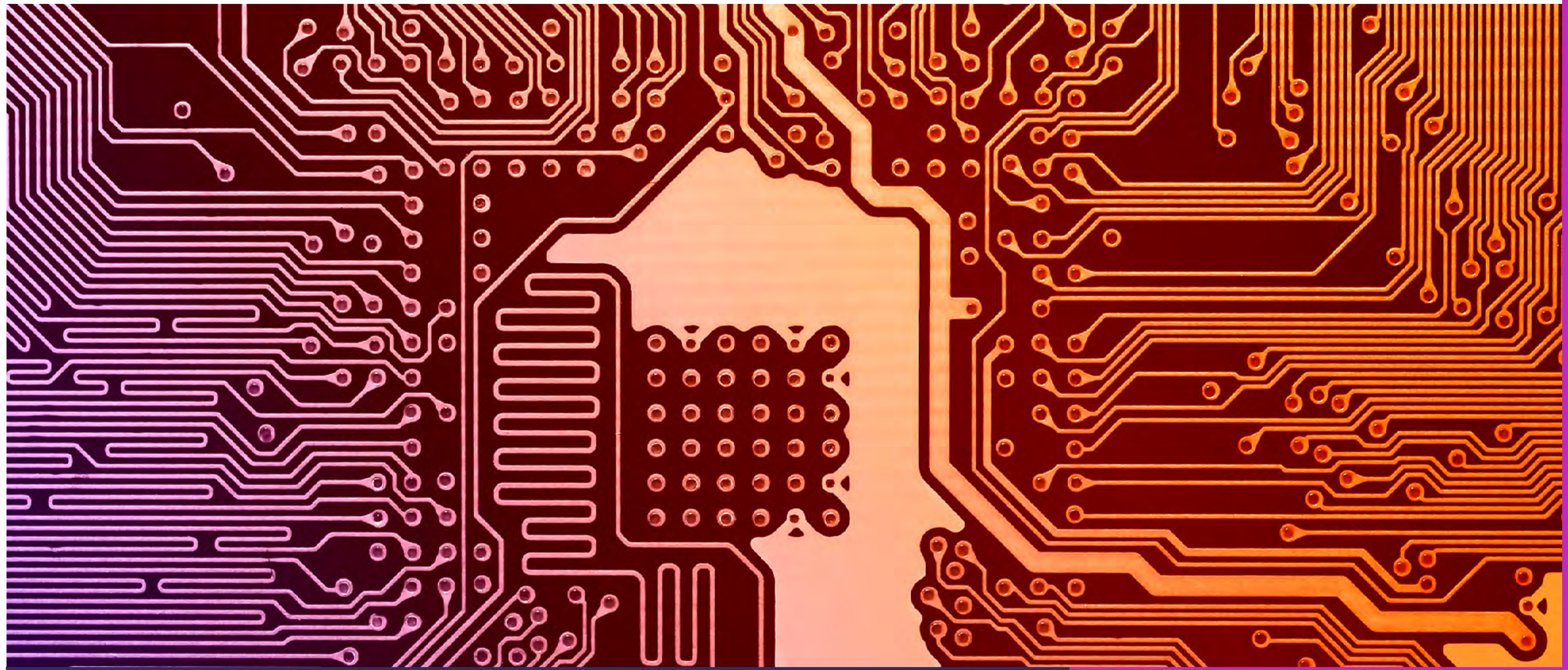
Given the lengthy time needed to bring new wafer fabs online, we expect new net zero technologies to drive a considerable demand squeeze on power semiconductor devices for at least the next decade. With GaN and SiC production capacity limited globally, there is a substantial opportunity for the UK to make up for lost ground in the power semiconductor market in general and secure supply chains by leveraging all the current activities in compound semiconductors together with legacy silicon production capacity.
Using these two groups of assets (emerging compound and legacy Si production) together would have the largest single positive impact on the UK's power semiconductor industry.

Low to mid volume, advanced semiconductor packaging

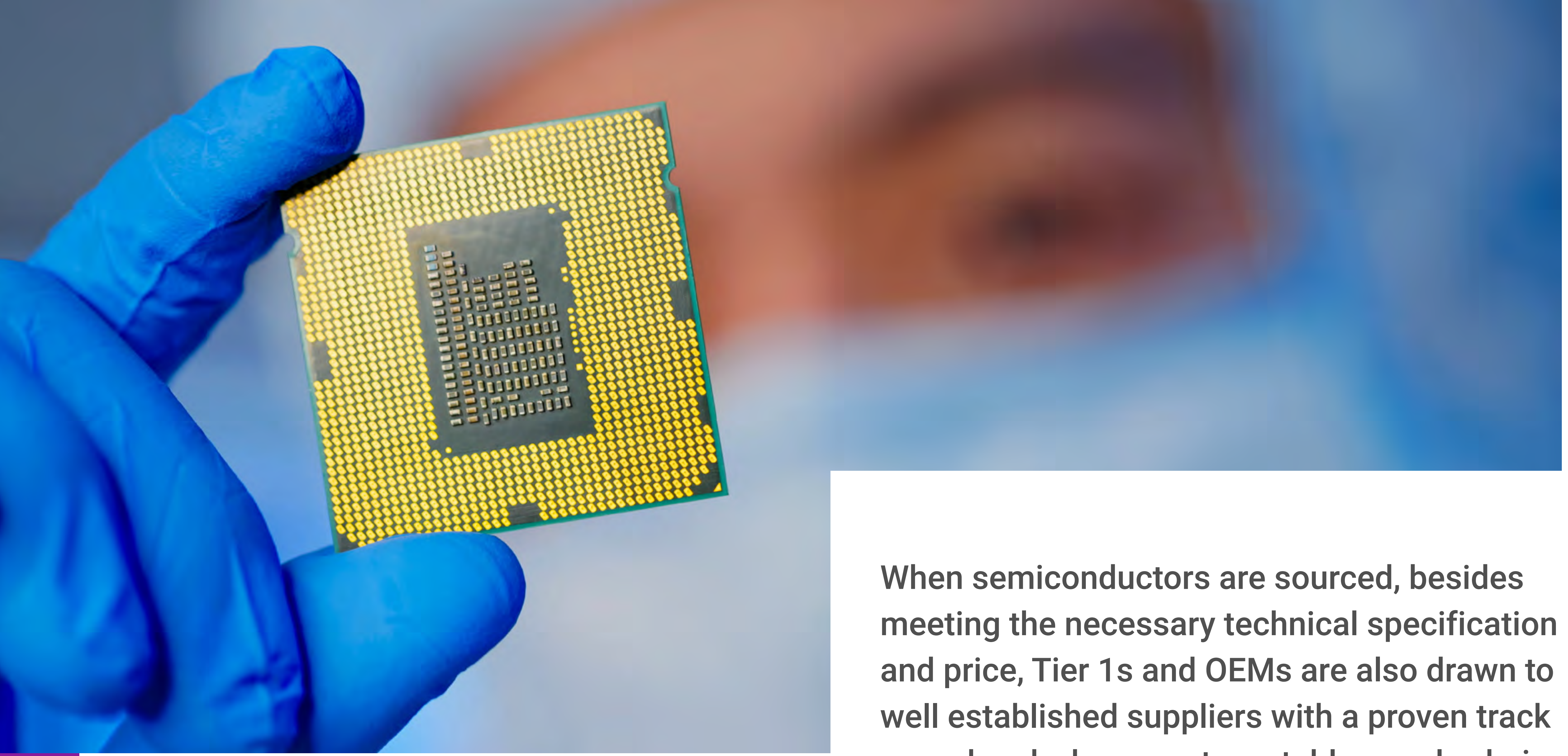
Over the last three decades the vast majority of semiconductor packaging operations have moved to Asia, where advanced, expensive semiconductors are able to be packaged cost competitively. It is worth noting, while end customers are willing to pay for the functionality that the semiconductor chip itself brings, the same does not apply to the package that goes around the die (chip). Nonetheless, and especially in the power world, the package plays an essential role in making the semiconductor a practical reality.

