FORESIGHTING REPORT

Power Electronics

For Members only

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V1.0

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ITI ENERGY INTRODUCTION

ITI Energy is one of three operating groups that make up ITI Scotland. Together with ITI Techmedia and ITI Life Sciences, we are investing in excess of £450 million over ten years in research and development. Publicly funded, but 100% commercially driven, our collective aim is to create new technologies and stimulate business growth in Scotland.

ITI Energy selects and invests in programmes based on assessing future market needs, identifying technology opportunities, and responding to ideas, initiatives and proposals from the research and business communities. We use our £150 million funding to commission and direct applied research projects in collaboration with partners from industry, academia and finance.

Throughout this process, we protect the Intellectual Property (IP) that our investments generate, enhancing its competitive positioning, and helping to bring the resultant technology to market.

Participation in our activities and projects is open to all businesses and research organisations, regardless of where they are located. We are based in Aberdeen, but our scope and vision is global. We closely follow research activities in other countries, and welcome involvement and collaboration from overseas. Our success depends on being able to develop new technologies that address market needs around the world.

Further information on ITI Energy may be obtained from Chris de Goey, Technology & Markets Director, ITI Energy on tel. 01224 282630 or email chris.degoey@itienergy.com.

EXECUTIVE SUMMARY

INTRODUCTION

This report captures the work that was performed by ITI Energy in its foresighting of Power Electronics. The results of a previous study into Future Power Networks (FPN) had indicated that the major breakthrough in FPN related technologies will come from new Power Electronic technologies. Also in other ITI Energy key interest areas –for instance renewables power generation, power storage and electric vehicles - Power Electronics forms an important aspect of the technology solution. The study therefore sets out to better understand the underlying Power Electronics technologies and their applications in the energy industry.

MAIN FINDINGS

The report provides an overview of current and emerging Power Electronics market applications, of Power Electronics devices and the underlying material and technology options and of the Power Electronics value chain. The main findings from the study are that:

- The Power Electronics market is worth $130Bn per annum and it will be of increasing importance to the electronics markets, which is greater than $1 Trillion
- Power Electronics is not yet widespread in applications for power generation, transmission and larger scale utilisation of energy. This is surprising as the related efficiencies would benefit these segments most
- Power Electronics are still expensive with a typical price tag between $250 and $350 per kW of managed power
- For high power applications (>10kW), Power Electronics make up only a fraction of these overall device cost, but determine some 70% of the overall costs
- Virtually all Power Electronics devices to date are made of Silicon. Although further technology developments are possible with Silicon, the use of this material is now being pushed to its theoretical limitations
- Other materials that are now entering the market at scale are Silicon Carbide (SiC) and to a lesser degree Gallium Nitride (GaN). These and a few other next generation materials have improved characteristics like wide badgaps and increased frequency. The downside for these materials is the cost to grow substrates of sufficient size and quality as well as the difficulty in doping the materials
- The above mentioned strengths and weaknesses of new materials apply even more for Diamond, which can be seen as the next generation solution
- The supply chain for Power Electronics is made up of materials manufacturers, device manufacturers, application manufacturers and end-users/integrators. Whereas for Silicon these different parts of the chain are largely separated, for SiC and other new materials we have observed a vertical integration
- SiC technology is mainly developed and commercialised in the USA, Sweden and Japan, and companies like Cree start to dominate the market. The UK is well represented in Diamond, through companies like Element6 and Universities like Heriot-Watt, Cambridge and University College London (UCL).

POTENTIAL TECHNOLOGY DEVELOPMENT AREAS

Key areas of technology development that were identified are:

1. Hybrid Semiconductors
2. Wide Bandgap Semiconductors
3. Grid Connection Electronics
4. Novel Device Packaging & Cooling Technologies
5. Open Source Architectures

ITI ENERGY AREAS OF INTEREST

ITI Energy considered the above identified technology development opportunities and investigated how they best fit with our current R&D portfolio and strategy. Our conclusions are that there are 2 broad areas with considerable opportunity for new technology development in Scotland:

1. Smart Silicon Hybrid Devices
2. New Material Devices with characteristics that go beyond what Silicon devices can achieve

1 – Smart Silicon Hybrid Devices

With Silicon devices reaching the limits of their capabilities in high power applications, potential significant gains can still be made by integrating Silicon technologies on one chip, thereby reducing space, increasing speed and efficiency of the device. Important markets for this technology include electric vehicles and micro-power generation. The key drivers for this technology therefore are: cost, weight, reliability, volume, low component count, low power losses and high conversion efficiency.

Skill sets that are required to develop new technologies in this area include:

- Converter design (control & hardware)
- Power Electronics device design
- Modular packaging
- Software design (embedded)
- Test/realisation skills

ITI Energy intends to launch a programme in this area in 2007 and we are currently developing a more specific scope of work, as well as identifying potential collaboration partners.

2 - New Material Devices

Due to its physical limitations, Silicon-based technology cannot provide all the solutions that are required in the power markets. ITI Energy identified the following specific areas where new materials may provide a better alternative:

- Medium Voltage (10 – 15kV) AC device
- Extended temperature operational range higher than 150 degC and/or lower than -30 degC
- Ultra high reliability – in terms of radiation hardness, robustness, etc.
- High frequency

Again, these improved performance characteristics will need to be delivered at acceptable cost.

Potential market applications for new material devices include:

- Distributed power generation direct grid interface at greater than 5MW, for instance wind turbines
- Rail System 25 kV single phase
- Machine Drives
- HVDC (High Voltage DC)
- FACTS (Flexible AC Transmission Systems)
- Aerospace power systems
- Marine power systems

The first of these development opportunities can be further qualified as a switch that can operate at 22 kV and 500A with a forward voltage drop of less than 10V.

ITI Energy is exploring this opportunity further with the aim to launch a R&D programme in 2007. In particular, a choice needs to be made between the leading two new materials, Diamond and Silicon Carbide. For this programme we will also look for relevant skills and expertise first, before a detailed project definition can be established.

NEXT STEPS

Over the coming months ITI Energy will further define the potential for a programme in the two identified key opportunity areas. We will be proactively seeking related relevant technical skills via public calls. But we also encourage Universities, R&D organisations and companies to come forward with technology development proposals in this area, independent of calls. If you would like to discuss this further, please contact Chris de Goey on chris.degoey@itienergy.com

ACKNOWLEDGEMENTS

Although the direction and steering of the study was conducted by ITI Energy, a large part of the work was carried out by specialist Power Electronics consultancy, Procentricity Ltd.

We trust that this report provides a good overview of Power Electronics technologies for our members and that it allows them to come forward with related technology opportunities for potential ITI Energy investment in this exciting field.

ITI Energy would like to thank all people and organisations that have contributed to this report (see also Appendix 1).

OVERVIEW

This foresighting study commissioned by ITI Energy maps out and reviews development trends in Power Electronics with the purpose of identifying future opportunities for technology development. The findings indicate that significant change within the industry is imminent in light of emerging semiconductor technologies. Pressure to adopt new technologies is also growing due to an increasing market demand for solutions that yield better efficiency and support a sustainable energy future.

The Power Electronics market is worth around $130B, covering everything from power management IC's in handheld computers to high voltage DC schemes transmitting gigawatts of power. In an increasingly energy conscious world, Power Electronics is known to improve the effectiveness of electricity utilisation from the point of generation through to its end use. Yet Power Electronics accounts for just 10% of a global electronics market worth around $1,300B. With a global generating capacity of over 3,900GW the key question is therefore why is Power Electronics not more widespread? Particularly what are the issues that presently limit its application to the generation, transmission and larger scale utilisation of energy?

The study has identified that the reasons for the relatively limited adoption of Power Electronics are complex, with social, economic and technical origins. Power Electronics is a relatively new innovation in comparison to an electro-mechanical electricity infrastructure that is now over 100 years old. Many design philosophies currently used today can be traced back to the earliest days of electrical practice. Even now system planners and OEM designers often remain reluctant to embrace the benefits that Power Electronics can bring in terms of improved control and efficiency. Perhaps the most notable example is how the Power Electronics can mitigate the impact of distributed generation on a system with an ageing infrastructure by improving dynamic stability and reducing fault levels. Nevertheless growing consumer awareness and political intent towards increasing sustainability of energy resources is likely to drive unprecedented changes in practice over the coming decade.

From an economic standpoint, Power Electronics is often seen as an expensive option with a typical price of $250-350 per kW of managed power. For many burgeoning applications the electro-mechanical alternative is still considered to be the cheapest option. Yet this can often compromise efficiency. Utilities such as National Grid have calculated the capitalised value of energy loss to be over $5000 per kW. Applying this value to watts lost through non-optimal efficiency, Power Electronics has the potential to be a more cost effective option over the intended lifecycle. Sadly initial capital price is often the deciding factor. The key for economic use of Power Electronics lies not with taking an individual plant item approach but to consider its fully integrated use within the context of the entire system. Only then can costly redundancy and overcapacity imposed by outdated equipment standards be overcome.

Optimisation of Power Electronics to the intended application is key to its successful utilisation. Only by taking into account the relationship between the source and load controlled by Power Electronics can significant improvement in efficiency be derived, making the difference between something that is 85-94% effective to one that is 95-98% effective. This means that Power Electronics cannot be handled in purely generic application terms. The cost of Power Electronics lie not just with the hardware, but with the bespoke engineering (hardware and software) that is needed to adapt to a specific application. This means that scope exists to support innovators in both the volume as well as niche manufacturing sectors of the industry.

The major part of the cost problem for Power Electronics lie at the heart of the technology with the limitations of the active semiconductor components. For higher power applications much above a few tens of kilowatts Silicon has now been pushed to its intrinsic limits. The result is that while the value of the power semiconductor components in power electronic systems represents just a fraction of the overall cost, as much as 70% of the remaining cost is due to the complex array of ancillary components necessary to overcome the limitations of Silicon.

Over the past twenty years several replacements for Silicon have been proposed. Yet, as researchers have discovered, none have proved to be a straightforward replacement. It is only in the last two years credible commercial devices have started to become available based on wide bandgap materials such as Silicon Carbide (SiC) and, less so, Gallium Nitride (GaN). These have been made possible not by breakthroughs in device concepts, but by the fact that the underlying materials technology has been brought to maturity by the demands of the opto-electronics revolution of the past decade. Only now is Power Electronics benefiting from these advances. Already Schottky diodes made in SiC are attracting much attention because of the savings they enable by simplifying and eliminating the need for significant numbers of passive components.

The new generation of wide bandgap devices are not an obvious replacement for Silicon however. For a start they are presently almost 20x more expensive than their Silicon counterparts. Further the developers of these new devices are not the existing power semiconductor manufacturers, but smaller emerging companies who often also produce their own material. The key to growth for these new devices lies in applications that can make best use of their superior thermal, frequency and power density capabilities and justify a price premium. These markets are likely to be in the automotive, aerospace and marine sectors with integrators such as Rolls-Royce, Bombardier and Thales at the vanguard of this adoption.

The cost of producing wide bandgap base materials, even with volume, means that the new generation of devices will never be cheaper than Silicon. In many sectors Silicon will continue to be the base technology of choice and scope for innovation remains, particularly for hybrid devices that combine control intelligence with power control in a single package. In the UK companies such as Cambridge Semiconductor and Enecsys are known to be exploiting this route.

One sector that stands to gain the most from the emergence of wide bandgap semiconductors is the energy sector. Devices based on these materials should, in theory, be able to operate at voltages close to the typical utility distribution voltage (11-15kV AC). The availability of devices capable of operating at these voltages and switching up a few hundred amps could potentially halve the typical cost per kW of Power Electronics. This in turn could represent the economic tipping point for the adoption of Power Electronics in many energy applications. Voltage, however, is not a major issue for the most likely early adopter markets and therefore a gap exists to support developments that would achieve this goal.

The study has highlighted divided opinion about which wide bandgap material will yield effective high voltage power switching devices. While SiC is the front runner, mixed optimism has been expressed that devices based on SiC will be capable of operating at much beyond twice the ratings that Silicon has already achieved (around 3,500V working voltage for a single Silicon IGBT device). The only material that is expected to deliver this performance is Diamond. Several issues remain with Diamond, in particular the ability to make it function as a semiconductor material, plus the quality and availability of the material. To date, credible devices have yet to be demonstrated in diamond.

The mantle of the new power semiconductor market is being taken up by a new generation of companies, for which Europe and the UK are not well represented. In the case of Silicon Carbide much of the technology has evolved in the United States, supported by big sums of government defence money. This has enabled companies such as Cree to emerge as a leading player, not only as a materials supplier but also as device developer, suggesting a trend towards vertical market integration that does not exist in the Silicon electronics industry. In Europe only Sweden is known to have invested heavily in Silicon Carbide through government programmes and companies such as ABB. Already consolidation is occurring in these industries with ongoing mergers in the US and Japan. In contrast the UK does have recognised leadership in Diamond materials and devices through companies such as Element 6 and universities such as Cambridge, University College London and Heriot-Watt.

The emerging wide bandgap market also has implications on other areas of Power Electronics. Packaging methods and materials used to house the semiconductor die require improvements to cope with greater electrical and thermal ranges of operation. Device packaging is as high value an activity as manufacturing the semiconductor wafer. So too are advances needed in areas such as cooling systems technology and passive component design – the latter especially necessary to cope with the higher levels stress placed from higher voltage and frequency operation.

The UK does have pockets of excellence in the area of power electronic applications development. It is globally competitive at academic level through universities such as Strathclyde, Manchester and Nottingham. It is no coincidence that these universities have established strong ties with system integrator companies such as Rolls-Royce and Smiths Industries. In terms of industrial capability much of the UK manufacturing infrastructure has been lost, leaving only design offices. However there are a number of small–medium players who have demonstrated that strong niches exist for applications requiring design expertise.

A problem that faces all smaller players is the fact that developing Power Electronics is not cheap, particularly at the medium and high power end of the market. Mistakes can be costly and, as a result, this end of the market is left in the domain of major international players such as Alstom, Siemens and ABB, who in turn focus on the volume markets (e.g. machine drives). The result is that a gap exists caused by the extent to which universities and small players can extend into the hardware development of higher power, Power Electronics. Yet there is now a recognised need for further developments to support several emerging applications that is not being addressed by major companies because there is not sufficient volume to attract them.

The result is that developers are forced to either unsatisfactorily adapt products such as standard machine drives or seek even less attractive electro-mechanical options, both of which represent sub-optimal solutions.

For Scotland's developing renewable energy industry it is highly likely that Power Electronics will be an integral and significant element of the sector. The study has identified that the demand for Power Electronics is likely to be at two distinct power levels: 20-100kW systems (e.g. traction systems, building energy supplies) and 1-5 MW (e.g. onshore and offshore renewables). Each sector presents different issues. Having an infrastructure that supports and properly utilises Power Electronics, is going to be key to being globally competitive.

Power Electronics will be a critical element in the blueprint for future electrical systems, facilitating more efficient energy generation, better transmission and distribution of energy and better energy utilisation.

One notable point of consensus expressed by respondents to the study is that a key success factor will be the creation of a strong local geographic cluster. There are essentially four levels in the supply chain, which are: materials, devices, applications and integrators. Therefore key to building a successful globally competitive Power Electronics community is to support a portfolio of companies who cover the supply chain and who can leverage each other's technologies and skills.

METHODOLOGY

This study was commissioned by ITI Energy and performed by Dr Gareth Taylor of Procentricity Limited. It was conducted in two phases. The first phase consisted of a comprehensive review of technical literature, market reports and website information. This was then followed up by a series of interviews performed in person or by telephone (see contributors list in Appendix 1) using a checklist questionnaire resulting from the first stage. The interviews also focused on reinforcing or debunking a number of hypotheses that resulted from the first stage. At the end of each stage workshops were held with ITI Energy staff to discuss and review the findings.