Given the very cost competitive nature of semiconductor packaging, the UK has no high-volume discrete power semiconductor operations. Indeed, this picture is replicated in much of Europe and the US, where high-cost regions can't compete with the low cost base and economies of scale offered by discrete packaging suppliers (assembly houses) in Asia. Nonetheless it should be noted, when it comes to packaging for power modules (multiple devices in one package), the global manufacturing landscape is far less Asia centric with large module production operations in Europe, Japan, and the US, albeit often with sister sites running legacy products on equivalent lines in China.

The UK has both highly regarded packaging R&D centres for global semiconductor companies and a handful of packaging suppliers with UK manufacturing operations which are mainly focused on lower power, multi-chip modules and Printed Circuit Board Assembly (PCBA) products. There are also a handful of suppliers producing very high-power devices in press-pack ('Hockey Puck') packages for transmission, traction and renewable applications. This type of packaging typically houses thyristor type devices which were outside the scope of this report so not analysed in detail at this stage. Nonetheless all of these suppliers are primarily developing products for high reliability, or volume limited markets such industrial, transportation, medical and aerospace with product volumes being in the ~100k units a year, compared with the multi-million-piece units a year for discrete MOSFET, IGBT devices that are assembled overseas. Working at a modular level, with a wide variety of processes, technologies and a highly customisable and agile approach these UK based packaging suppliers have been able to work competitively, on a wide range of solutions that add considerable value compared to mainstream overseas packaging houses.



There are considerable growth opportunities for this sector if the advanced and innovative technologies being employed today such as sintering, chip embedding and high temperature operation, can be scaled up to address the major growth markets for power semiconductors, namely automotive and renewables. We believe these opportunities to be realistic, not only due to the strong drive of the companies we met in the course of this research, their technical capabilities and track record, but also due to the supply chain squeeze for power semiconductors mentioned above; backend will face the same demand pressures as front end operations if net zero goals are to be met.



When semiconductors are sourced, besides meeting the necessary technical specification and price, Tier 1s and OEMs are also drawn to well established suppliers with a proven track record and who operate a stable supply chain.

UK's unique approach to power electronics

Although the semiconductor industry is deeply technical, the choice of a certain semiconductor technology or product in a system is rarely a decision based purely on a technical data sheet. Due to the criticality of these components and the complexity around manufacturing, in application usage, quality and supply chains the softer, less tangible factors around a supplier's capability come into play when governing success in global markets. Customers understand that the complexities of semiconductors are such that if there are issues, they are highly reliant on their semiconductor supplier to solve such issues, so look for partners and supply chains that are dependable.

Furthermore, especially in power electronics, with the rush to more electric solutions there is great pressure on OEMs and Tier 1s to solve complex technical challenges in short time periods in increasingly competitive markets. To do this they need to work hand in hand with vendors further down the supply chain, especially power semiconductor vendors. Therefore, **the ability to work in a close, innovative way with a semiconductor supplier is of increasing value. This is illustrated by the changes in supply chain dynamics that have occurred over the last decade**. Traditionally the main point of contact with semiconductor vendors was the Tier 1 manufacturer and then this manufacturer would supply a 'black box' of electronics to the OEM. This strictly hierarchical way of operating has changed dramatically over the last decade, with Tier 1s but also OEMs are far more involved in the specification and sourcing of semiconductors and even in the device design and pursuit of supply chain partnerships. As complexity and functionality of electronics systems increases, both technologies and supply chains are becoming more integrated.

Based on the work done in this report, **industry believes that the UK is strong in innovating in an agile way and adopting a pragmatic approach to problem solving and collaborating on new technologies.** Industry partners were able to speak to several examples, especially in the power system arena, where they were able to solve a customers' problem quicker and with a more novel technical approach compared to international competitors that preferred to offer conventional 'off the shelf' type of solutions. At least in self-reflection, industry believed the UK approach to power electronics innovation to be unique, while hard to measure there are notable examples of large overseas companies (Continental, Daimler and Turntide being recent examples) making inward investments to acquire UK power electronics-based businesses, then retained those sites as key assets in their global R&D operations. In terms of further differentiating the UK's power semiconductor abilities versus international competition, Germany, Italy, France, Japan the US and China are home to the largest power semiconductor entities. While it could be imprudent to make generalisations or comparisons on a regional level, each of these regions will have a very different mix of semiconductor heritage, quality and supply track record and approach to innovation and problem solving compared to the approach taken in the UK, thereby giving ample scope for the UK to differentiate and bring value.

Furthermore, several of the Tier 1 industrial partners interviewed were keen to stress that **the UK also has some strong 'power semiconductor adjacent' industries especially in magnetics, motors, switch gear and PCB stencil design. With systems becoming more integrated, there is opportunity to further strengthen the UK power semiconductor landscape with increased collaboration with the wider power electronics industry, bringing bilateral benefits**.

UK power semiconductor weaknesses

While the UK has undoubtedly some very strong attributes in the global power semiconductor supply chain, there are some notable gaps, which if not addressed risk seeing the industry fall onto an unsustainable footing. Some of the key challenges identified are outlined in more detail in Figure 6.

Talent development

Access to a suitably experienced and qualified workforce was universally the number one challenge for the industrial partners interviewed and it has therefore considered as a major weakness in the UK Power Semiconductors landscape, across all stages of the supply chain. It is worth noting that all the industrial interviewees raised this issue without being prompted.