Power Electronics represents a broad area of study. This report has deliberately focused on the applications and opportunities for Power Electronics in medium and how power applications (i.e. greater than 100kW). Particular emphasis has been given on the role of Power Electronics in energy systems and the underpinning technologies that will enable it to have greater impact. The study also aimed to identify key established and emerging players (where possible) at all stages of the supply chain from basic research to systems supply.

The key output of the study is to identify major areas for potential new technology development, within the field of Power Electronics, which ITI Energy could seek to invest in.

Where possible figures have been identified using published data for estimated market values and current price levels. However some of these figures are based on anecdotal information and should not be treated as being 100% reliable. The conclusions highlighted in the following sections of the report are those of the author based on a combination of his own background knowledge, the information collected while performing this study and that of the people interviewed. They should therefore be treated as subjective.

Section 1 - Power Electronics in the Energy Sector

The growth in power electronic devices is linked to the evolution of digital electronics. Originally Power Electronics devices were simple discrete devices intended to convert AC electrical energy to DC electrical energy with little or no control sophistication. However as the digital revolution kicked in, engineers realised that many more applications could be realised through more intelligent control of the action of the power devices. With the increasing speed of digital microprocessors the sophistication of the control systems has led to Power Electronics being able to provide highly flexible real-time control of electrical loads. In turn this has meant that the electrical loads under the control of the Power Electronics have been able to display performance and efficiency improvements that have justified the expense of what are often considered to be add-on systems.

Today Power Electronics systems are utilised at all stages of the electrical energy process from generation of electrical power, to management of flow through the electricity grid and finally to the management of power in applications all the down to hand held equipment. The market landscape for Power Electronics is shown in Figure 1 below. As the diagonal line shows it is clearly dominated, in terms of volumes, by the low power end of the market. In fact the largest market (by volume) is not shown on this graph, which is for active power management devices. These operate at 15V and below, handling currents up to a 100A in current and are often embedded in micro-electronic applications.

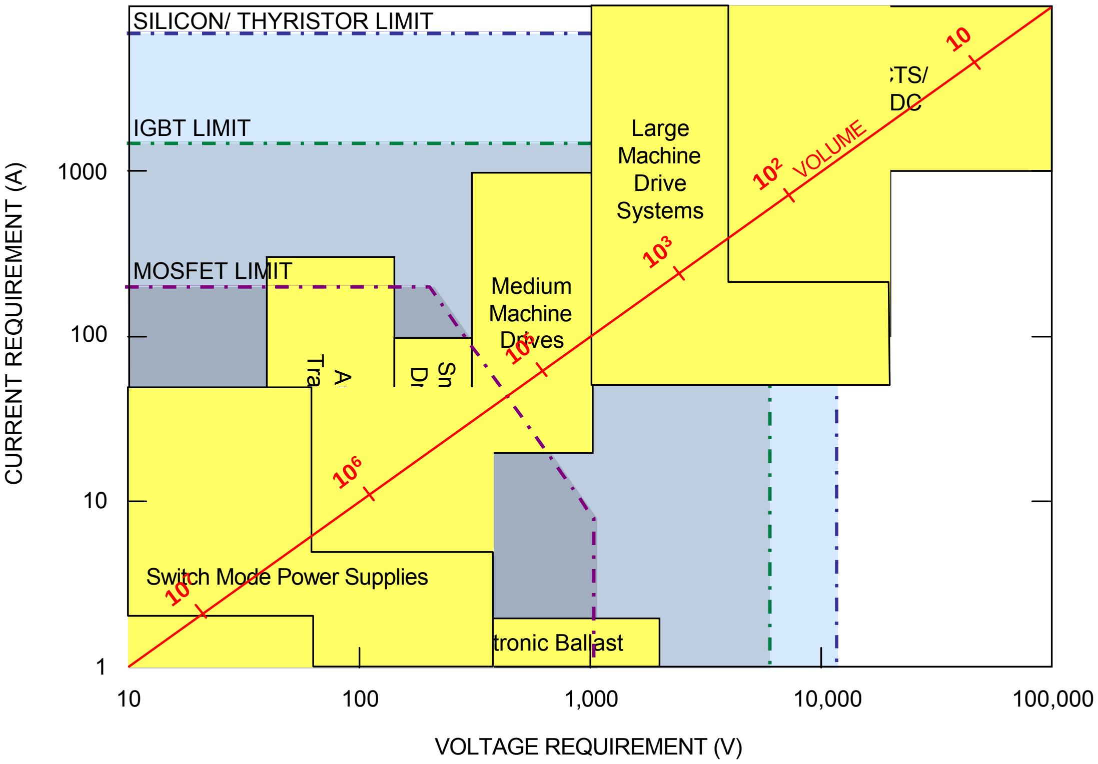


Figure 1: **Power Electronics market by application and ratings requirement, the red line indicates the typical production volumes**

High volume mass-manufactured units dominate the low power end of the market. It is only at the high end that greater added value is created, through the need for bespoke engineering and significant know-how relating to the design of such systems. As this section will show, at the upper end of the applications discussed here, up to 50% of the contract is accounted by the human cost of delivering turnkey solutions.

This study's focus is primarily on power electronic applications where the amount of energy being controlled is greater than a few kilowatts. This relates to the role of Power Electronics in the primary energy cycle from generation through to major load management. This can apply to open networks such as the national grid and closed networks such as those increasingly found on ships, planes, trains and automobiles.

The applications of Power Electronics have been classified according those that are well established in the market place and those where their use is still at an emergent stage or significant penetration has yet to be achieved. In summary these are:

- Established power electronic applications
    - Static excitation and adjustable voltage regulation systems
    - DC Transmission systems
    - Machine drives and controls
    - Uninterruptible power supply systems
    - Traction systems (rail)
- Emerging power electronic applications
    - Flexible AC Transmission Systems
    - DC Light Transmission
    - Solid state breakers and fault limiters
    - Prime mover interface
    - Traction systems (automotive, aerospace and marine)

These applications exist as separate markets with needs specific to the environment they will be required to operate in. The later part of this section will discuss the role of Power Electronics and ways to increase its scope within the energy chain that will only arrive through more effective joined up thinking. Only by taking a systems perspective about the deployment of Power Electronics will benefits accrue, such as more effective implementation that in turn will drive the cost of Power Electronics through more optimal design.

1.1 Established Power Electronic Applications

1.1.1 Static Excitation and Adjustable Voltage Regulation (AVR) Systems

Virtually all electrical generators 10MW and above are synchronous machines. As a machine that is in turn part of a much larger machine (i.e. the grid), generators are subject to not only local fluctuations from the prime mover, but also fluctuations in the grid itself. Power electronic systems have steadily replaced the auxiliary DC generator that was traditionally used to provide the necessary current to drive the electromagnets on the main generator rotor. By moving towards Power Electronics systems it has become possible to regulate the performance of a generator more efficiently and reducing the impact that external fluctuations might have. Considering the impact and cost of generator downtime, the benefits of static excitation and AVR systems is one that has been widely embraced. These systems are typically rated at around 2% of the main generator design, e.g. a 50MW generator would have an excitation system rated at around 1MW. These systems are low voltage (a few hundred volts) the important point being the generation of current to magnetise the rotor. The market for these systems is probably around $500-600m per annum.

1.1.2 High Voltage DC Transmission

DC transmission systems have seen a steady evolution over the past 40 years. DC has always been the more efficient way to transmit power, offering an automatic 40% increase in the amount of power you can feed down the same piece of copper. Yet AC became the system of choice for one key reason, and that was the transformer. By increasing the voltage at which large amounts of power were distributed the electrical current and hence the amount of copper needed to conduct the power could be minimised. No such simple solution was available to DC.

Figure 2: 700MW, 250kV HVDC converter station installed in Japan

As electricity systems have become increasingly complex, DC has developed into a significant niche market. Its main use has been to interconnect large electrical systems that could not otherwise be connected due to frequency or synchronisation issues. DC schemes are often big, with rated capabilities up to several thousand megawatts. The technology underpinning this continues to be the thryistor, which today still remains the highest rated and most robust of all power electronic devices. To the grid system a DC converter of this type looks like a giant induction machine requiring the grid to commutate the AC voltage back through zero every half cycle.

The market leader for HVDC by a significant margin is ABB who claim to have installed over 60% of the world's capacity. According to their marketing information, the world market for HVDC and FACTS (see later) is $2,800m per annum. Given the size of DC projects, which are also likely to include the interconnection cost between stations, HVDC is the larger component of that figure. The indicative cost of HVDC is around $90 per kW per station (i.e. the Power Electronics cost is effectively twice that since two stations are always required), a price that is only achievable through the laws of scaling for such large pieces of equipment.

DC is an expensive option, but is considered to be better than breakeven on links where the power transmission distance is over 400 miles over land or just 25 miles for subsea or underground links.

1.1.3 Machine Drive and Control Systems

Depending on whose estimate you believe, around 40 - 65% of the worlds electrical energy consumption is accounted for by electrical machines. Most of these are induction generators whose operating speed is a function of the mains frequency. Machine drives alter the frequency of the mains supply so that depending on the load conditions of the machine the correct speed and torque can be delivered according to need. The upshot is that a machine drive not only improves the performance of a basic machine, but also permits significant improvements in efficiency. It is claimed that energy savings of up to 60% can be made. In practice the cost of energy consumed represents around 95% of the lifetime cost[1], hence the purchase of a drive system makes a lot of sense to heavy users of electricity.

The same is not true at the lower end of the machine market. 98% of motors produced are rated less than 5kW – although they only account for 30% of the energy consumed by electrical machines[2]. At this level, purchase cost is the prime driver and energy consumption is seen as secondary. While drives at this end have made some limited inroads in markets such as HVAC cooling systems, most machines are just directly connected and their eventual speed dictated by a gear box. Yet studies commissioned by the US Department of Energy[3,4] have indicated that the use of better materials motor construction and use of power electronic drives could each yield a 10-15% improvement in energy efficiency. With increasing energy prices, consumers are likely to become attracted to more energy efficient designs, which could open up markets for low end mass produced drive systems for use in applications such as air conditioners, washing machines.

The conversion of electrical energy back to mechanical energy consists of two distinct two categories:

- Continuous rotating plant managed through machine drives
- Intermittent drive systems (e.g. stepper motors, linear motors etc.) requiring motion control systems

According to IMS research the market for low voltage motor drives (AC & DC below 690 volts) was worth an estimated to $5.1 billion market in 2004. IMS have projected that over the next five years the highest growth in this market will occur at the lower power end (< 22kVA). For the larger drives market IMS estimate that it was worth $414 million in 2004, with growth in excess of 25% during 2003 and 2004. IMS also notes that only 8 manufacturers have market shares in excess of 2% in this sector; these include Siemens, ABB, Rockwell, and Alstom.

The motion control market is also large. Publicly available market data tends to include the cost of the motor components, which estimates a $2B market in Europe alone. The power electronic component is likely to be around 20-25% of this.

The dominating device technology for machine drives is the IGBT and, less so nowadays, the GTO (due to its poor switching frequency). To drive costs down manufactures have moved towards the use of standard modular building blocks. The software and hardware is designed so that by paralleling up multiples of these standard units larger loads can be supported. This is considerably cheaper than bespoke engineering and construction to meet a specific application need, with the result that machine drives are often used for other applications such as traction controls for marine. However this approach is rarely satisfactory and niche markets that address the need for more optimal solutions continue to exist. Here the production volume tends to be measured in tens rather than thousands.

1.1.4 Uninterruptible Power Supplies (UPS)

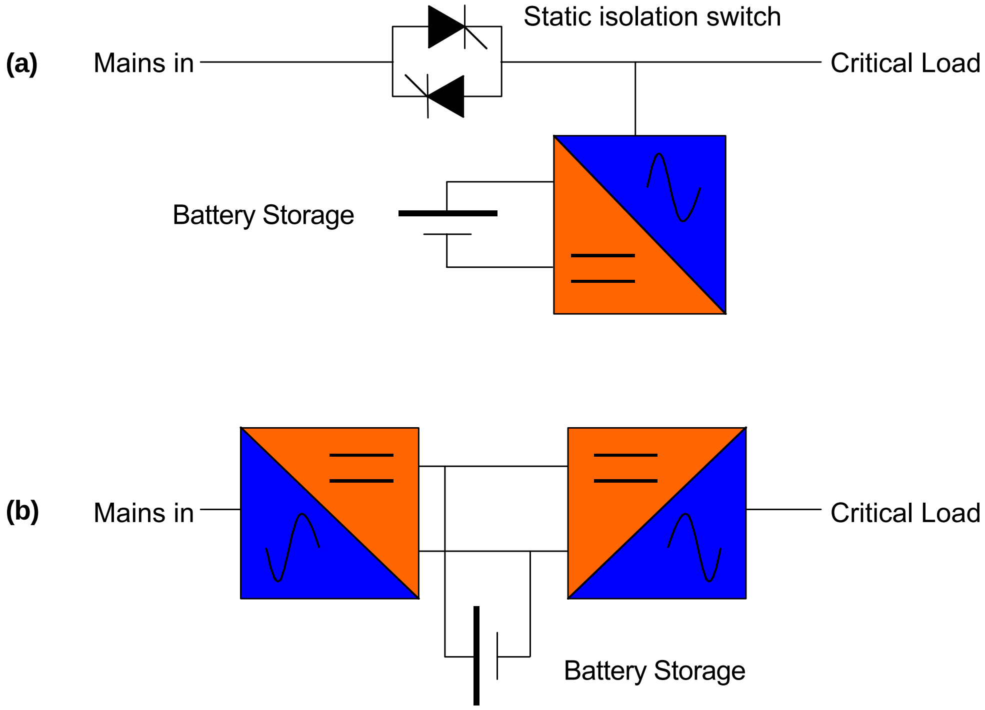


Figure 3: Basic configurations of UPS systems (a) Offline UPS (b) Online UPS

The UPS has become a critical element in the protection of data and control systems. Essentially a UPS is a power converter with an energy storage system that can supply electricity to a critical load in the event of a power outage. The two basic arrangements of a UPS are illustrated in Figure 3 above. Offline UPS are the cheaper option, but do not necessarily provide seamless transfer and their use is normally restricted to the cheap and cheerful sub 1kVA end of the market. The main implementation of UPS systems are the online variety; these are effectively a mains voltage back-to-back DC link, with a battery storage system on the link. These are less efficient than the offline type but provide better protection. Manufacturers have developed variations but essentially all are based this theme. Nearly all UPS systems operate at no more than 690V.

UPS highlight one of the major issues for energy systems, which is the effective storage of electrical energy. While batteries offer good energy density they age with use and gradually lose their storage capacity. Depending on the duty cycle and the type of battery used, UPS systems usually need to have their batteries replaced every 5 to 10 years. One variant that has emerged in recent years is the use of superconducting inductors as an alternative energy storage medium. Companies such as American Superconductor are leading this and are now supplying commercial installations that are competitive at the higher end of the UPS market.

According to IMS Research the UPS market was estimated to be worth in excess of $4.3 billion in 2004, and is projected to experience healthy growth levels throughout the forecast period 2005-2010. In terms of power rating, the highest growth is anticipated for the 21-100kVA range; however the 1-5kVA sector is forecast to remain the largest segment, accounting for nearly one-third of all UPS revenues.

1.1.5 Traction Systems

The traction market covers the use Power Electronics in vehicular applications and are mainly an extension of the machine drives and controls market, with the important difference that the environment they are required to operate in is far more extreme and difficult to manage.