The talent gaps identified mainly fall into three distinct groups:

- **UK electronic engineering graduates:** From an industry perspective, although UK graduates are well qualified on the theory of basic power electronic components and circuits, there are often gaps around the practical application of their know how, especially in power electronic applications. It is not sufficient for

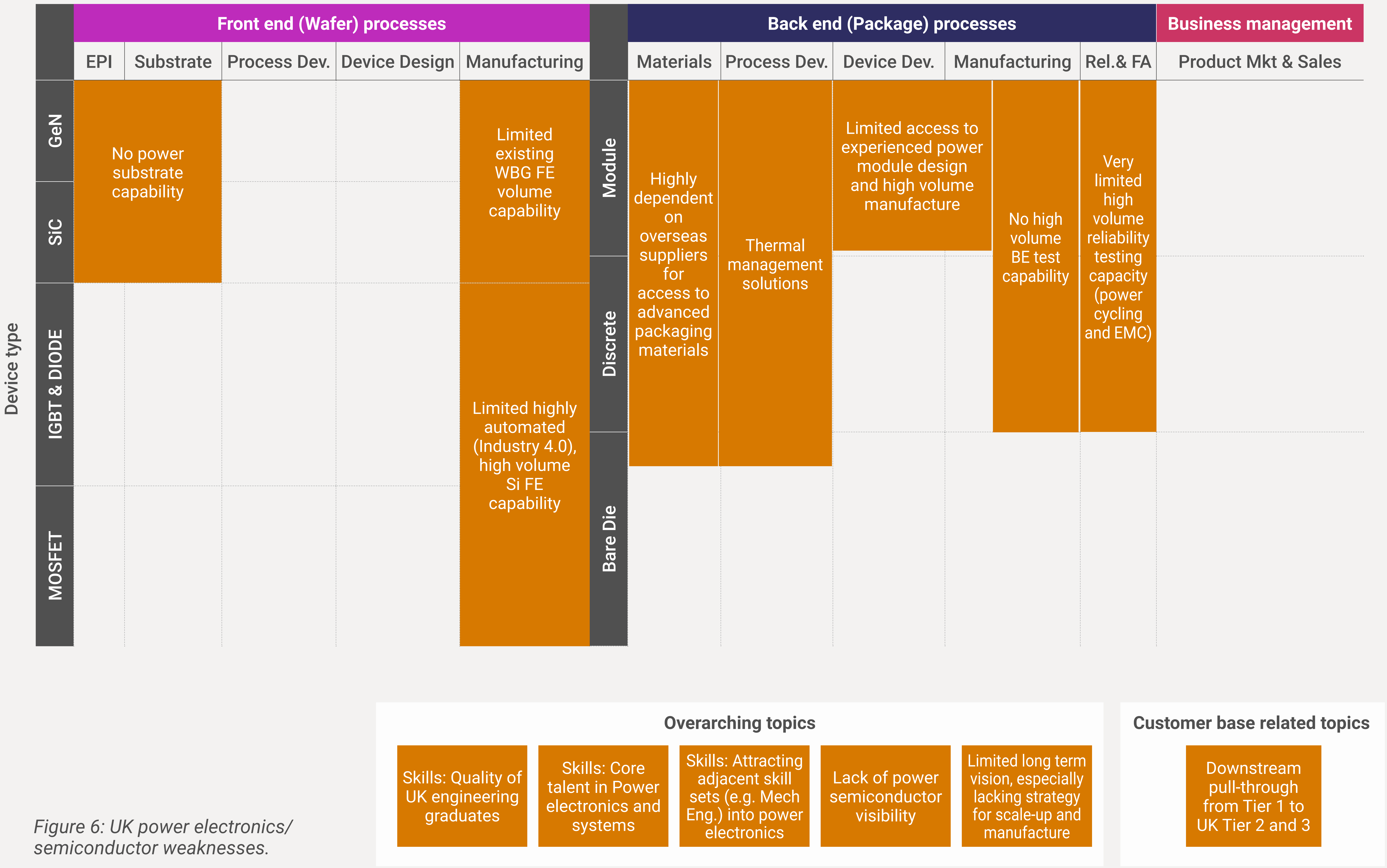


Figure 6: UK power electronics/ semiconductor weaknesses.

students to have just studied the theory of power semiconductor devices, they need to understand why the electrical properties of different devices are important and how these can be of practical value (or limitation) in a power electronic system.

■ **Core talent for power electronics and power semiconductors:** Through the 90s and early 00s with the comms and mobile industry boom the more digital side of electronic engineering was a highly popular field for EE graduates. This has meant that historically industry has had a smaller pool of candidates to pull on in the power electronics field. These challenges continue today with notable gaps in power device design, process design, application engineering, thermal design and power systems engineering. Industry partners interviewed also struggle to recruit engineers who are able to lead complex projects and have a system engineering mindset.

It should also be noted that the talent gaps cover the whole skills spectrum from low to high skilled. Several examples were identified that showed that even attracting entry level or unqualified people into the industry is proving tough, with many open positions for factory operators and lab technicians being among the roles which are routinely hard to fill. In many cases industry partners are open to onboarding new employees with no technical background whatsoever. But even this relaxation of selection criteria in reality does not appear to have unlocked a large pool of talent due to the strong desire for many to work from home and a wish not to pursue shift work, even if well remunerated and with good prospects for progression.

■ **Attracting adjacent skill sets into power electronics and power semiconductors:** Due to the complexity of power semiconductors and the systems they go into, the expertise needed to develop, produce and use such devices goes well beyond electronic engineering. Expertise in materials science, chemical engineering, thermal design, system design and mechanical engineering are vital to the success of the UK PE & PS supply chain. However, many graduates and experienced professionals in these 'power adjacent' sectors often are not aware of the opportunities that are available in the 'electrical world'. The UK has a workforce that is well skilled in these adjacent fields, but the UK PE & PS industry sees a weakness in getting these workers into their sector.

Visibility and strategy

As reflected in the skills gap, there is a general feeling in the Power Electronics (PE) & Power Semiconductors (PS) industry of a lack of visibility versus other areas of electronics and semiconductors. Notably this lack of visibility is very stark when PE & PS is compared to the general understanding in the wider population about electronics which naturally gravitates around digital type electronic systems and 'computer chips'. As outlined earlier in sections 1.1 and 1.2 of this report, given the importance of all types of semiconductors and the different needs and dynamics of these different semiconductor technologies, the poor visibility of PE & PS is not helpful in setting this sector up for success versus other electronic and semiconductor sectors.

The challenges around the poor visibility of the PE & PS sector are compounded by the lack of a long-term strategy that focuses on the specific dynamics of this sector. The UK power semiconductor supply chain eagerly awaits to see how the Government's National Semiconductor strategy develops and hopes that the strategy will evolve to support the varying needs of different parts of the UK semiconductor supply chain.

During the course the investigations existing government support was a frequent topic raised at interview. Feedback was generally positive towards existing support schemes that support R&D and early-stage development. However, a common theme in the feedback was how weak the UK is at building on this early-stage government investment and following through to high volume production. There is a chronic lack of support for scale-up, to take small to medium size businesses to the next level. It was also frequently remarked by industry that manufacturing (even very technologically advanced) appears to be a poor relation to R&D in the eyes of government support schemes. It should be noted that the support for scale-up is distinctly different than the support to retain existing large legacy manufacturing companies in the UK. Also due to the highly complex nature of semiconductor technologies, their sensitivity to manufacturing conditions and tool sets and the iterative process needed for R&D, good development and volume manufacturing must be intrinsically linked for sustainable success.