Traction actually breaks down into two components: main drive systems and auxiliary power units (APU’s). The latter covers a range of converters that take power from the main bus and convert it to whatever voltage is needed for local needs. One example of a typical of APU is the one that generates standard mains voltage to power lighting systems and other hotel services such as the sockets provided for laptops nowadays on trains. APU’s are usually unique to the application and are produced in low volumes often by smaller Power Electronics manufacturers. The main drive systems still tend to be made by larger companies even though the volumes involved are not overly attractive. However the know-how associated with designing very high power, Power Electronics still tends to carefully guarded.

While mainline rail traction systems can be up to 25kV, the power electronic systems do not operate at this level. Consequently most large locomotives carry several tonnes of electrical transformer.

Each sector has different issues & requirements, which are summarised in table 1 on the next page. The rail traction sector is the only one that can be considered to be mature. While Power Electronics is used in places with the other three markets their widespread deployment is still emerging. Of these the marine and automotive sectors are nearer term than the aerospace sector.

Sector	Power levels	Requirements	Issues
Rail	2-5MW	Main drives, auxiliary power supplies	High voltage electronics (up to 25kV)
Marine	10-100MW	Main propulsion drives, auxiliary power supplies	Large islanded distribution, modular systems
Automotive	20-100kW	Main drives, , auxiliary power supplies	Cost, operating temperatures up to 150ºC
Aerospace	1-10MW	Shaft power take-off systems, auxiliary power supplies, actuation systems	Operating temperature – 50 to +400ºC, energy density of <1kW per Kg

Table 1: Summary of requirements and issues for the various end applications within the transport sector.

1.2 Emerging Power Electronic Applications

1.2.1 Flexible AC Transmission Systems (FACTS)

FACTS is an acronym coined in the early 1990's by the Electric Power Research Institute (EPRI) and was a technical response to anticipated grid stability issues caused by the unbundling and privatisation of the electricity industry. However FACTS has been around since the early 70's and relates to the use of Power Electronics to dynamically alter the circuit impedance of grid systems. Original FACTS systems used thyristor stacks to switch in banks of capacitors or inductors in response to a control requirement (usually referred to as reactive compensation). By varying the point in the AC cycle when the thyristors were switched it was possible to make the capacitor bank or reactor appear to be continuously variable and hence ensure that the correct amount of compensation was always delivered.

In the mid 1990's, after disposing their original compensation business, Westinghouse (now Siemens) backed by EPRI proposed an alternative method of providing compensation using GTO thyristors to mimic the effect of capacitors and inductors. This is often referred to as third generation FACTS. Despite several high profile projects installed in the late 1990's by Westinghouse, Areva (then Alstom) and a Japanese consortium of Mitsubishi, Hitachi & Toshiba, the later technology has failed to take off, even though it brings an inherent performance advantage. The underlying reasons are that they are still more expensive to implement than the earlier more mature technology, and that grid operators have not encountered as many problems requiring a FACTS solution as was originally forecast. Grid operators today have developed a rule of thumb that only a minority portion of system compensation needs to be dynamic with the rest being met by static compensation provided by fixed or switched passive components (i.e. capacitors or inductors).

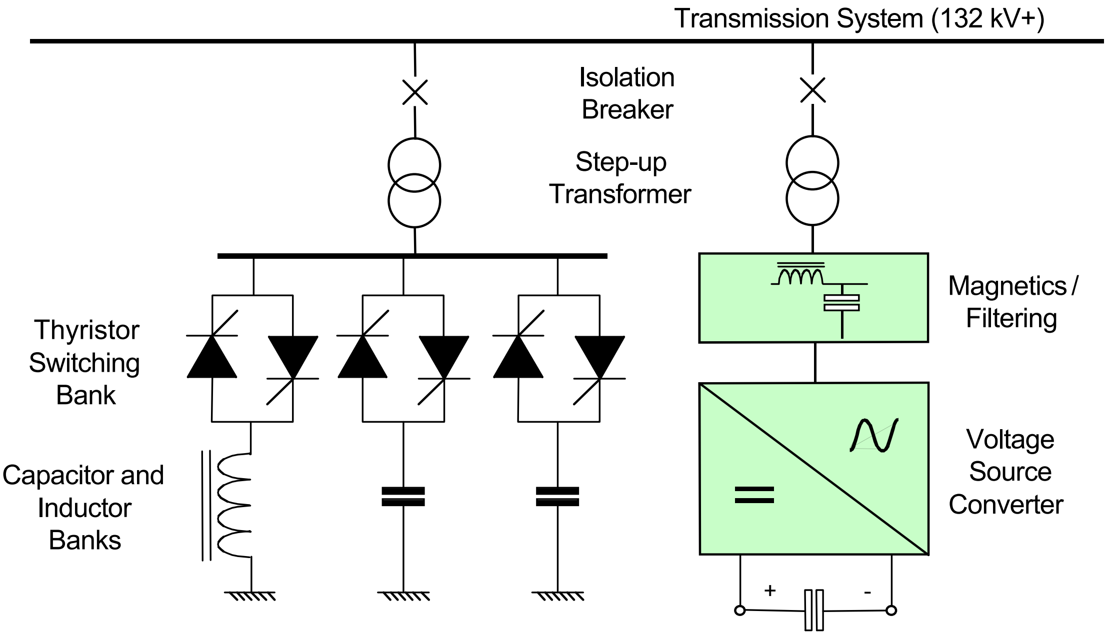


Figure 4: **Basic building blocks of second (left) and third (right) generation FACTS shunt compensation systems**

FACTS devices are rated at few percent of the actual power flow at the point of connection with 60 to 160 MVA being typical. One potentially useful aspect of third generation FACTS is that they can be coupled with energy storage to provide primary and secondary generation support for emergency system stability. This could lead to third parties installing such systems at strategic points on a grid in much the same way as they might build a generator. Such systems can justify a higher premium than a standard FACTS device due to multiple revenue streams that they can command from selling reactive power and premium real power. However previous studies that the author has been involved in indicate that, based on the typical revenues that might be achievable, the present achievable capital cost is around 70 - 80% above what could be economically justified. This is clearly something that should be revisited however.

1.2.2 Custom Power

Custom Power emerged at the same time as FACTS and was effectively a distribution version of the same third generation concepts. There was a key difference however, whereas FACTS was concerned with grid dynamic stability, Custom Power was focused on wide area power quality. This was enabled by the fact that the underpinning Power Electronics technology was based on IGBT's rather than GTO’s. This meant that systems based on these devices could react far more quickly to system events because of the kilohertz frequency that their inverters ran at.

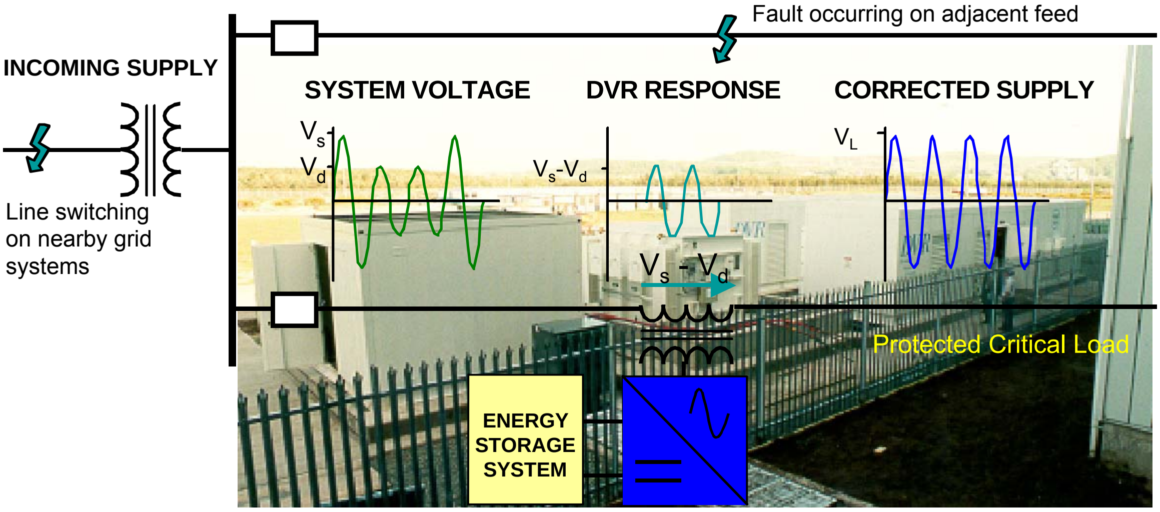


Figure 5: **Example of the operating principle of one of the custom power devices known as a Dynamic Voltage Restorer (DVR). The DVR is able to mitigate transient dips by injecting a supplemental voltage on the line that is only seen by the protected load. The unit in the background is a 4MVA unit that installed at Caledonian Paper in Irvine in 1997.**

Custom Power systems were designed to provide 2 major functions. For polluting loads that caused harmonic or flicker disturbance a shunt connected (Statcom) device was an effective solution as a high-speed active filter system. However the big market was perceived to be a solution to the most common form of disruption - voltage dips. These are momentary sags in the line voltage due to disturbances on the network that last only a few cycles. Ironically the most susceptible loads to these disturbances are power electronic systems used in production processes - which switch off rather than over-drive themselves to maintain a constant voltage to whatever they were driving. The proposed solution was a device called a Dynamic Voltage Restorer (DVR), the principle of which is illustrated in Figure 5 above. This is a series connected device that aims to inject the missing portion of voltage caused by a dip using locally stored electrical energy or by cycling power between phases. By not having to be rated to the full line voltage (typically a unit would be rated to just 20-50% of the load to be protected) the amount of Power Electronics needed was minimised and hence cost kept down. The energy storage for these systems is also expensive. Most implementations used capacitors or superconducting magnetic energy storage, which at the few MVA these systems are designed to run at usually provide less than 1 second of support.

Again despite confident predictions of large demand with high value customers (e.g. hospitals, semiconductor and paper manufacturers) the market has never really taken off.

The reasons for this are fourfold:

1. The technology implementation is expensive.

2. Despite many of the high value customers claiming significant losses due to downtime and lost production, in practice this is much harder to quantify and hence the payback analysis is not clear-cut[5].
3. It was unclear who the customer was, the end user or the utility. Further most regulatory frameworks continue to make the practice of charging a premium for electricity difficult.
4. UPS manufacturers scaled up their offerings, thus eroding the lower end of the custom power market. Further many of the drives manufacturers simply improved their designs to make them more robust to voltage dips as customers became more attuned to the issues.

Perhaps the best illustration of this is the fact that in 2002 Siemens sold the custom power business it acquired from Westinghouse to S&C[6] - who in turn are still using case studies from projects installed during the Westinghouse era. Despite this, there remain opportunities for these systems - particularly with the emergence of distributed generation - which may bring transmission grid problems down to the distribution level. However it is likely that future implementations will be adapted machine drive systems – an approach that has been taken by ABB amongst others - hence capitalising on the cost savings derived from the much higher volume market.

1.2.3 Solid-State Switches and Fault Limiters

The idea of a solid-state switch to replace the conventional electro-mechanical circuit breaker has a great deal of appeal to network operators. It is safer and faster to operate and, potentially, could be buried in the ground - eliminating the conventional substation. The solid state breaker (SSB) was proposed around the same time as Custom Power. In the late 1990's Westinghouse built a number of prototypes which never saw any serious operating conditions. Similarly Hydro Quebec and Powell also developed prototype breakers that diverted a fault into a current limiting element using GTO's to switch the fault and thyristors to limit the fault. The Powell design[7] tried to overcome the cost issue associated with GTO’s by using the much cheaper (and more robust) thyristor with a novel commutation circuit.

The problem is that SSB technology is still not established, nor is it cost effective. To make a breaker suitable for switching at the utility 15kV requires stacks of up to 3 or more GTO's or thyristors connected in series. For a three-phase device this means at least 18 devices are needed at a typical cost of around $2500 each. Taking into account the rest of the design this means that SSB’s are (a) bulky and (b) upwards of $150k (in steady state production) compared with normal circuit breakers costing less than $10k. Further a circuit breaker consumes virtually no energy whereas an SSB typically consumes around 5-10kW - mostly manifesting itself as heat.

Despite the high cost and complexity there are still applications for SSB’s in certain network applications. While a premium price can be commanded it is likely that the sustainable price is going to be no more than 5 times that of a conventional breaker.

Further to appeal to utilities, ideally it should be based on a single device, rather than a stack of devices to engender any confidence in the SSB's reliability, (Figure 6. over the page).

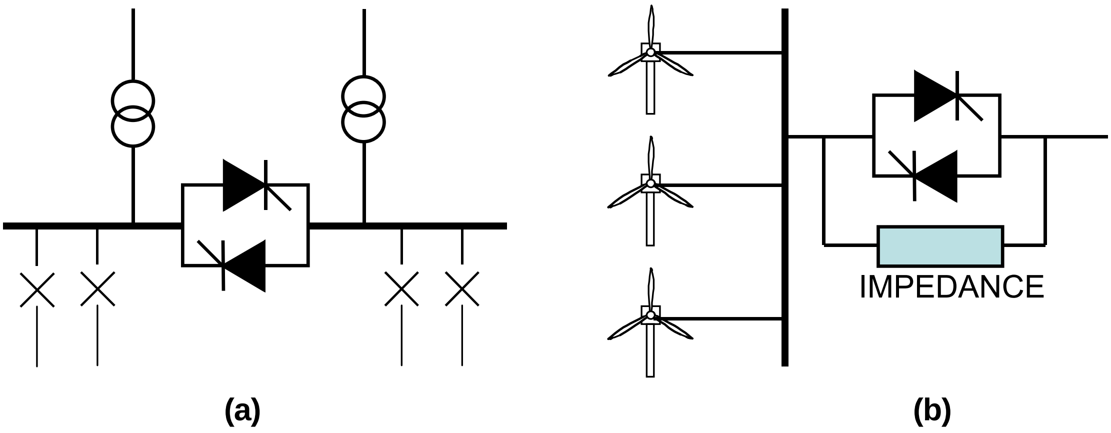


Figure 6: **Potential applications of a solid state breaker (a) as a bus tie to sectionalise busbars in the event of a fault and (b) used in parallel with a limiting impedance switched in by the breaker going open circuit in response to a detected fault**

1.2.4 HVDC Light

In the last 10 years ABB have begun to promote a scaled DC technology with lower ratings. Unlike their larger cousins the smaller systems are based on IGBT or IGCT technology and can therefore force commutate. In other words appear like a synchronous machine on the network and do not require a strong grid to ensure that they remain synchronous. HVDC Light (as it has been named) is seen as a good option for DC schemes up to 400MW. It has been widely expounded as an effective way of linking wind energy schemes to the grid, or interconnecting smaller networks. Because ABB have focused on using their proprietary IGCT technology they have, to date, largely operated as a monopoly in this market - something that has not encouraged its take-up. There are indications that ABB along with others have now developed IGBT's with ratings of 6500V & 1700A. These are not yet easy to obtain but look set to replace IGCT's because of the better power quality and potential savings from the volume pull effect of the machine drive market.

Other manufacturers such as Areva and Siemens are developing their own versions of HVDC Light in a bid to catch up. They appear to be favouring IGBT's as the base technology but potentially they may try to leapfrog ABB's lead position by adopting Silicon Carbide IGBTs which are forecast to be available later this year.

In May 2006 renewable energy developer Airtricity announced a proposal to lay what would effectively be a fully privatised sub-sea electricity grid based on ABB's DC technology[8]. This would be laid so that offshore renewable energy developers in the

Biscay, Atlantic, North Sea and Baltic Sea areas could tap into this network rather than go through the complex and expensive process of putting in a direct connection to the land based grid. Considering that so far only one multi-terminal DC scheme exists (a 3 terminal scheme in Canada) this scheme is ambitious and calls into question a number of security and reliability questions from only using one equipment manufacturer.