Automated front end manufacturing

While legacy front end wafer fabs are identified assets to the UK power semiconductor supply chain earlier in this report, these substantial assets are at risk with respect to future contribution to the UK power semiconductor supply chain. The legacy high-volume front-end manufacturing in the UK lags behind international competitors in two respects.

Firstly, while the UK supply chain is capable of producing power devices on ultra-thin (~70 μm thick) wafers with advanced front metallisation needed for next generation packaging, existing UK production sites are limited to wafer diameters of 200mm for power devices. This is in contrast to the majority of new front end production capacity being constructed overseas at this time for the same types of semiconductors which are increasingly being produced on 300mm diameter wafers. Going to the larger wafer diameter allows semiconductor fabrication to leverage greater economies of scale, typically reducing individual chip costs by 20-30% compared to those produced on 200mm diameter wafers. This economy of scale improvement is of benefit to both legacy semiconductor technologies that need cost improvements to remain viable throughout their long lifecycle, and for new generation devices, where the end market aggressively pursues power semiconductor switch technologies that offer the best performance for lowest cost ($/A performance).

Secondly, new overseas front-end fabrication plants for all types of semiconductors, are now heavily reliant on implementing Industry 4.0 levels of automation. While it is common for individual tool sets to run in an automated fashion in wafer fabs, the cassettes of wafers (wafer lots) are often manually moved around the fab and between tools, with an operator then calling up the required recipe for a given product on each machine as a given wafer lot is loaded. This is the standard process used in majority of the UK's legacy high volume fabs. The latest newer generation overseas fabs however, are implementing much higher levels of automation with overhead transport systems or Automatic Material Transport Systems (AMTS) being implemented that automatically move cassettes of wafers around the clean room and between tools. Such systems ensure that wafer lots are moved accurately and speedily through the factory; shortening cycle times, reducing production bottlenecks and overall improving the cost effectiveness of the wafer fab. Adopting Industry 4.0 levels of automation has enabled severall large global semiconductor companies in the US and EU to re-shore wafer fab operations from the far east in recent years and adoption of automation will be vital to sustain the UK's considerable legacy front end power semiconductor production capabilities in the medium to long term.

Packaging materials supply

While UK Tier 1s noted that they struggle to get access to local experienced, high power module design expertise and volume manufacturing supply, the UK has a small but vibrant footprint of low to medium volume multichip module packaging and PCBA production capabilities. The offering from these companies today is either in lower powers or smaller volumes than needed for the next generation, mass market more electric applications like EVs and renewables.

However, this part of the UK power semiconductor sector is eager to grow and develop new, differentiated products by leveraging new materials and processes.
In power semiconductors the importance of materials can't be overstated. As much as the package not only needs to protect the physically fragile and delicate die (chip), power packaging must also allow heat to easily be extracted (low thermal resistance) from the die and high currents to flow through the die with ease (low resistance) and be switched efficiently (low inductance). Therefore, the use of advanced materials is of great value when packaging both silicon technologies and newer compound semiconductor devices.
Advanced thermal interface and thermal management materials are also an important consideration when Tier 1s take power semiconductor devices and incorporate them into their power electronics systems.

In both of these respects the UK is highly dependent on overseas suppliers (largely based in Japan) for many of these key materials. While the UK has a variety of smaller materials companies which are developing new and innovative materials to rival the established overseas players, many of these technologies are still in development, yet to be scaled up or not fully exploited by the UK semiconductor packaging industry today. With the UK power semiconductor packaging supply chain being so heavily reliant on overseas suppliers for key materials, this results in supply chain security concerns and early access to next generation materials as being challenges for this sector.
It should be noted however that the market dominance of very well-established Japanese companies in this sector also affects global power semiconductor packaging companies outside of the UK; this is not a unique vulnerability to the UK.

Testing and reliability

In order to successfully make the transition from fossil fuels to more electric systems, the new electrical systems must not only be performance and cost effective, but also be highly reliable. This is particularly true in safety critical applications like automotive aerospace. To prove reliability, semiconductors must be subjected to thousands of hours of reliability testing and at a system level whole circuit boards must be tested to ensure they are reliable and also do not cause unwanted disruption to other electrical devices through Electromagnetic Interference (EMI).
Doing the reliability testing on power semiconductors and EMI (or Electromagnetic Compatibility (EMC) testing on systems is expensive and time consuming. Often very specific equipment sets are needed and the tests form part of an iterative R&D cycle. In the course of this work multiple industry partners highlighted the limited availability of reliability testing resources in the UK. Two specific gaps that were identified was access to adequate power cycling test capacity, and also access to facilities to undertake system level EMC certification. In EMC certification, the finished system is subjected to tests to ensure it does not have the potential to cause unwanted interference with other electronic systems.
In power cycling, the power semiconductors are subjected to repetitive, high-power loads that are designed to replicate the conditions that the power semiconductor will see in the real-world application. It should also be noted that a shortage of power cycling capacity is a problem experienced by many power semiconductor companies globally and it can cause a great bottleneck in the development pipeline of new products and technologies.

Section 6: Recommendations

The research and analysis undertaken in the course of this report has flagged up a number of opportunities and threats for the UK power semiconductor industry and the wider power electronics ecosystem. Below, based on the observed UK situation and benchmarking of international competitors are a set of high-level proposals to strengthen the UKs power semiconductor supply chain. Further work is needed to add specific details to the proposals below and in some instances, adoption will likely be needed.

1. Put UK front end activities onto a sustainable commercial footing

Globally, the power semiconductor industry is at a crossroads; while silicon products will continue to be manufactured in very large quantities for the foreseeable future, the rapid ramp up of compound devices brings considerable uncertainty for silicon based high voltage power switches such as IGBTs and Super Junction MOSFETs with opinions divided on just how much of this market will be superseded by compound devices. However, compound devices are already playing a major part in the power semiconductor landscape. Nonetheless a key advantage that silicon devices currently have is around economies of scale and cost competitiveness – silicon technologies will have to foster these strengths to bring value versus compound type devices.

Despite this dynamic environment, the UK has strong existing activities in both fields that should be fostered to help the UK power semiconductor industry navigate this technological change.

It is recommended that the following are undertaken:

a. Develop a national scale-up strategy for compound semiconductors through:

   i. Supporting existing dedicated SiC low volume capacity to take the next step to higher volumes through incremental investment.

   ii. Assessing the technical and commercial feasibility of adapting existing high volume legacy silicon capacity for SiC and GaN on silicon fabrication.

b. Provide support for all UK fabs, especially legacy silicon high volume power fabs to adopt higher levels of Industry 4.0 automation in the first instance and also consider wafer diameter increases.

2. Take a differentiated route in packaging (back end)

As outlined earlier in this report, UK packaging operations are sensitive to a high reliance on overseas material supplies and needing to keep the product offering differentiated versus very high volume, cost competitive assembly houses in Asia.

It is recommended that the following activities are pursued:

a. Foster links between UK material suppliers, UK power semiconductor packaging and Tier 1 industrial partners, with a view to develop new innovative packaging and material solutions for next generation products rather than actively look to displace specific products from large incumbent overseas material suppliers.

b. Support UK power semiconductor packaging companies to step into higher power (>50kW) module technologies needed for net zero applications by:

   i. Fostering collaboration with front end wafer fabs to enable new novel die-package interaction challenges to be solved and technologies to be implemented (e.g. die stacking and chip embedding) that will add system value.

   ii. Supporting custom package development activities between UK OEMs/Tier 1s and UK back-end manufactures. Not with the aim to develop new mass market standard packages, but rather high value, medium volume solutions who's development will especially benefit from the UK's agile approach to innovation.

3. Power chips talent development

There are many national initiatives to enhance science and technology focus in education and workplace training. However, in order to maximise the strengthening of talent and skills in the power semiconductor space it will not be sufficient to rely on general schemes to enhance science and technology and hope that there will be a trickle-down effect. It is our opinion that the market is too crowded and the skills too short (both in the UK and overseas) for an indirect approach to have a meaningful impact. Instead, initiatives such as the Electric Revolution Skills Hub (ERS) with precisely defined knowledge areas for PE and PS should be strengthened further, to provide a highly relatable and engaging set of initiatives, to improve the following areas in particular:

a. Visibility of power semiconductors both in schools and universities, but also wider society. Semiconductors are already one of the core technological building blocks of this century and industry and government should collaborate to ensure a minimum level of understanding is achieved.

b. Ensure that for those wishing to pursue studies and education in power electronics and power semiconductors, there is strong pull-through of UK students from secondary education into industry either directly into the workplace or via higher education. This pull through will require specific steps to change the narrative around engineering and power electronics and should also include specific semiconductor and power electronics elements added to A-Level Physics curricula.

c. At a graduate level teaching of power semiconductors should encourage an emphasis beyond device physics and basic circuits (ERS device knowledge areas 1, 3 & 4) to focus more on end applications and how the device level performance trade-offs have tangible implications in the application (Device knowledge area 5 and power Electronics knowledge areas 17, 18, 19 & 20).

d. Increased focus on power system design and system integration at graduate level (ERS drives knowledge areas 2 & 3, power electronics knowledge areas 12, 13 & 14 and devices knowledge areas 8, 9 &10).

e. Cross sector promotion of power semiconductor career opportunities at a graduate, post-graduate and industry level particularly in the fields of mechanical engineering, materials science, physics and chemical engineering.

4. Unlock the UK power electronics and semiconductors ecosystem

a. Expand activities to stimulate more industry activity and collaboration at the Tier 3 and Tier 2 levels. In addition, foster collaboration between power electronics and adjacent digital and sensor technologies to enable 'smarter' power solutions.

b. Foster pull-through, particularly to strengthen the link between OEMs and Tier 1 and the UK Tier 2 and Tier 3 supply base. Undertake initiatives to help UK Tier 2 and Tier 3 to better promote their activities further up the value chain and for OEMs and Tier 1s to better identify such players vs. more established international competitors.

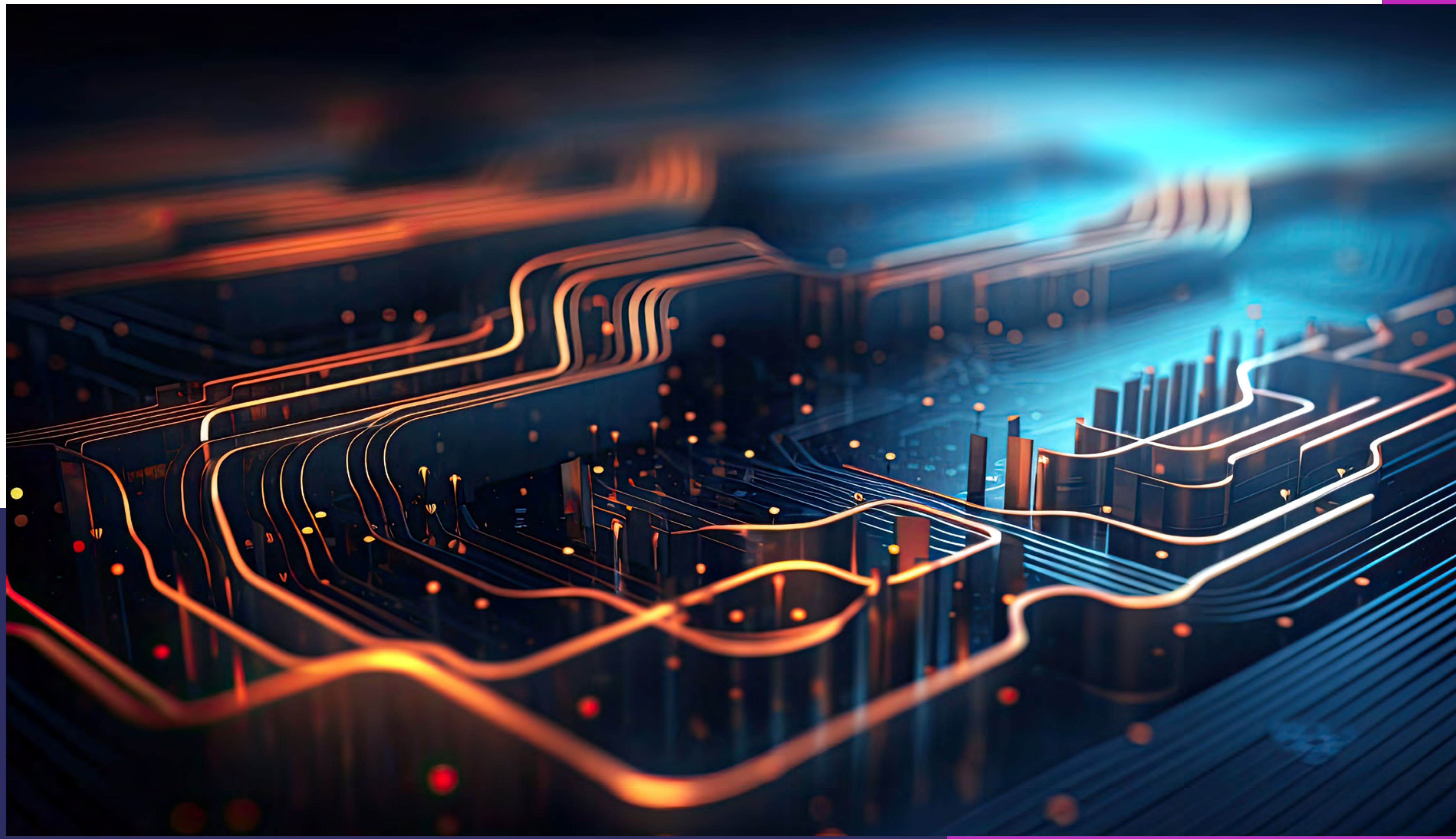
c. Undertake focused investments to indirectly help the whole value chain to better scale-up and be more competitive by identifying and setting up 'core services' that can be drawn on by any industry partner with consideration specifically in reliability testing, failure analysis and electromagnetic compatibility testing.