1.2.5 Prime Mover Grid Interface

Many of the emerging new generation systems do not generate power at the usual grid frequency of 50 or 60Hz. For example, fuel cells generate DC and many of the renewable generation technologies generate AC but not at the right frequency or regulation. In the case of fuel cells, developers have little alternative but to use a power electronic converter to interface to the grid. The renewable developers have a bit more flexibility with the option of using mechanical methods to ensure that the output from the generator remains constant, however in many cases this means that the design no longer operates in the optimal regime that ensures maximum energy output. It can be argued that even wind turbines can be made more efficient by eliminating the gearbox and interfacing through a power converter to regulate the electrical output. Companies such as Enercon (Germany) already offer wind turbines that use an alternative ring generator design and rely on Power Electronics for interfacing to the grid.

The problem facing developers of new power generation technologies is that the cost of the power converter is driven up higher by the need to comply with existing grid connection standards. There is perhaps a touch of hypocrisy here that the requirement for connecting Power Electronics interfaced generation equipment to the grid (set by standards such as G59 and G83) is more onerous than the requirements for connecting loads (even ones that regenerate electricity), even though they are basically the same technology but applied in reverse. This partly relates to the fact that such generation has to conform to standards set for traditional rotating plant. Yet power electronic interfaced systems are to all intensive purposes inertia-less. The potential conditions that any generation plant may experience are more complex than just a case of pumping out the right voltage and frequency though. This means that control systems are often more complex and using back-fed overrated machine drives is not the ideal option. The upshot is that the cost of the converter system is typically upwards of $300-400 per kW, or around 15-20% of the perceived sustainable cost of a renewable generation scheme.

In the case of wind turbines, one development increasingly being adopted is the Double Fed Induction Generator (DFIG). This uses Power Electronics to feedback a portion of power generated with suitable adjustment of the phase angle so that the generator remains synchronised even with a weak grid connection. The advantage is that the generator works more effectively and the amount of Power Electronics required is around 10% of the generated output. However DFIGs are not without problems, they are highly sensitive to external system fluctuations in voltage and the harmonics they generate has already caused problems on one offshore wind farm in Denmark requiring replacement of the generator transformers that are in every turbine. A number of respondents viewed DFIGs as being an interim solution only.

The problem for developers of new energy systems is that unless a new Power Electronics technology based on a new material greatly simplifies system design, the prospects for driving the cost down is very limited. As such the cost of the power converter interface is now one of the greatest barriers to the proliferation of these new generation technologies.

1.3 Scope, Trends & Opportunities for Power Electronic Systems in the Energy Sector

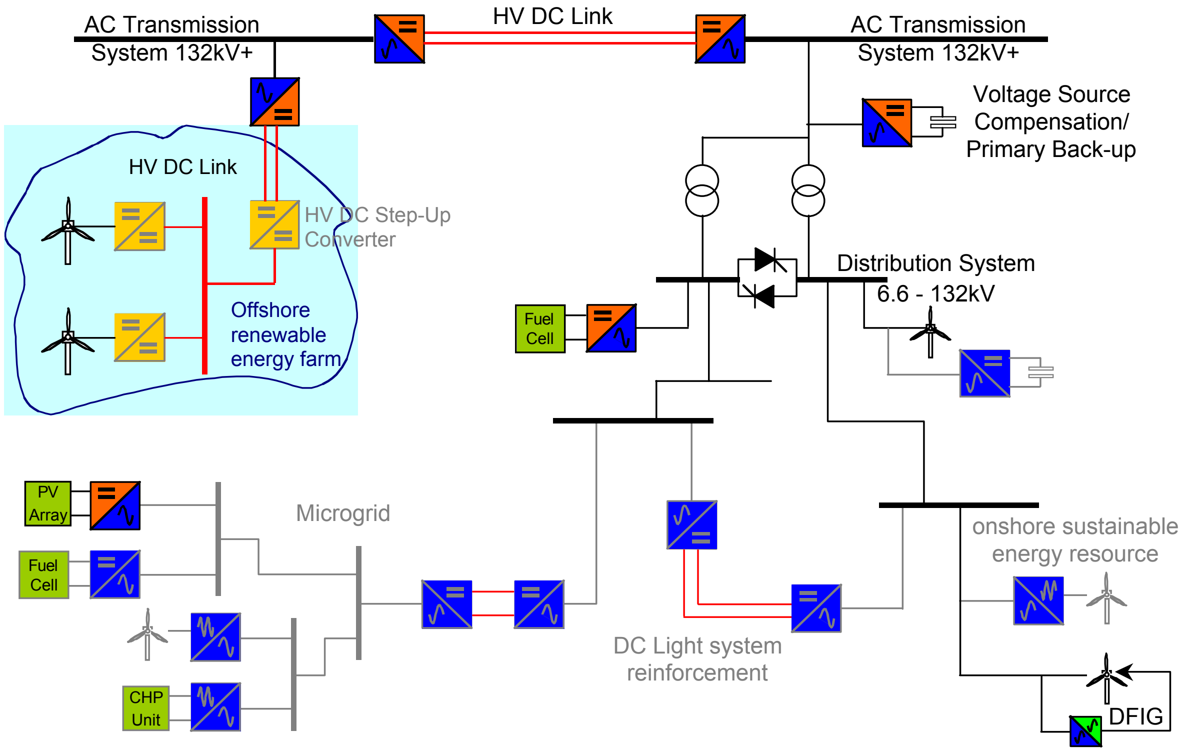


Figure 7: **Illustration of some of the applications of Power Electronics in the existing electricity network. Emerging applications are shown in grey.**

As this section has already highlighted, there is a significant role for Power Electronics to play throughout the energy cycle. Some of these applications in the main electricity network are shown in Figure 7. Despite the operational advantages that Power Electronics can bring, in the case of many of the emerging applications it has struggled to gain a significant foothold. However it is these applications that represent the largest opportunities for Power Electronics in the future.

The key problem for Power Electronics is price. Figure 8 shows the typical price level per kW for industrial power converter systems against power rating. There is an obvious disconnect at around the 10kW level where MOSFET technology reaches its practical implementation limit and IGBT's become the only design option primarily driven by the voltage that the converter is required to operate at. The price rises towards the 1MW level because of the reduction in volumes and the (often greater) amount of customisation that is required at these levels. For very large systems there are benefits of scaling that can be, to a certain extent, mitigated by the additional infrastructure needed to realise such systems.

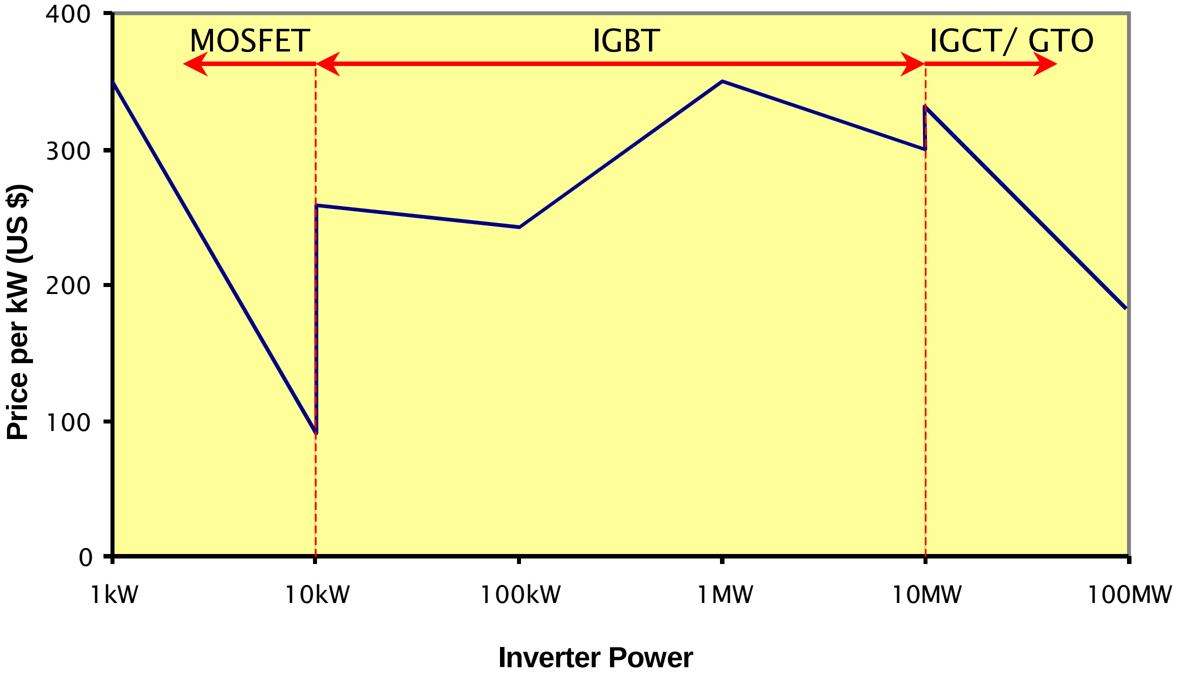


Figure 8: Typical price levels of power electronic conversion systems according to power levels.

Several respondents to the study are in belief that the typical power levels of many of the emerging applications will lie in two bands; at the 20-100kW level and the 1-5MW level. In both cases the typical price level encountered of $250-$350 is perceived to be around 50-100% above what is considered to be economic in the context of many of these applications. For example in the case of renewable technologies $1,500 per kW is widely seen to be the economic target. At this price level Power Electronics at its present cost would account for over 20% of the system price. Until this level drops to around 10-15%, developers will continue to employ less optimal mechanical alternatives.

Apart from the difficulty of achieving cost savings due to the relatively low production volumes, there are two underlying reasons for the present cost of Power Electronics:

(1) Much of the technology is mature and there is limited scope for further significant cost reductions due to the limitations of the silicon devices, which are now at the intrinsic limits of the material.

(2) Power Electronics is often implemented in discrete contexts (i.e. specific to the particular application) rather than in a system context leading to over-

rating of designs – something that is often driven by out of date standards that apply to electro-mechanical equivalents.

1.3.1 Moving Beyond Silicon

The design of power electronic systems is a constant juggling act where design decisions that impact on complexity are dictated by the limitations of the semiconductor devices. For example a device rated at 4,500 volts, 2,000A in theory can switch 9MW of energy. In practice the voltage at which the device is operated is only 35-50% of this and the current is also derated by 40-50% to prevent thermal stressing of the device (which leads to ageing) as it gets hot (this in turn is a compromise with the type of cooling system used). The net outcome is that the practical power switch rating is as little as a quarter of quoted rated value.

The basic building blocks of a grid connected power converter system are illustrated in figure 7. Many of these building blocks such as the grid transformer and filtering circuits are there because of the relatively low voltage and frequency that such systems operate at. Other complexity is not illustrated here, such as that of the control system needed to manage the correct firing of the parallel and series array of semiconductor devices necessary to achieve the functional rating. Further detail of how power converter systems operate is discussed in Appendix 3.

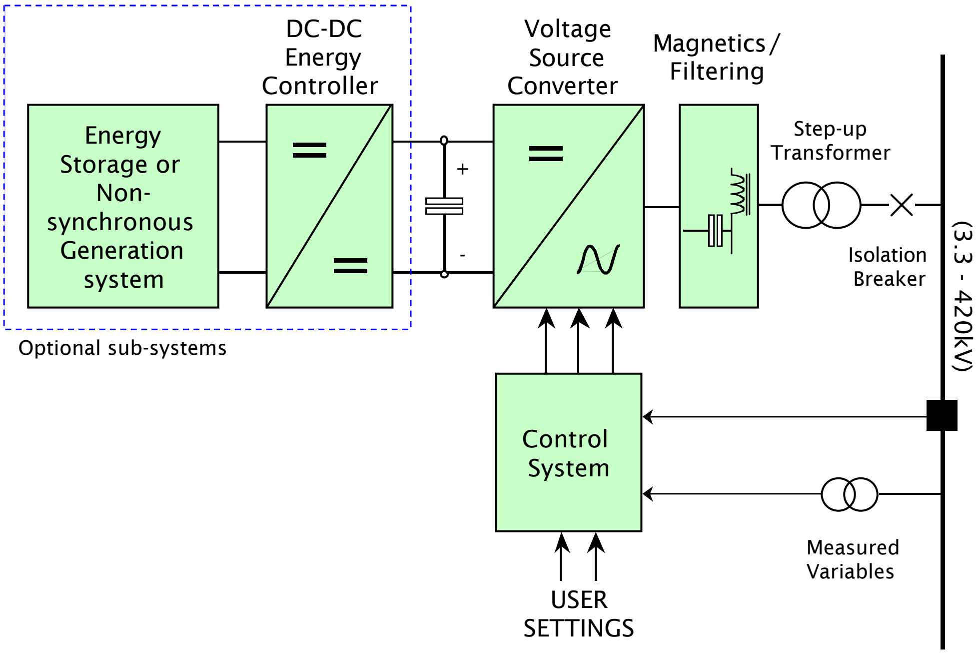


Figure 9: Basic building blocks of a grid connected voltage converter

A cost breakdown analysis for a 2MVA rated Statcom, based on models previously made available to the author, is shown in figure 10 below. The Statcom is effectively the same as the converter shown in Figure 9. The only difference between it and an application for a prime mover interface, for example, would be the optional additional hardware necessary to interface the primary energy source to the converter.

The analysis of Figure 10 shows that discrete power semiconductor devices are actually a small proportion of the cost, with the largest chunk actually being the engineering and management associated with delivering the system on a turnkey basis. Some of this engineering relates to bespoke elements and could be driven down through repeat volume. However some of it is associated with the logistics of implementing a design made complex by the sheer number of devices and their associated hardware. Around 70% of the ancillary hardware and production costs in the example are dictated by what is necessary to overcome the basic limitations of the active power semiconductor devices at the heart of the equipment.

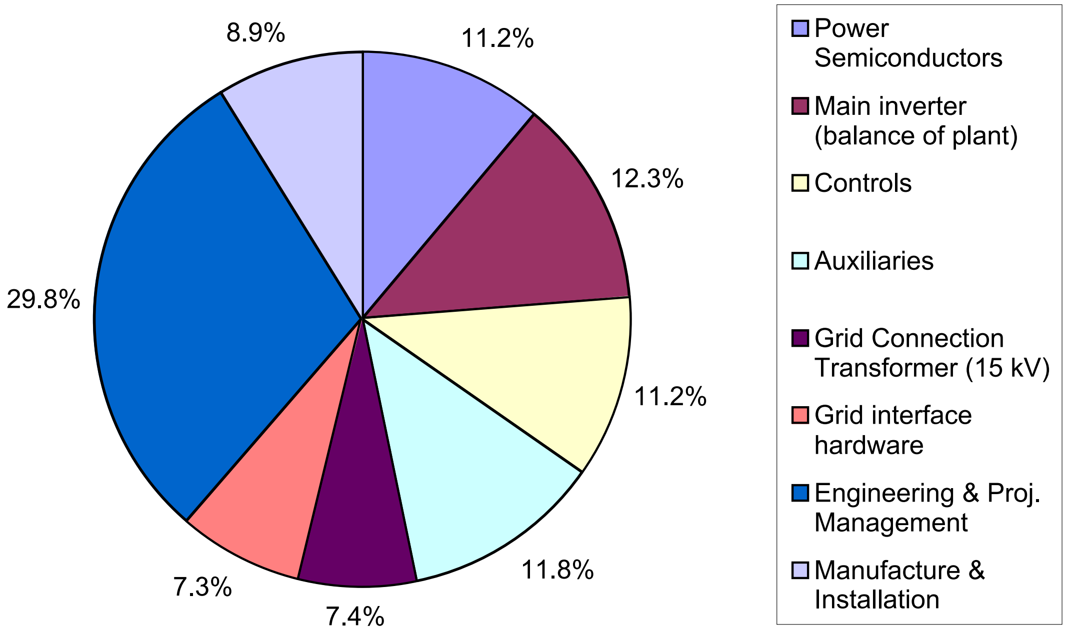


Figure 10: Cost analysis for a 2MVA grid connected Statcom system based on 3,500V IGBT technology. The Statcom is a shunt connected device similar in design to the type of system that would be used to interface non-synchronous generation systems to the grid. Capital cost of this system would be around £600k.