Section 7: Conclusions

The huge technological transformation away from fossil fuels, to more electric solutions will be highly reliant on power semiconductors which are a key enabling technology. Net zero applications like electric cars, heat pumps, renewable energy sources, smart grid systems and efficient lighting and heating systems all have power semiconductors at their heart. To make a transition away from legacy fossil fuel solutions, the new technologies must do everything that the legacy carbon-emitting solutions could do, but better, and more cost effectively. Power semiconductors will be instrumental in enabling the required cost-performance targets to be achieved to make these carbon-neutral applications viable.

All of these applications will require new types of power semiconductors to unlock their full intended potential; recycling legacy products and technologies will only deliver a portion of the success that is needed to move away from fossil fuels. Similarly, the huge increase in power semiconductor content (number of devices per system) in these new more electric applications will fundamentally and permanently increase demand for power semiconductors over the next decade as illustrated in Section 5.

This is the very moment when power semiconductors have their time. Based on its semiconductor heritage, unique approach to innovation and both the front end and back-end manufacturing and development sites that already exist today, and their specific capabilities and roadmaps, the UK is very well placed to benefit from this global mega trend. But due to the intensely bright prospects and critical nature of power semiconductors, many other global players are keen to exploit this opportunity. The UK already has many of the key ingredients, but a supportive, stable, long-term environment needs to be put in place to secure and unlock the UK's power semiconductor prospects.



"In line with the recommendations in this report, it is vital that proactive national strategic initiatives are undertaken, to ensure that the UK has the necessary power semiconductor capabilities in a sustainable form to meet the UK's technological and economic aspirations and net zero commitments going forward. This is important because power semiconductors will enable new low cost, high performance, carbon-neutral applications to be created."

Venn Chesterton, Deputy Challenge Director – Driving the Electric Revolution Challenge, Innovate UK

Section 8: Next steps

Feedback

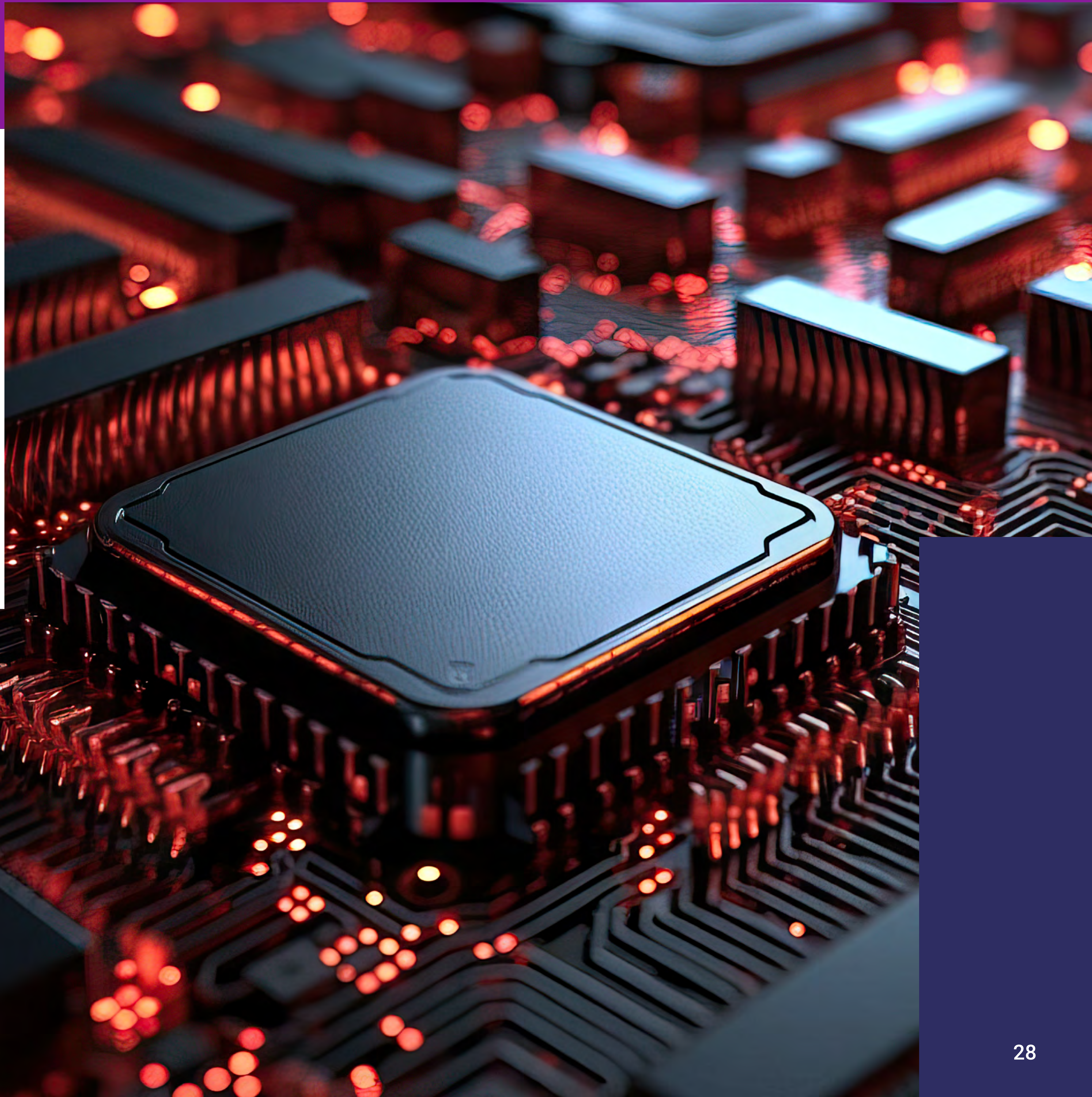
Firstly, it should be noted that this is an interim readout of the UK Power Semiconductors Landscape Report. The authors are keen to receive feedback from all stakeholders with UK based power electronic and power semiconductor operations through the Driving the Electric Revolution Challenge team.

Further investigations

The suggestions above are from the interim findings of the work done, and as mentioned in section 2.0 the authors are still keen to engage further with more industrial partners to develop a fuller picture of the UK power electronics and power semiconductor landscape further. In particular the team would like to engage with companies working in the GaN and more legacy silicon front end manufacturing.

Formulating a strategic plan

As feedback is incorporated along with additional investigations, the report team will now be working to see, in collaboration with the National Semiconductor Strategy how the recommendations in the UK Power Semiconductors Landscape Report can be taken forward, either as focused power semiconductor specific initiatives as part of the national strategy or as separate undertakings which can help strengthen the existing national strategy.



Appendix 1
Industry participants

Industry review workshop participants

Name	Organisation (as of May 2022)	Position (as of May 2022)
Dr Will Drury	Driving the Electric Revolution Challenge	Challenge Director
Jillian Hughes	NMI Networks	NMI Networks Director and Office Manager
Dr Paul Huggett	Knowledge Transfer Network	Interim Head of Industrial Technologies and Manufacturing
Ben Jackson	BDJ Group Ltd.	Power Semiconductor Consultant and workshop lead
Dr Chunjiang Jia	Offshore Renewable Energy Catapult	Principal Engineer, Power Conversion
Dr Alastair McGibbon	Compound Semiconductor Applications Catapult	Head of Business Development
Professor Phil Mawby	University of Warwick	Head of Electronics Power and Microsystems
John Regnart	Advanced Propulsion Centre	Automotive Trend Strategist
Mark Urbanowski	Driving the Electric Revolution Challenge	Innovation Lead

Contributing industrial partners

Name	Position in supply chain	Focus Area
Clas-SiC Wafer Fab	Tier 2, Front end	SiC power semiconductors
Control Techniques	Tier 1	Power electronics (industrial)
Custom Interconnect	Tier 2, Back end	Power semiconductor packaging and Printed Circuit Board Assembly (PCBA)
McLaren Applied	Tier 1	Power electronics (automotive)
Microchip	Tier 2, Back end	Power semiconductor packaging
Siemens	Tier 1	Power electronics (industrial)
Turbo Power Systems	Tier 1	Power systems (industrial, renewables, grid)

Appendix 2
Glossary

Back end The portion of the semiconductor manufacturing process that is concerned with taking the output of the front end manufacturing (e.g. Bare die) and placing the die into a semiconductor package (see packaging). Back end is also often referred to as the Assembly or Back end assembly process.

Bare die (Die) A single semiconductor device (or chip) that has been cut out (singulated) from a semiconductor whole wafer.

Compound semiconductors Whereas legacy semiconductors are fabricated from one element (typically silicon), compound semiconductors are semiconductors that are made from two or more elements. Examples include Silicon Carbide (SiC) and Gallium Nitride (GaN). Such devices are also often referred to as wide band-gap semiconductors, thought not all wide band-gap devices are necessarily compound of more then one element.

Driving the Electric Revolution Driving the Electric Revolution Challenge, is an £80m Innovate UK initiative running from 2019 to 2024 to invest in electrification technologies, including power electronics, machines and drives (PEMD). The investment will support the UK's push towards a net zero carbon economy and contribute to the development of clean technology supply chains.

Discrete A single semiconductor device (bare die) housed in its own package. See modules.

Economies of scale The cost reduction advantages that a factory or wider organisation may achieve by ramping up volume or size of activities undertaken. Due to the very high up front capital costs involved in developing and manufacturing semiconductors, achieving (or having access to) good economies of scale is essential for any semiconductor business to be viable.

EDA Electronic Design Automation – a category of computer-aided design tools that are used to design electronic systems, circuits and components, including semiconductors.

EE graduates Electrical or Electronic Engineering graduates from either an undergraduate degree (e.g. BEng) or post graduate degree (e.g. MEng and higher).

EMC Electromagnetic Compatibility (EMC). Describes the ability of electrical and electronic equipment and systems to function without causing unnecessary electromagnetic radiation to occur or being adversely affected by reception of electromagnetic radiation from other electrical and electronic systems which may cause unwanted effects such as electromagnetic interference (EMI).

EMI Electromagnetic Interference (EMI) is the unwanted effect of electromagnetic energy that is generated by another electrical or electronic system which then interfere with the operation of other systems causing their performance to degrade or stop functioning altogether.

Epitaxy The process of growing semiconductor compounds in the form of thin uniform films on a base substrate wafer. These films then act as a foundation (or staring layer) on which specific semiconductor devices can be created through photolithography in the wafer fab.

Front end The portion of the semiconductor manufacturing process that is concerned with taking the raw semiconductor substrates (e.g. Silicon wafers) and creating semiconductor devices on these wafers. The final output of the front end is either a whole semiconductor wafer or a ‘sawn wafer’ where the individual die (‘chips’) have been separated from each other. Front end is also often referred to as the wafer fab or foundry process part of the semiconductor supply chain.

Gallium Nitride (GaN) A type of wide band-gap compound semiconductor, which is able to be switched much faster and with lower losses than legacy silicon based semiconductors.

HV High Voltage. Exact value varies between industries, sectors, suppliers and customers. Assumed to be greater than 300V for the purposes of this report.

IC Integrated Circuit is a single semiconductor die that has multiple semiconductor devices on it (e.g. transistors) which are connected together to create a circuit which performs a specific functionality. ICs are generally low power, logic based devices used to aid the computation of functions in a wider system. However it is also possible to have Power ICs, where a portion of the IC is switching higher currents and voltages while another part is performing logic functions, in such an instance both the ‘compute’ and ‘actuate’ functions are on a single chip.

ICE Internal Combustion Engine with no hybridisation (see xEV).

IGBT Insulated Gate Bipolar Junction Transistor – this is a three terminal power transistor (electronic switch) that is used to control the flow of electricity in many applications in consumer, industrial, automotive, renewable and other high reliability applications. Typically these devices are used in higher voltage (>600V) applications and with moderate switching frequencies (10-80kHz), with motor control being a very popular application. Such devices are usually fabricated from silicon and advanced wafer thinning and ion implantation technologies are now employed to make the devices as efficient as possible.

Inductance The electrical property that describes an electrical conductor’s tendency to oppose the rate of change of an electrical current flowing through it. A conductor with a high inductance would strongly oppose a change being made to the current through it, which would result in energy loss when trying to turn the current on or off.

Industry 4.0 The 4th Industrial Revolution, describes the integration of intelligent digital technologies into manufacturing and industrial processes to achieve greater levels of automation and efficiency. Industry 4.0 can include many technological cornerstones, such at Artificial Intelligence, Internet of Things, Big Data and robotics.

LED Light Emitting Diode. A two terminal semiconductor device that emits light when an electrical current passes through it.

Logic devices Low power semiconductor devices that are used to perform logical computations by processing discrete ON (1) and OFF (0) signals. Logic devices can vary from simple logic gates, to customised Integrated Circuits through to Microprocessors.

LV Low Voltage. Exact value varies between industries, sectors, suppliers and customers. Assumed to be less than 300V for the purposes of this report.

Mask count Thee number of photolithography masks (or layers) that are needed to be used to build up a given semiconductor device. Usually the higher the mask count, the more complex and expensive the given semiconductor device is.

Memory A logic based semiconductor devices that has the ability to store information for it to be later recalled and used by the system.

Metallization The process of (or result of) adding a metallic layer to a semiconductor device to enable the connection of the device to the package and wider system. Metallization is typically applied to the under (back) side of the wafer and the top (front) side of the semiconductor wafer allowing it to be mounted in a package (typically through soldering or sintering) and electrical connections made.

Microprocessor (MCU) A microprocessor (or MCU or processor) is a logic based semiconductor in a single package that performs a wide variety of computing functions. The device will normally be a single die, that has the ability to perform many different functions, primarily built around arithmetic, logic, and control circuitry.