The scope for simplification and hence cost reduction of such a system would be enabled by just two improvements in Power Electronics technology:

- Availability of higher voltage power devices
- Availability of faster switching devices

In the case of higher voltage ratings, the specific requirement is for devices that would enable the direct connection of the converter to the grid with two or less devices in series. A device capable of switching at 22000V (the peak voltage for 15kV AC) and conducting around 150A could have significant implications on the whole energy sector.

Such devices would significantly reduce the number of ancillary components and greatly simplify the control system. Also by increasing the voltage the current through the devices would be reduced hence reducing the size of the cooling system. In the case of higher frequency operation the filter design could be greatly simplified. Of the two improvements voltage is the key one.

To illustrate the potential system cost reductions that could be achieved from using a device able to directly interface at the distribution utility 15kV level, the Statcom model has been re-run based on such a device. At the core, just 6 devices have replaced the 24 switching devices assumed to be required to achieve the 2MW rating. A further assumption has been made that these devices will command a tenfold premium over the price paid for one of the lower rated devices. Figure 11 shows a breakdown of the costs of such a system. What the chart doesn't illustrate is that by eliminating significant numbers of components the overall cost of the system is reduced from around $350 per kW to around $200 per KW - even allowing for the premium price of the active semiconductor devices.

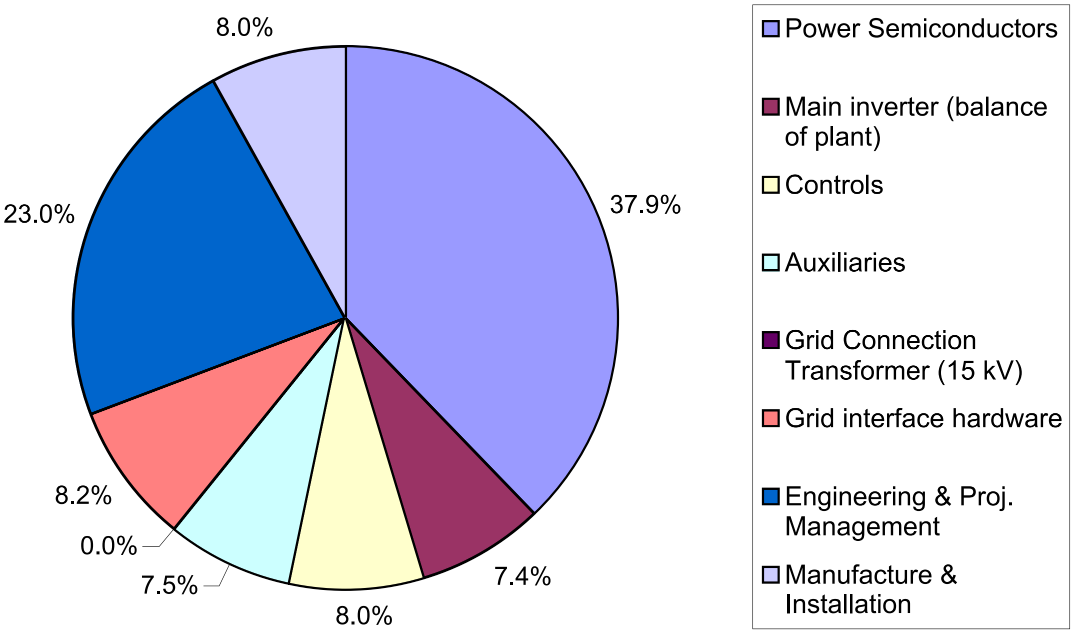


Figure 11: Cost breakdown of a 2MVA voltage converter system based on a switching device able to switch at the utility distribution voltage (11-15kV). Capital cost of such a system would be around £330k

The opportunity for a new device technology for large power converter systems is clear. At the bottom end differentiation is much more difficult to demonstrate. While new MOSFET devices in Silicon carbide are emerging, the fact that they are 4 times more efficient but 10 times more expensive than their silicon counterparts does not factor in a market where system price is the driving factor. This therefore presents the biggest hurdle to device developers working with new material technologies; the fact that greatest opportunity is also where the biggest technological challenge lies.

The only differentiation that new materials technologies are likely to bring is: greater robustness and an ability to operate in harsh environments such as those encountered in transport (automotive, aviation etc.). Thus lies a dichotomy, the market knows that a replacement for silicon is highly desirable, yet market conditions means that the introductory path for its successor is not straightforward.

1.3.2 Implementing Systems Thinking

A systems approach is one that looks at the needs of the whole network and then works backward. Power Electronics offers new ways to look at electrical networks. For example the concept of fault level is something that does not need to exist with networks based on Power Electronics. In a fault situation a rotating generator will supply a significant short time current based on the spinning inertia of the generator. A converter interfaced system is does not have any inertia and therefore does not contribute to the fault level. Yet connection standards today require that all generator systems are able to deliver fault current. This means that Power Electronics have to be over-rated to meet this specification and hence additional cost is incurred, driving up the cost per kilowatt.

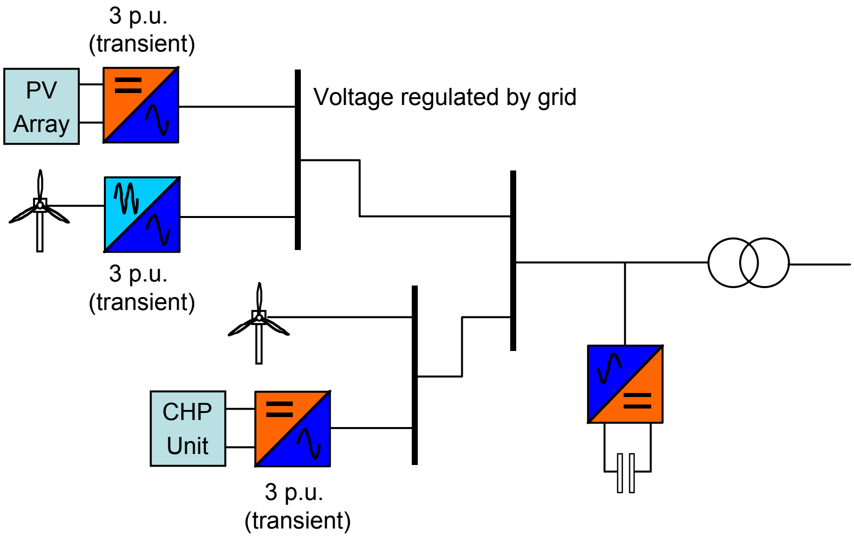


Figure 12: Illustration of a microgrid distributed generation system; Power Electronics are rated to deliver fault current

To illustrate the impact that systems thinking might have, take the example of the microgrid concept of Figure 12. This consists of small generation units, all synchronised with the grid and connected through a mix of rotating or static plant with additional electronics to provide dynamic stability at the grid interface point. As it stand now these devices would need to be fault rated (~3x normal load for a transient period). However taking a systems approach a more economic approach is illustrated in Figure 13.

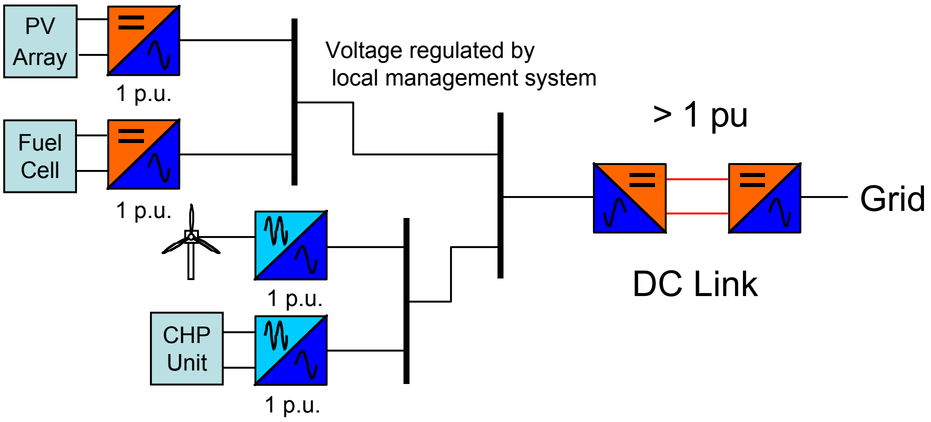


Figure 13: Example of a microgrid partially islanded using Power Electronics, here the converters are cheaper because they only need to be rated at 1 p.u.

In this example the microgrid is isolated from the main grid using a back to back DC arrangement. All generation sources use power electronic interfaces and network protection is managed using unit rather than time graded protection. The result is that converters only need to be rated at 1 per unit and the DC link would only need to be rated to cope with the expected difference between peak demand and local capacity. The flexibility of the Power Electronics interfaces would also ensure all the reactive power needed to satisfy demand would be met by the local generators.

A further example of where cost savings lies with the embedding of Power Electronics into the electro-mechanical systems they provide control or interface for. Power Electronics is often produced as a separate add on, yet if manufacturers and designers worked more closely taking a mechatronic approach, unnecessary hardware could be eliminated.

1.4 Conclusion

Power Electronics has an important role to play throughout the energy cycle. Yet while significant markets already exist, its proliferation remains hampered by the high cost of implementing it. The emergence of new semiconductor devices and better systems thinking could have a significant impact on driving this cost down to a more sustainable level of $150-200 per kW, in turn triggering markets that are presently served by less efficient mechanical alternatives. In the near term it is likely that most innovation and growth will be driven by the needs of the transport sector (marine, automotive and aerospace). This will generate impetus on the design of islanded power networks which, in turn, may stimulate the sector with the most growth potential, that of energy interfacing and grid management.

SECTION 2 - POWER ELECTRONIC DEVICES

A significant number of power semiconductor devices exist today. The device family tree is shown on the next page in Figure 14. Essentially semiconductor devices fall into two categories:

- **Bipolar:** devices of this type rely on the interaction that occurs between p-type and n-type versions of the base semiconductor material. Conduction through the device in the on-state is effected by the movement of both negative (electrons) and positive charge carriers (holes). Because the net charge in the device is zero during the conduction phase they are capable of carrying very high currents. Bipolar devices have a fixed voltage drop associated with each p-n junction (in the case of silicon this is 0.7V). Where bipolar devices score is that they inherently have good voltage hold-off capabilities, are robust and are easily scaleable. Their downside is that to turn such devices off requires a finite amount of time and/or the injection of energy to neutralise the positive and negative charge carriers in the material, making them suitable only for low to medium frequency applications.

- **Unipolar:** The general principle of most unipolar devices is the field effect. Devices based on this principle use a locally applied electric field to cause charge carriers (electrons or holes) to tunnel between two similarly doped semiconductors held apart by a thin layer of oppositely doped material. This means that only one form of charge carrier is used to conduct through the semiconductor. As a result unipolar devices are inherently faster to operate since they don't require suppression of charge in the material, and they tend to have lower on-state losses. The drawback of unipolar devices is that that the forward resistance increases exponentially with depletion thickness (the tunnelling layer that gives insulation strength); hence they are essentially low voltage devices. Further current can be become space charge limited. The exception to this is the Schottky diode, which can exhibit high voltage operation, but it is difficult to achieve high currents through such devices.

The design and engineering of power electronic devices is all about trade-offs. From a high power perspective, the key element is that voltage hold-off is traded off against switching speed and/ or device losses. From a system design perspective a power semiconductor device should have the following characteristics:

- Turns instantaneously on and off
- Does not require any energy to initiate the switching action
- Does not conduct in the off-state
- Has zero losses in the on-state

Since by definition a semiconductor is only a partial conductor of electricity, no device can deliver all these characteristics. However depending on the operating regime, certain devices perform better than others. As Figure 8 in Section 1 illustrates there are basically three power areas that are currently satisfied by just a few of the devices illustrated in the family tree of Figure 14.

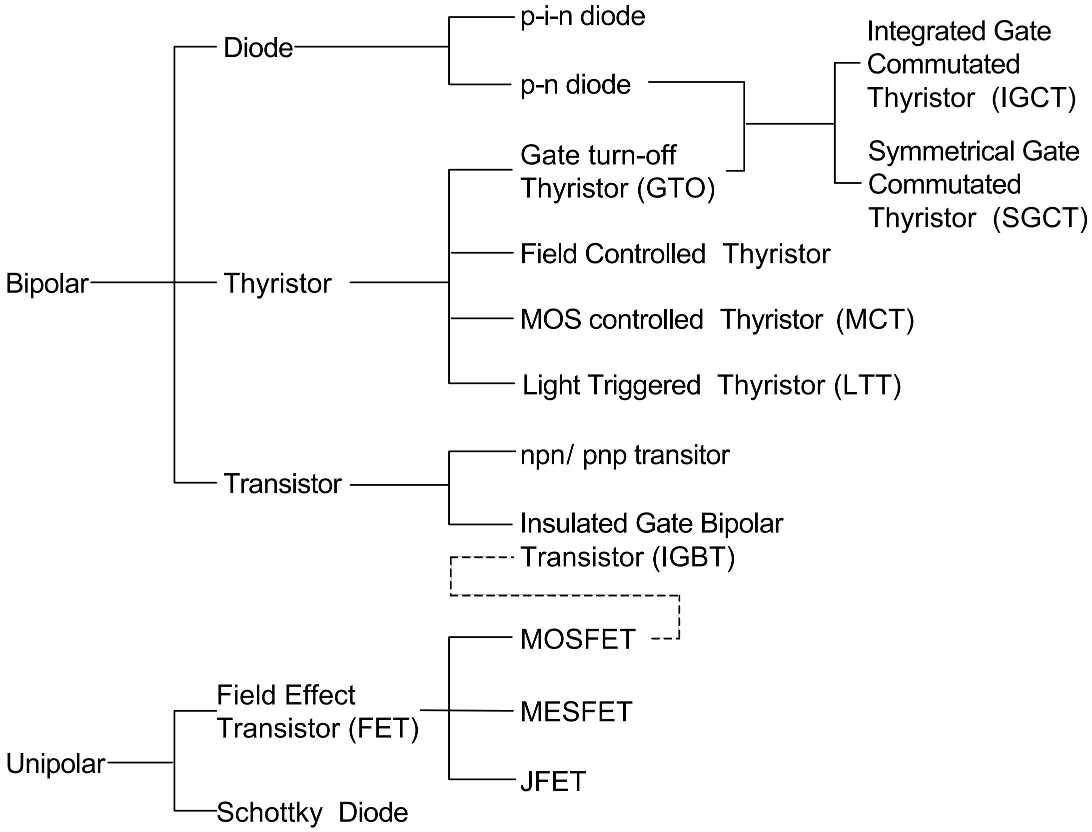


Figure 14: Silicon power device family tree

2.1 Device Choices for Low Power (<10kW) Applications

The low power market is dominated by the MOSFET and its variants. As a unipolar device the MOSFET is capable of operation up to several hundred kilohertz and has become the logical choice for most low voltage applications. The problem of the MOSFET is that on-state losses increase with temperature. For emerging applications in the automotive sector the issue of thermal stability is key to adoption. It is likely that the IGBT or basic transistor will be the device of choice in these applications.