Module / Multi chip module A package that contains two or more semiconductor die. The die may be connected to each other with the module (package) or each have their own connections to the external environment.

MOSFET Metal-Oxide-Semiconductor Field-Effect Transistor – this is a three terminal power transistor (electronic switch) that is used to control the flow of electricity in many applications in consumer, industrial, automotive, renewable and other high reliability applications. Typically these devices are used in lower voltage (<600V) applications and with higher switching frequencies (>100kHz), with power supplies being a very popular application. Such devices are traditionally fabricated from silicon, but now increasing MOSFETs are made from compound semiconductors such as SiC and GaN. This move to wide bandgap technologies allows the MOSFET to switch much more efficiently at higher switching frequencies and also makes the devices viable at higher voltage nodes (~1200V) especially in the case of SiC MOSFETs.

Node size	A measurement (usually in nano metres) which describes the feature size that a given semiconductor manufacturing process can create. Generally the smaller the node size, the more complexity and functionality can be implemented in a smaller area of semiconductor. Node size is an important metric for logic based devices such as microprocessors, but it a much less meaningful performance metric for power semiconductors which do not need to be produced on ultra small node sizes to exhibit benchmark performance.
OEM	Original Equipment Manufacturer – definition varies by industry. In this report the definition is more aligned with automotive norms, namely a company that assembles various subsystems and components into a finished product that is sold to end-users, e.g. BMW, Ford, Toyota are vehicle OEMs.
Packaging	The assembly which houses the semiconductor die. The package physically protects the die from the outside environment as well as making good electrical and thermal connections to the outside environment, thereby allowing the semiconductor to operate efficiently and reliably.
PCB	Printed Circuit Board (Circuit board) – a substrate made up of both electrically conducting and electrically insulating parts, which allows components of many types to be mounted on it and be connected together to produce a functioning electrical circuit.
PCBA	Printed Circuit Board Assembly – the process by which a bare circuit board has various components attached to it (e.g. via soldering).
Power cycling	A testing process used on power semiconductor devices at the end of their manufacturing process (back end) where the devices is connected to power supply and an electrical load and then repeatedly turned on and off many times, thereby replicating the real world application conditions that the device would see in the field.
Power Electronics (PE)	This is the branch of electrical and electronic engineering which uses a verity of different component types (resistors, capacitors, connectors, circuit boards, semiconductors) to control large amounts of electrical power (high voltage and/or high current) in a wide variety of applications.
Power Semiconductor (PS)	A specific group of semiconductors used in power electronics systems. Power semiconductors can control the flow of large amount of electrical power, often replacing simple legacy mechanical switches or enabling new advanced and highly efficient functionality which could never have been possible to achieve using traditional means of controlling large amounts of electrical power e.g. using mechanical switches. Common power semiconductors include MOSFETs, DIODES, IGBTs fabricated in silicon, and also the same types of devices fabricated in SiC or GaN.
Resistance (Electrical)	Electrical Resistance is a measure of the opposition to current flow in an electrical circuit. Resistance is measured in ohms.
Semiconductor	A material which has a conductivity between conductors and non-conductors (insulators) and can be manufactured in such a way that the material has the ability to change its conductivity between a conductor and an insulator based on external factors acting on it (e.g. temperature, voltage, current, light, force, electromagnetic fields etc).

Silicon Carbide (SiC) A Wide band-gap compound semiconductor material that is comprised of the elements silicon and carbon. Two common SiC devices are SiC DIODEs and SiCs MOSFETs, both of which exhibit superior electrical performance when compared to legacy silicon based devices, albeit generally at higher cost.

Sinterable Describes the ability of the metallization on a semiconductor to form a sinter joint with another adjacent metals. Sintering is the process by which two separate metals can be joined through a process of compacting and forming a solid joint between the material by use of pressure or heat without melting the materials. A sinter joint will offer both good electrical and thermal conductivity. Sintering is increasing being used as an alternative to soldering to mount power semiconductors in their packages, owing to its better reliability and longevity of good thermal performance.

Solderable A surface that can have an electrical connection made to it via a process of melting a metal or metal alloy to join two metallic bodies together.

Thermal resistance How well a material resists the flow of heat. A good thermal insulator would have a high thermal resistance. In Power Electronics, it is desirable for components (including Power Semiconductors) to be housed in packages that have a low thermal resistance so that heat generated in the devices can be conducted away so that devices remain as cool as possible and thereby work efficiently and reliably.

Thyristor A three terminal power semiconductor device that allows an electrical current to flow in one direction through it when triggered by an external control signal. When the flow of current through the device stops, or tries to reverse, the device will no longer conduct until it is re-activated by the external control signal. Sometimes these devices will also be referred to as silicon-controlled rectifier (SCR).

Tier 1 Definition varies by industry. In this report the definition is more aligned with automotive and industrial norms, namely a company that designs and manufactures various subsystems form individual components (see Tier 2) and then sells the systems on to OEMs for integration into complete systems, e.g. Bosch, Continental, Delta would be examples of Tier 1 manufacturers.

Tier 2 Definition varies by industry. In this report the definition is more aligned with automotive and industrial norms, namely a company that designs and manufactures various individual components from raw materials and then sells these components to Tier 1 companies for integration into subsystems systems. Most semiconductor companies would be considered Tier 2 companies.

Wafer fab (Fab) A factory which takes semiconductor substrates as an input, and undertakes various processes on the wafer to modify the substrates to create additional layers and features that result in a semiconductor being produced. The output of the wafer fab is a semiconductor wafer with many die on one wafer, or a sinuated wafer with individual die separated. The wafer fab manufacturing portion of a semiconductor manufacturing flow is also known as the front end.

Wafer probe The process of using fine metal needles to form an electrical connection to specific terminals on individual die on a finished wafer. Typically performed before the wafer is sawn as an end of line test in front end to check the electrical performance of the semiconductor devices that have been fabricated.

xEV A vehicles with some from of electric propulsion i.e. where an electric motor is connected to the wheels of the vehicles for a portion or all of the driving cycle, e.g. Battery Electric Vehicles (BEV), Fuel Cell Electric Vehicles, Hybrid Electric Vehicles (HEV) are all forms of xEVs.

Yield Manufacturing or production yield is the expected proportion of products that pass all tests at the end of their production process, e.g. a yield of 95% would mean that 95% of products at the end of the production line tested as ‘good’ while 5% will have failed the final production test and be deemed as bad and can’t be sold.

Delivered by Innovate UK

About Innovate UK

Innovate UK, part of UK Research and Innovation (UKRI), is the UK's innovation agency.

It works to create a better future by inspiring, involving and investing in businesses developing life-changing innovations.

Its mission is to help companies to grow through their development and commercialisation of new products, processes and services, supported by an outstanding innovation ecosystem that is agile, inclusive and easy to navigate.

For more information visit ukri.org/councils/innovate-uk/

Follow us

Telephone: 01793 361000
Email: support@iuk.ukri.org
ukri.org/councils/innovate-uk/

10248.0424