2.1.2 Device Choices for Medium Power (>10kW – 10MW) Applications

This represents a wide bandwidth that is dominated by just two devices. For many applications the thyristor remains a popular choice. The thyristor is one of the earliest silicon devices, yet has persisted throughout the development of the power semiconductor market because of its robustness. It has a similar structure to the transistor except that instead of having three layers it has an additional layer – most commonly in the form of np-np. The dual p-n structure means that the device has extremely high voltage hold-off capabilities and is relatively easy to turn on. The problem with the thyristor is that once it is turned on it can only be turned off by the action of the external circuit going to zero. The fact that a thyristor can turn on at any point in the AC cycle means that energy can be controlled simply by determining how much of the AC cycle the load sees. For many applications such as machine drives this has been adequate. The great beauty of the thyristor is its inherent simplicity, which has enabled developers to realise large devices made out of single wafers up to 150mm in diameter. Thyristors have been developed with simultaneous rated switching capabilities of 10KA and 12kV.

For more demanding applications, there is a need to control when the device both turns on and turns off. The device developed for this application in the 1960's was the Gate Turn-Off (GTO) Thyristor. The GTO is basically a more complex version of the thyristor. However while turning on a GTO is fairly straightforward, turning one off requires the injection of a current equal to around 10% of that flowing through the device. This for a device conducting 2,000A say, this requires a gate driver capable of delivering a very fast 200A current pulse – a power electronic design problem in its own right. This means that the control technology for GTO's is complex and expensive.

Several alternatives to the GTO have been pursued. One device was the MOS controlled thyristor (MCT); however despite highly promising results in laboratories the device did not scale. The problem that emerged was that the design of the MCT lent itself to a cellular structure. Attempts to scale the technology resulted in failure as it became apparent that it was too difficult to make the cells on a wafer share the duty evenly.

In the 1990's the IGBT emerged as lead contender to the GTO. It is basically a hybrid of a conventional bipolar transistor with an integrated MOSFET driver built into the device structure. The result was a high power switching device that had vastly reduced control requirements because no high current was needed to turn the device on or off. The IGBT also scored over the GTO in that it could be operated at much higher frequency. Whereas GTO's are limited to several hundred hertz the IGBT is capable of switching at several kilohertz, greatly simplifying inverter design. For medium power applications the IGBT has now largely replaced the GTO.

The IGBT has rapidly matured with 6.5kV 1700A units now available. The prime driver for high power IGBT development was the traction market, which did not need higher rated devices and for several years the maximum rating remained at 3.3kV. Also, while GTO's are available with 4500A current rating, IGBT's achieve less than half of this due to their method of construction, which uses parallel chips rather a single monolithic wafer.

As Figure 15 illustrates, device ratings are now achieving their useful limits as the intrinsic limitations of silicon are encountered. While higher voltages can be achieved the trade-off is switching frequency. For IGBT's this means that while 8kV may be possible, designers may gain better overall savings on system cost by sticking to the faster switching 4.5kV devices and accepting that more in series will be required.

When looking at device ratings the nameplate rating can be misleading. For example, for IGBT's the usual engineering rule of thumb is to derate the current by 30-50% and the voltage by just over 50%. The net effect is that in practice IGBT's typically can only switch a quarter of their nameplate power rating. There are a number of sound technical reasons for this, in particular the fact that IGBTs are not fault tolerant and equipment designers must take this into account.

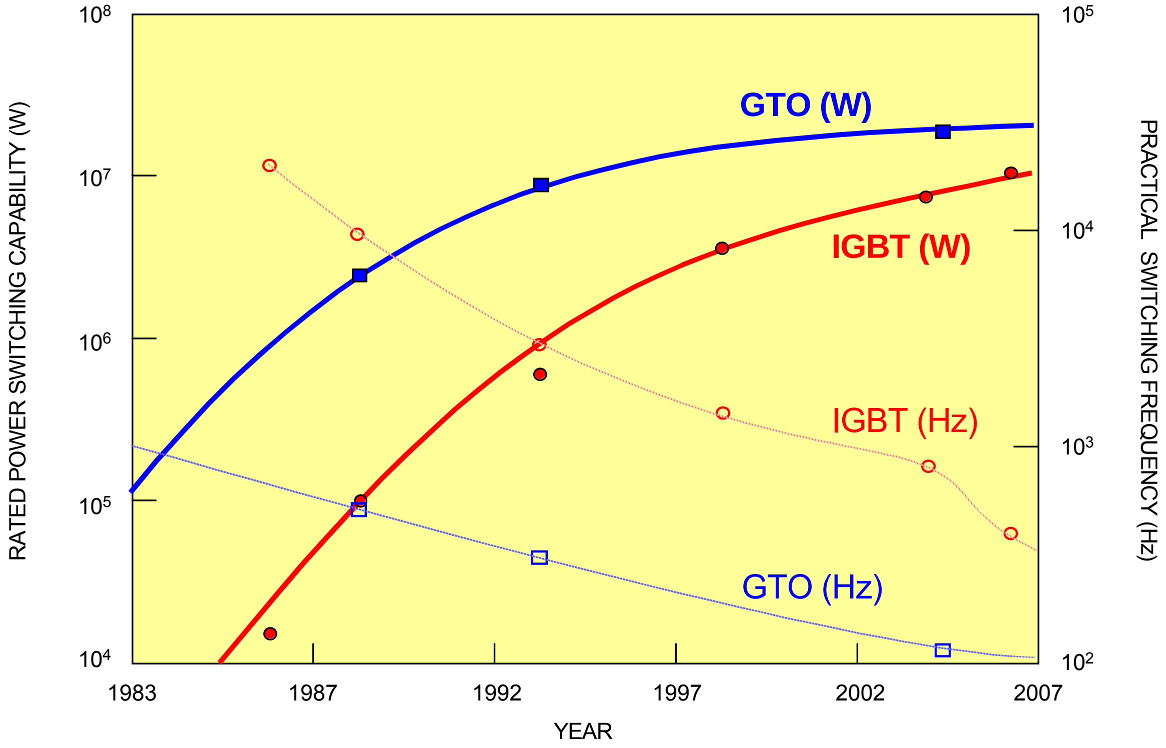


Figure 15: Improvements in power ratings for IGBT and GTO devices

2.1.3 Device Choices for High Power (>10MW) Applications

For high power applications the choice of device is highly limited. The thyristor continues to have the highest voltage rating and has been the device of choice for many applications such as Static Exciters, HVDC and early generation FACTS. However it is widely recognised that many of these applications would benefit from the use of a switching device that could be turned on and off. Until recently the only available device that fitted this bill was the GTO. However as GTO voltage and current ratings have progressed to the point where 6500V 4000A devices are available, these represent the sustainable trade-off of rating verses switching speed. At this rating it is difficult to operate devices at much more than synchronous speeds (i.e. 50 or 60Hz) without incurring unacceptable energy loss. For example, the GTO FACTS projects built by Alstom (now Areva) and Westinghouse (now Siemens) in the late 90's were around 99% efficient. Since these were 100MVA systems, this meant that the better part of a megawatt of heat had to be dissipated. Cooling systems are therefore a critical issue at these power levels.

At very high power ratings devices tend to be monolithic i.e. a single device on a single wafer. It is very difficult to make devices share the load either at packaging or multi-device level. For instance the Westinghouse FACTS designs employed a very expensive intelligent control system to ensure that 5 GTO's connected in series effectively appeared as one and, further, used complex balancing transformers to ensure that parallel stacks would properly share the duty.

The search for a credible replacement to the GTO for high power applications has been going on for over 20 years. One device widely researched was the light triggered thyristor (LTT). The idea here is that a high intensity light source would be used to trigger the device into conduction. The appeal was that for high voltage applications it eliminated the problem of how to safely connect the control electronics. The drawback of this approach was that while it was relatively easy to turn the device on, turning off was far more difficult. To ensure that this happened meant significantly increasing the intensity of the light source to compensate for the fact that the junctions could only be lightly doped. A key element in the design of any power device is that all parts of the device on the wafer turn on or off at once. As devices got bigger the problem of ensuring that the light would trigger all parts of the device simultaneously became insurmountable and the idea largely died – although it has been used in Japan for HVDC schemes.

The only progress in high power switching devices made in the last decade has been led by ABB, who in the late 1990's introduced the Integrated Gate Commutated Thyristor[9]. The IGCT basically represents a better way of engineering the GTO to achieve better switching speed. Key to the design has been the integration of the anti-parallel diode (that is always needed to prevent overvoltages generated by the switching action of the main device) into the same wafer as the switching device coupled with making the gate control part of the device housing. The emergence of the super-capacitor meant that it became possible to store the charge necessary to initiate a turn-off action to a certain extent using the on-state voltage drop (around 4V) to charge the capacitors. By doing so ABB have succeeded in creating a device that operates at up to a few hundred Hz (which helps to simplify converter design). However ABB have also tied up the IP relating to the IGCT to the point were they have a monopoly. This has meant that while ABB have shifted the design of their own high power systems to the IGCT others have been more reluctant to do so.

A variant on the IGCT has emerged recently called the symmetrically gate commutated thyristor (SGCT). This is essentially a simple thyristor with a force commutation circuit (to turn the device off) integrated into the device packaging. The SGCT is not as tightly bound up in terms of IP and already being offered by a number of manufacturers.

2.2 The Impact of New Materials Devices on System Design

To date no new material technology has yielded devices able to compete with silicon. One device that is creating a great deal of interest though is the Silicon Carbide Schottky diode, now commercially available from Cree and Infineon. This diode recovers up to a 100 times faster than its Silicon equivalent, which is important for Power Electronics design. All power-switching devices need an anti-parallel diode to support switching device recovery and damp switching transients. The faster the anti-parallel diode, the lower the switching transient. This can have two knock on benefits:

- Enables designers to run the devices closer to their nameplate voltage rating
- Makes the circuits less susceptible to parasitic effects caused by the physical layout of the components and hence a less onerous design requirement.

It is likely that a significant market will develop for SiC Schottky diodes at the low to medium power end of the market. Schottky diodes are relatively low voltage devices and although 1,200V devices are now becoming available, their ultimate blocking voltage is not likely to be much more than twice this. In many cases the SiC Schottky's will be integrated into IGBT packages as companies such as SICED (a joint venture between Siemens and Infineon to develop SiC devices) are already doing.

The future is less clear for switching devices in new materials. SiC's problem, at the moment, is that the devices being produced are low voltage (<1,200V) and compete with Silicon devices of the same rating. While SiC devices offer a number of performance benefits application designers are reluctant to embrace a component that costs up to 20 times more for many applications where price rather performance takes precedent.

2.3 The Lessons Learnt in High Power Switch Design

The experience of 40+ years of high power device design has taught many valuable lessons that apply equally to any candidate replacement technology. The key lessons are summarised below:

- Bipolar devices work better for high voltage applications
- Simple designs work better than complex designs
- High current devices tend to work better when they are monolithic
- Cellular topologies don't necessarily scale
- Turning-off a device is far more difficult than turning it on
- Minimising the charge in a device structure in the on-state will help to increase the switching frequency
- Heat is the enemy – and power switches can generate a considerable amount requiring increasingly sophisticated cooling systems
- The physical package design can be as important as the wafer design – materials need to be matched to ensure thermal compatibility
- At high currents everything needs to be tightly clamped down
-

- When holding off 5,000V across a fraction of a millimetre, make sure you've got your stress management right
- You may be holding off 5,000V across your semiconductor, but air and surface interfaces aren't so robust

2.4 Moving Towards a New Generation of Devices

Extending the range of silicon, or delivering a new generation of devices based on a new material, raises a number of key issues. There are a number of problems that will continue to require innovation:

- Removing heat generated at the semiconductor junction from the devices
- Reducing the component count by integrating the control intelligence and basic circuit topology into a single package
- Identifying new materials and packaging arrangements to cope with greater thermal operating range and dielectric stress placed by higher operating voltages and frequencies

2.4.1 The Heat Problem

Heat generation continues to be a major problem for all devices. The thermal problem can be broken down into two components:

- Immediate dissipation of heat from the active junctions in the semiconductor die
- Dissipation of heat from the system

The former is key to device ratings. Power electronic devices come with a thermal resistance rating. This is a measure of how effectively heat is removed from the wafer by the surrounding packaging and is used to determine the junction temperature of the wafer for given electrical current levels. The latter component then determines how quickly heat emitted from the device package is subsequently removed from the system. The more effectively these components are implemented, the closer devices can be pushed to their nameplate ratings.

The problem for any designer of device packages is that heat removal is only part of the equation; electrical insulation, mechanical clamping (to negate force effects caused by high electrical currents) and differential thermal expansion must also be taken into account. While improvements have been made in packaging materials, the rate at which heat can be removed remains an issue. It is also one that is likely to restrict the practically achievable power density of devices based on new wide bandgap materials. Although they are generally capable of higher current density and better thermal conduction, this may be negated by the thermal limitations of the packaging technology. Further while most wide bandgap semiconductors can operate at higher temperatures, other components in the system are no. Except in specific applications, keeping operating temperatures much as they are is likely to be the favoured option, thus reducing one of the major benefits that the new materials bring.

Often the weakest element in a Power Electronics system is the external cooling equipment. The standard approach is to use large metal heatsinks coupled with forced airflow if necessary. However heatsinks can be impractical for higher voltage applications since their finned shape tends to be at odds with the demands of good electrical insulation design. If natural convective removal of heat is not sufficient, assisting this process using forced airflow is the next step. To prevent dust and particulate contamination that would otherwise compromise integrity of the electrical insulation, air filtering is required. This in turn imposes a maintenance burden and requires overrating of the fan system to compensate for the restriction on airflow caused by the filters. At very high power levels the only option is to use liquid cooling systems. These are very costly to engineer, require custom built heatsinks, coolant pumping systems and heat exchangers. As some utilities have discovered, internal corrosion of heatsinks in FACTS and HVDC applications has meant that the biggest problems encountered with these technologies lie not with the electrical aspect of the design but with the ancillary electro mechanical components.

Surprisingly little progress has been made in thermal management. Some technologies continue to be explored such as Peltier effect heat pumps and heat pipes for conducting heat more efficiently away from the packages. Yet their ongoing problem is that they cannot be cost justified even taking into account the performance improvement that they can offer. At the package level, the only real prospect is to be able to spread the heat away from the working part of the device. For microelectronics applications technologies such as heat spreaders have been considered for increasing the emitting area of the working device. A heat spreader is a highly thermally conductive substrate that is bonded to the device die to increase the heat transfer process. Materials such as AlSiC and polycrystalline diamond have been explored for this application (e.g. SP3 Inc., USA). However these are only practical for devices where all electrical activity takes place on one side of the substrate. Again, in a price sensitive market, they have not made any significant progress due to the cost of incorporating such materials into the package construction. For power applications the energy flow tends to be through the whole wafer rending heat spreaders impractical.

Most emerging wide bandgap semiconductor materials have notably superior thermal conductivity characteristics over Silicon. It is possible that higher power densities within packages may be achieved by increasing the die size so that the active device is centred within a piece of larger non-active substrate. Indeed this approach may fall out as a consequence of needing to increase surface creepage distances to accommodate higher voltage operation. Unless the former approach can be coupled with the latter it is not likely to appeal, since it would almost invariably impact on the number of devices that manufacturers might produce from a single wafer.

2.4.2 Hybridisation

Several respondents to this study highlighted that, for many markets, there is still tremendous scope for development in silicon – especially with regard to increasing the functionality of single packages. This can be achieved by one or both of:

- Incorporating multiple power devices into the same electronic package
- Embedding some of the control functionality into the same package as the main power-switching device.

Each of the above has the obvious benefit of helping to reduce component count and thus help to drive down the cost of power electronic system. Already it is highly common for devices such as IGBT's to have their accompanying freewheel diode integrated into the same package. However there is more scope for integrating yet more components such as further IGBT devices (e.g. for H-bridge configurations) and input bridge rectifiers into a single package. It is likely that such strategies are going to dominate development at the lower end of the Power Electronics industry.

A clear example of the move towards hybridisation arose in April 2006 when Semikron and STMicroelectronics announced a collaboration[10] to develop and deliver integrated power modules for industrial, consumer, and automotive markets. The stated aim of the tie-up is to embed ST's control devices in Semikron's power device packages.

In terms of greater intelligence in a package, start-up companies such as Cambridge Semiconductor have generated a lot of interest with the hybrid modules they are developing that embed control functionality onto the same chip as the power devices. The key challenge for them is isolating the low voltage control requirements of the digital part of the device from the much higher voltages being handled by the power electronic devices themselves. It is likely that the benefits of such integration will be seen in low power applications such as portable equipment supplies and lighting applications.

2.4.3 Packaging and Insulation

The state of the art for electrical insulation design is demonstrated by the fact that 10kV thyristors have been produced. At this rating a very high voltage is insulated by just a very small thickness of semiconductor. The weak link though is the packaging materials used and the external air insulation. The construction of the package to manage electrical stress, avoid voids and weak insulation paths around the wafer, as well as protect the gate electrode is of paramount importance. Similarly ensuring that there is stress relief around all metal semiconductor contacts is vital for safe operation and longevity of the devices. A good example of what happens when this goes wrong was reported when the first generation of Schottky diodes supplied by Infineon that had to be recalled due to the fact that the contacts where eroding because of high voltage stress (for a few hundred volt device).

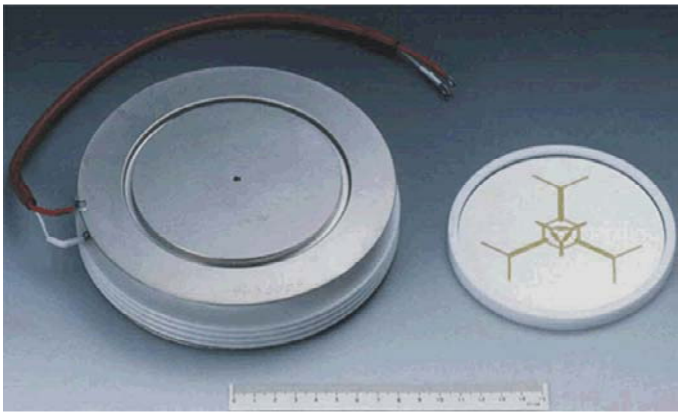


Figure 16: Examples of the two types of packaging used for high power semiconductor devices. The encapsulated modules are useful for hybridisation and part reduction, but have reduced thermal performance while the press-pack above gives better thermal performance but only really works with monolithic devices (i.e. everything on a single wafer).

The package design, (See Figure 16 above for examples) at any voltage above a few hundred volts is critical. The main issue here is the need to design for high electrical insulation strength, while ensuring that the device maintains a low thermal resistance. Often materials that exhibit good electrical insulation properties are not good thermal conductors and so a compromise must be sought. For high voltage applications the press pack (or hockey puck) design seems to have become a preferred standard as this ensures that a good mechanical connection can be made. However advances in encapsulated module design can now accommodate devices up to 6500V and 2000A. This has been made possible by using heat spreader plates made of high thermal conductivity materials such as Aluminium Silcon Carbide (AlSiC) at the end of the market that can justify the additional cost that these present.

The difficulty of designing device packaging is that all the materials used have to expand at more or less the same rate, which limits materials selection. The compromise may be to use conductive (electrical and thermal) greases; however these can be awkward for press pack designs. They are more commonly used in encapsulated systems – albeit with the trade-off of that this arrangement results in a lower power performance. There is considerable value in knowledge relating to effective package design, with many companies having proprietary methods. For example with the trend towards encapsulated hybrids incorporating multiple dies (discrete devices) has enabled companies such as Powerex to operate in an intermediate tier. Rather than produce raw devices in-house they purchase processed wafers from other manufacturers and use their package expertise to integrate them into functional modules for specific market applications.

Developing a device package is not cheap. One estimate has calculated that each new package design costs upwards of $1M to implement. In a market where volumes are low by electronics standards, this means that a considerable R&D premium is placed on the device price.

Most Power Electronics operate in controlled environments; however there is a growing demand for devices to operate in greater extremes of temperature and mechanical stress. This is being driven by the aerospace, marine and defence sectors – which may struggle to create the volumes needed to justify the considerable investment necessary to develop devices for their specific needs.

For wide bandgap semiconductor devices it is not clear if existing packaging materials will be thermally compatible. There are still significant issues that will need to be addressed, in particular taking into account the greater thermal range that these devices are capable of operating over.

2.5 Conclusion

Silicon is now at its practical limits for most power devices. However, there remains continuing scope for innovation, especially at the lower power end of the market for hybrid devices that combine active control with intelligence in a single package. For higher power applications and emerging applications in the transport sector it is clear that an alternative to silicon is required. The issue for these emerging sectors is whether they can provide sufficient market pull to justify the cost of developing a new generation of power devices. It should also not be forgotten that in order to accommodate the benefits that a new semiconductor material will also require advances in packaging materials and techniques.

SECTION 3 – FINDING A REPLACEMENT FOR SILICON

As this report has already highlighted, the percentage value of the semiconductor devices at the heart of power electronic applications represents a small fraction of the overall cost, but the limitations of the current generation of silicon devices dictates up to 70% of the additional costs. All respondents who expressed a view on the subject agreed that in many applications silicon has now been pushed to the limit of its intrinsic capability and is a barrier to greater proliferation of Power Electronics.

The semiconductor industry now has 50+ years experience of producing silicon; as a result, electronics grade silicon is the purest material available to man. This is the reason why it has been possible to push device performance to the absolute intrinsic limits of the material. Silicon is now a commodity material whose production is dominated by just four major manufacturers who together account for 80% of output. In 2005 around 4.3 million square metres of silicon was produced equating to around 7-8,000 metric tonnes of material[11]. The value of that market was $7.9B suggesting a price level of around $1 per gram (approx. $12-15 for a 100mm wafer).

Figure 17: Raw Silicon boule grown from a liquid melt

For power applications there are a number of candidate materials that could be used to replace silicon. What they have in common is the following:

- Production is much more costly (10-100x) because materials must be grown from the vapour phase rather than liquid phase as in the case of Silicon
- The quality of the materials is not as good as silicon, which tends to negate many of the purported advantages they bring
- Their electrical and physical properties mean that they cannot be used as a direct replacement for Silicon
- Their reactive chemistry means that they cannot be produced using existing silicon fabrication facilities without a degree of modification or process separation to avoid cross-contamination

The challenge for any alternative materials technology is therefore to overcome the extraordinary inertia that exists in the industry. A problem that several respondents identified is that, for the bulk of the market, cost far outweighs performance and efficiency. The challenge for any new materials technology is to establish itself in significant niche applications, with end users who are able and willing to invest and share the pain of adopting a new technology.

Over the past 20+ years several contenders have been proposed with various justifications made to support claims as to why they would be the logical successor to Silicon. Some of these various evaluation criteria are detailed in Appendix 4. With the exception of Diamond and Silicon Carbide all the proposed materials are generally compounds consisting of a group III and group V element i.e. the same periodic groups that currently supply the elements used to dope silicon.

Of all the materials proposed, however, only three have emerged as serious contenders (and for different reasons), these are: Silicon Carbide (SiC), Diamond and Gallium Nitride (GaN). It is possibly no coincidence that two of the three are based on elements in the same periodic group as Silicon. Some of the basic properties of these materials is summarised in Table 2.

	Silicon	Silicon Carbide (SiC) 4H polytype	Gallium Nitride (GaN)	Diamond
Electrical Breakdown Strength	1	8.1	13.5	~30
Saturated carrier velocity	1	2	2.2	>2.5
Baliga figure of merit	1	290	400	>11000
Thermal Conductivity	1	3.3	0.87	13.5
Thermal Expansion coefficient	1	~1.7	2.15	0.03
Growth Rate	1	0.1	0.1	0.025
Cost (at present)	1	30	100	1000

Table 2: Some key physical parameters for main candidate wide bandgap materials normalised relative to silicon.

As the figures above show, each of the potential replacement materials offers significant performance advantages over Silicon. The likelihood of any one of them superseding Silicon essentially boils down to 4 basic criteria:

- Availability of the base material in sufficient quality and purity to enable devices to be made
- Availability of the base material in sizes that support efficient production processes

- Ability to process the base material to make meaningful devices
- Demonstrable devices that deliver significant performance advantages over Silicon enabling cost savings to made elsewhere

3.1 Wide Bandgap Base Materials Production

All the leading candidate wide bandgap materials need to be grown from the vapour phase rather than the liquid phase. Inherently this is both a slower and more energy intensive process. The other challenge is that to obtain high quality materials require high quality seed substrates to start off with. Unlike Silicon which can be nucleated from a small seed, the other materials require seed substrates of highly pure material that are equal in size to the desired wafer upon which further material can be grown. The considerable value associated with these seed substrates in turn has led to materials producers being highly reluctant to release the highest quality specimens. This means that the substrates (non materials producing) device developers are able to procure may not be of sufficient quality to take full advantage of the superior properties of the material.

Of the three materials Silicon Carbide is the most mature of the wide bandgap semiconductor materials. It has steadily evolved since the 1990's driven primarily by the US defence sector who have invested tens of millions of dollars into its development, with market leader Cree being one of the major beneficiaries. Others include Bandgap and Dow Corning - the latter having recently received a $3.6m contract from the US Navy to develop 100mm wafers. Just about all US manufacturers grow SiC using physical vapour epitaxy (PVE)[12]. This process uses infra-red heating to sublime SiC material (this occurs at 2200ºC onto a seed substrate under very tightly controlled conditions. One drawback of the PVE process is that the material can only be produced in batches with just a few centimetres of growth possible in a single production run[13]. Okmetic, a Swedish company, have developed an alternate process using chemical vapour epitaxy (CVE) in which the material is grown by reacting out gases containing Carbon and Silicon. The promise of this process is that it will permit continuous growth and could potentially yield higher quality material. Okmetic have now spun this activity into a start-up subsidiary called Norstel.

Silicon Carbide is known to come in over 200 crystal forms (or polytypes). Of these three types have been identified for use in electronic applications. These are:

- 3C-SiC - This is a cubic form of SiC being touted as best for high frequency and optoelectronic applications
- 4H-SiC - This is a hexagonal form of SiC and is the form that is predominantly grown for use in electronic applications in particular of power device applications
- 6H-SiC - This is another hexagonal form of SiC, and is the easiest form of the material to grow

While SiC’s potential for Power Electronics applications were first demonstrated with early prototype devices in the early 90's, its evolution has been slow. Today SiC’s predominant application is for blue LED's and lasers either as the electronic material or as a substrate for other materials such as Gallium Nitride. Because of the small sizes of these devices obtaining large contiguous working areas of high quality material has not been a priority. Although progress and growth is now being made in SiC power devices, the fact remains that the driver for materials improvements is still the opto-electronics industry. With improvements in GaN there are signs that lighting manufacturers such as Osram who are a massive purchaser of LED's & lasers may switch to solely GaN based devices. This could affect the progress of future development of SiC as a material.

Gallium Nitride is grown in a similar way to SiC. However while SiC requires an SiC substrate, GaN can also be grown on Sapphire (one form of Al_2O_3) which can be produced in large single crystals for a lot less than SiC. The difference in materials chemistry also makes it comparatively easy to separate the grown material from the seed substrate. Coupled with a lower growth temperature, GaN is therefore potentially cheaper to grow than SiC. Signs that the industry is moving with GaN are exemplified by the recent mass production facility opened by Sumitomo in Japan. The problem for GaN from a power device applications standpoint is that the wafers are not homogenous single crystals and the very high dislocation density means that it will be difficult to push the material towards its intrinsic limits[14].

Diamond is significantly behind SiC and GaN as a materials technology. Diamond is a metastable form of carbon and requires specific conditions to cause its growth. The best known method is by the application of high temperature and high pressure (HTHP), but for electronics applications growth using plasma assisted chemical vapour epitaxy (PA-CVE) is the process that will allow large wafers of diamond to be produced. The advantage of this process is that growth occurs at relatively low temperatures; however a considerable amount of microwave energy (10's of kW) is also required to stimulate the reactive chemistry, which makes it a very energy intensive process.

PA-CVE diamond has seen significant progress in increasing growth rates - until about 5 years ago 1µm an hour was seen as good (for single crystals), now that rate is closer to 10-20µm per hour. It appears that this may pushed further with the research group at Carnegie University in the US claiming to have achieved 100µm per hour, although it not clear how good the crystal quality was. The quality of PA-CVE diamond is very high with companies such as Element Six already claiming to be able to produce material with dislocation densities of just 10^3 cm^{-2}. Because the growth process requires a high quality seed substrate to which the subsequent growth is effectively a clone, there is considerable inertia from the existing materials manufacturers (E6 and Sumitomo) to commercialise their diamond technology. There is no sign that either currently have any plans to scale up their growth processes to produce wafers that would permit even early stage production prototype devices to be manufactured. While this is, in part, due to an absence of credible application developers it is highly likely that the lead here is going to taken by one of the smaller start-ups such as Apollo Diamond in the USA or Iljin in Korea.

	Silicon Carbide (SiC) **4H polytype**	**Gallium Nitride (GaN)**	**Diamond**
Growth Process	Physical Vapour Epitaxy or Chemical Vapour Epitaxy (*)	Physical Vapour Epitaxy or Chemical Vapour Epitaxy	Microwave Assisted Chemical Vapour Epitaxy
Seed Substrate	SiC	SiC or Sapphire	Diamond
Growth temperature (ºC)	1650 – 1850	1150-1250	700 - 800
Growth Rate (mm per hour)	0.2 – 2(	0.2 – 2	0.02 – 0.2
Quality Issues	Micro-pipes, screw dislocations, polytypes	Dislocation density (10^9 cm^2), lattice stress	Lattice stress, crystal defects, single crystals > 1cm^2
Major suppliers	Cree, Intrinsic, Hoya, Norstel (*)	Cree, Sumitomo, ATMI	Element Six, Sumitomo, Apollo

Table 3: Comparison of growth processes and issues for leading candidate wide bandgap materials.

Table 3 above summarises the various differences in the production processes. The most important parameter is the eventual cost of producing the substrates. At present with all materials production technologies still maturing the cost of substrates will continue to fall. Since all rely on manufacturing processes that are inherently more expensive than Silicon, it is highly unlikely that any of materials will be producible for much less than 5-10 times the price of silicon. However it is also likely that costs will also bottom out to a similar level for all three, leaving the choice of material not being determined by cost but by the other three criteria outlined at the start of this section. Figure 18 over the page shows an estimate of materials price with time. These projections are based on the assumption of significant volume markets emerging that will help to drive production costs down.

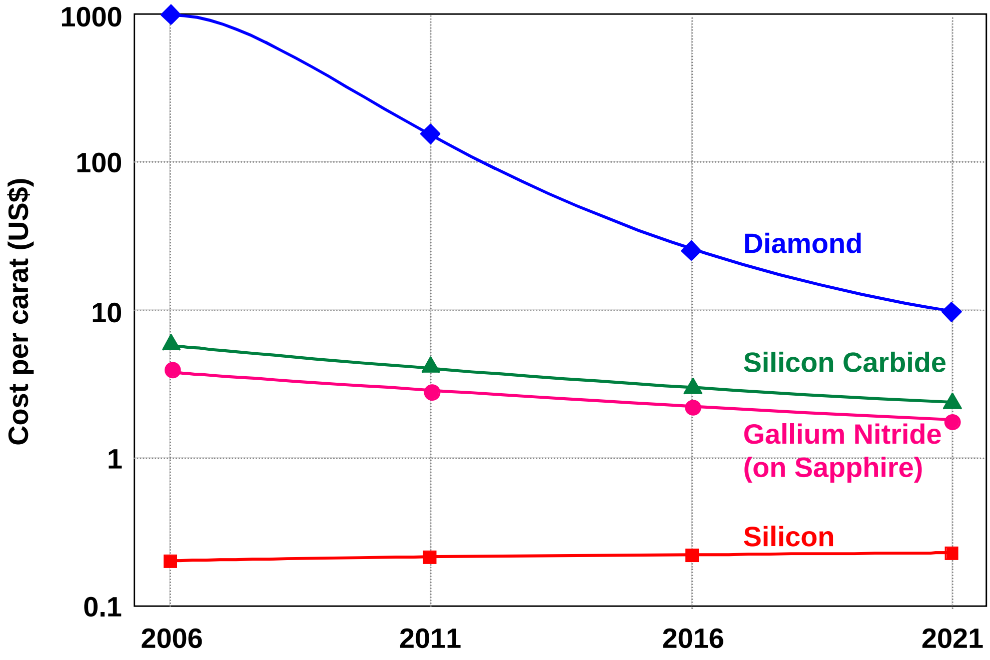


Figure 18: Projected prices of various substrate materials (N.B. 1 carat = 0.2g)[15,16]

3.2 Availability of Base Materials

Both SiC and GaN are available commercially from a number of manufacturers with Cree leading the SiC market and Cree/ Sumitomo leading the GaN market. For device manufacturers two parameters are critical: substrate size and yield. The cost of processing a 50mm wafer is pretty much the same as processing a 100mm or 150mm wafer, with the only difference being in the energy and chemicals cost associated with larger substrates. Because such a high proportion of device manufacturing cost is fixed, the only way to produce competitively priced devices is to work with larger substrates. This is illustrated by the fact that Silicon device manufacturers now work regularly with 300mm diameter wafers as a matter of course (although not in the power sector where 150mm is more typical). Device yield is also important because it determines how many working devices can be produced from the substrate. A high rejection rate is therefore expensive, not just because of wasted processing but because of the additional testing that is necessary to discriminate bad from good.

In the case of SiC high quality 50mm substrates are widely available. Market leader Cree now claims to produce substrates with micropipe densities of less than 10^{-2} cm^{-2} (i.e. less than 1 defect per $100cm^2$) and a 78% device yield for devices up to $1cm^2$ in area compared with an 86% yield for devices of up $1mm^2$ in 2000. In the past 12 months a number of manufacturers are now claiming to be able to produce 100mm diameter wafers. However respondents indicated that while the quality of 50mm substrates is now very good, the quality of 100mm substrates is still not up to the standard required for commercial production and they are not expecting such substrates to be available until at least 2008.

For GaN its rapid take up in the opto-electronics sector has meant that that 100mm wafers are already available. The problem with GaN continues to be growing substrates with sufficient crystal quality to enable production of large area devices. However given the lower cost of producing GaN coupled with benefits of working with larger wafers means that yield is not as critical. Companies such as Velox Semiconductor (a spin-out from Emcore, who have just sold their remaining compound semiconductor materials business to UK based IQE) are pursuing GaN based power diodes and transistors, albeit with low power ratings. Like many emerging wide bandgap businesses Velox are producing both their own substrate materials and devices.

Diamond is significantly behind in the race to develop a replacement for silicon. As it stands at the present time while it is possible to purchase HTHP materials up to 5mm square on a commercial basis, no manufacturer is offering the PA-CVE films that will be needed for proper exploitation. The prospects for larger substrates essentially lie with a handful of materials developers who carefully control the market. One issue is the availability of high quality seed substrates, which each developer appears determined to keep out of the hands of their competitors. For example in 2000, 1cm square HTHP substrates were announced by both de Beers (now Element Six) and Sumitomo only to be quickly withdrawn from the market for no apparent reason other than that they significantly simplified the potential production of larger substrates. Clearly this is unhealthy for an emerging market and not helped by the geographic spread of the main competitors (UK, Japan and USA), which does not engender competition.

The technique for growing larger diamond substrates appears to rely on a tiling method, whereby smaller grown single crystals are placed in a tight fitting mosaic and further diamond is then grown on top. This does not yield a larger single crystal, but instead results in a larger substrate with defined areas of single crystal. For small devices (up to 8mm die size) this offers the prospect of being able to source diamond substrates at a practical working size (50 - 75mm diameter) with consistent defects that can be worked around. This is not likely to be good enough for power devices though. Surface modification techniques are available that could help to eliminate defects and a laborious process can be envisaged whereby an iterative cycle of new substrate growth, surface manipulation and subsequent growth etc. could result in much larger single crystal substrates. The question therefore remains about where the impetus to make the necessary development investment is going to come from.

With improvements being made in vapour phase growth processes it is highly likely that all the materials technologies will benefit from common advances made in process equipment technology. This suggests that the maturity cycle for any of these technologies will be significantly shorter than Silicon. With the prospect of suitable high quality wafers for power electronic applications on the horizon, the key issue will be the infrastructure needed to support a devices business and extracting their performance benefits over Silicon.

3.3 Semiconductor Processing of Wide Bandgap Materials

A semiconductor device essentially works because of the differing electronic properties that result when the base material is deliberately contaminated with foreign elements (otherwise known as doping). When two or more variants of the base material are brought together the electrical behaviour is modified allowing the flow of electricity to be controlled and hence the basis of the devices discussed in the previous section. For electronic devices not only is the level of doping an issue but also the geometry and topology of how the variants are positioned. To produce any electronic device two factors need to be addressed:

- The ability to selectively modify the electronic properties of the material using dopant elements
- The ability to modify the structure of the substrate using process chemistry

3.3.1 Material doping

None of the wide bandgap materials offer a straightforward replacement for Silicon. To make a semiconductor device requires both n and p-type versions of the material plus, in many cases, a compatible insulation material (such as in the case of Silicon its oxide SiO_2). A dopant is a foreign element that substitutes for some of the base material atoms leaving spare chemical bonds that are either electron deficient (in electrical terms a hole – the basis of p-type) or electron rich (the basis of n-type). It is these unfulfilled chemical bonds that yield the semiconductor properties. The principle dopants of the main candidate wide bandgap materials are summarised in Table 4 below.

	Silicon Carbide (SiC)	Gallium Nitride (GaN)	Diamond
n-type dopant	Nitrogen or Phosphorus	Silicon	Nitrogen or Phosphorous
p-type dopant	Boron or Aluminium	Magnesium	Boron
Insulating oxide	SiO_2	Ga_2O_3	None/ intrinsic Diamond

Table 4: Summary of most commonly used dopants for wide bandgap semiconductors

One of the problems that have beset device developers has been the difficulty of producing equally high quality n-type and p-type material. For instance SiC is easily doped to produce very good n-type material, but the same is not true for p-type where it remains difficult to produce low resistivity p-type material. Consequently the first bipolar (IGBT) devices that have been produced in SiC are p-channel rather than the more conventional Silicon n-channel.

For diamond doping continues to be a difficult issue. Carbon is a small atom and diamond has a very closely packed crystal structure. This makes it difficult to insert doping atoms into the material without unduly distorting the lattice structure or causing break-up of crystal uniformity (and hence destroying the material properties that you wish to exploit). The two natural dopants of diamond (the adjacent elements, Boron and Nitrogen) are not good dopants since they require significant energy to trigger the semiconductive state, particularly the n-type dopant, nitrogen. In the past 20+ years a significant amount of diamond research has been invested to find a credible n-type dopant. While several have proposed such as Phosphorous (causes major lattice distortion) and Deuterium co-doping of Boron doped (p-type) material, none have yielded a stable workable material. At a recent Institute of Materials conference on Diamond, one presenter proposed the use of (highly toxic) Arsenic as a potential dopant, much to the obvious chagrin of those attending who were active in materials growth.

The continuing saving attraction for diamond is that the whole mobility of diamond is greater than the electron velocity of most other semiconductors making the potential of unipolar devices based on boron doped diamond possible. However even for this class of devices some form of n-type (even if poor) is needed and it not clear if simply using Nitrogen or Phosphorous doped materials will suffice. As one respondent noted, diamond remains stuck with the vacuum tube, since even for a unipolar device the minority carrier version of the material must exist in order to restrict the space charge that will otherwise throttle current flow.

Another problem for wide bandgap semiconductors is that doping by diffusion or implantation of the foreign elements is not as effective as it is with Silicon. For example implantation can cause significant damage to the crystal structure – and the case of Diamond actually causes graphitisation of the material. This result is that the best route for achieving good doping is by introducing the dopant elements during the materials growth phase. Since any subsequent growth process are done by epitaxial methods similar to basic material growth method, a much closer relationship between device developers and materials developers is going to be necessary than presently exists in the silicon industry. It also means that the material developers who are also developing devices have a distinct edge.

3.3.2 Material Processing

None of the wide bandgap materials are straightforward to process. Although the basic production systems are much the same as those for Silicon, the reactive chemistry and process flow are not. While it appears that SiC can be processed in a silicon facility, a major issue is that silane (SiH_4), a highly toxic gas that requires special handling, is required. Potential contamination of process equipment coupled with unfamiliarity and potential infrastructure upgrading, means that very few fabricators are willing to put SiC through their systems. However some limited production facilities are emerging such as Royal Institute for Technology (KTH) in Stockholm and Newcastle University (research only).

In the case of GaN many of the problems of processing III-V compounds have been resolved through the progress made with gallium arsenide (GaAs) in the last 20 years. While GaAs is handled in specialist fabrication facilities, the emphasis of these plants is on high frequency components and they are not likely to be geared to support power device production. Further there is little spare infrastructure in GaAs to support jobbing fabrication.

At a first glance it would be logical to assume that diamond being immediately above silicon in the periodic table would have similar chemical properties. Diamond however is extremely inert and, as a metastable form of carbon, has different reactivity to the more common graphitic or amorphous forms of the element. One of the major difficulties in processing diamond is the fact that processing often requires it first to be decomposed to graphitic carbon, which must then be quickly removed to prevent choking of the reaction. Coupled with a high sensitivity to contamination this makes Diamond difficult to process. This means that any device fabrication facility is likely to have to be dedicated to the material.

3.4 Demonstrable Devices Using Wide Bandgap Materials

It is only in the past couple of years that commercial wide bandgap devices based on SiC and GaN have started to become available. The improvement in these materials technologies means that both unipolar and bipolar devices are now feasible. At this stage SiC is clearly the frontrunner with several companies developing SiC replacements for all existing major Silicon devices. GaN manufacturers are also starting to offer devices with companies such as Velox already offering low rated Shottky diodes priced competitively against similarly rated SiC with similar performance. A route map showing the evolution of major expected devices and their commercial availability is shown in Figure 19, (over the page).

SiC Schottky diodes are already attracting a significant market with estimated device sales of around $10-20m at present and forecast to rise to $35-45m by 2009[17]. Despite being 20x more expensive than their silicon equivalents, the appeal for applications developers is the overall benefits they bring by significantly reducing the passive component count and hence overall system cost.

For Diamond the future is not as clear. Without an obvious solution to the n-type problem developers will continue to struggle to make credible devices. The problem here appears to be that developers appear to have got stuck in the rut of trying to make Diamond behave like a direct replacement for Silicon. However it is a unique material and maybe the solution to using Diamond lies not with trying to replicate Silicon concepts, but to go back to basics and try to exploit some of the other unique attributes such as its novel electron and optical transport properties create new devices unique to carbon.

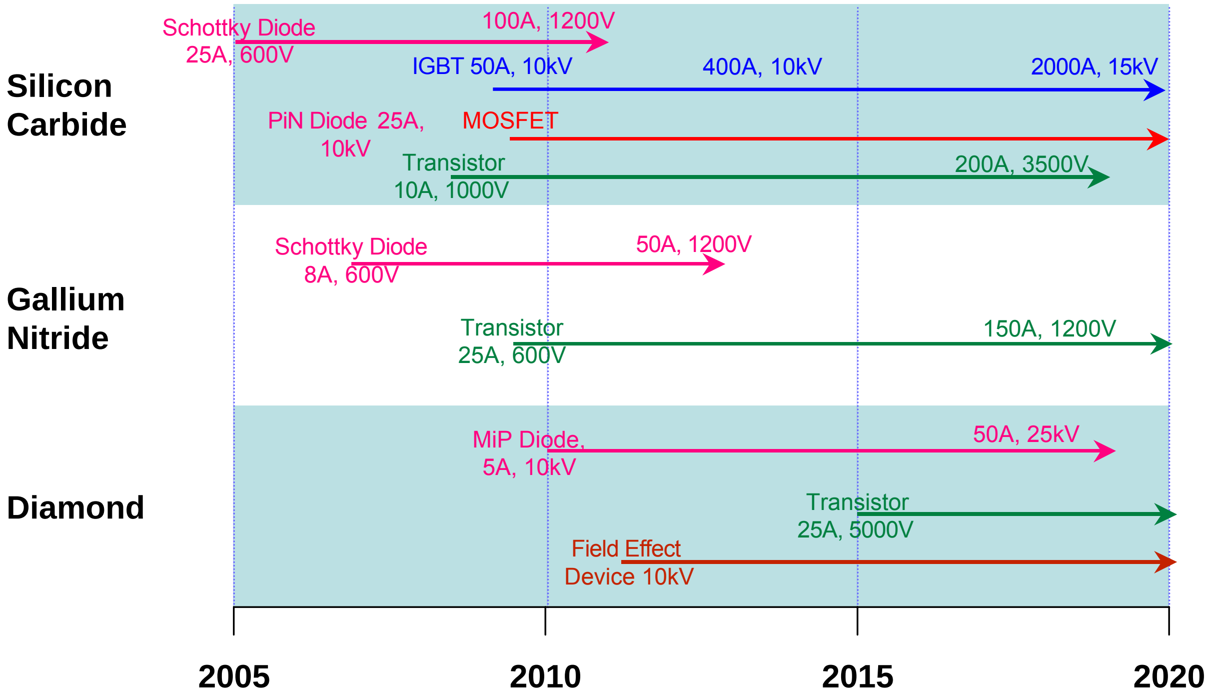


Figure 19: **Indicative roadmap of major device developments using wide bandgap semiconductors**

3.5 Overcoming the Silicon Barrier

Based on the criteria outlined at the start of this section, only SiC and GaN are anywhere close to meeting all four criteria at this time, with SiC being the clear favourite. Yet the study has highlighted that opinion is divided on whether SiC will successfully supersede Silicon. At present it is clearly the front-runner, yet several respondents expressed a belief that sufficient progress will be made in diamond to enable it to ultimately succeed over all other materials technologies. What all the candidates have in common is that the base materials will always be more expensive to produce than silicon, by around an order of magnitude, simply because of the energy intensity and method of growth that they employ.

At present SiC devices incur about a 20x price premium on equivalent Silicon devices, which for some applications is cost justifiable such as with the impact of the Schottky diode. As the next section highlights in the case of Silicon the base substrate material cost only accounts for around 5-8% of the device cost. Thus, even with the price premium payable for wide bandgap substrates, with volume it should be possible narrow that premium to around 3-5x and ultimately 2-3x.

The problem for all developers of wide bandgap devices is overcoming a highly established and cost optimised business that is able to satisfy 80% of its needs with currently available devices. It is clear that any new non-silicon device technology will have to offer one or both of these benefits:

- Greatly reduces the overall system cost associated with the intended application

- Offers margins of performance that silicon cannot deliver
- Enables operation in environments where Silicon cannot

These could be construed as being rather obvious, however in the case of the non-silicon technologies the problem is that the entry route is through devices of sizes and ratings that directly compete with silicon. Here, while there may be a performance benefit, system designs are not all that greatly simplified in the majority of applications through using new devices – particularly anything more complex than a diode.

The major pull for wide bandgap devices is coming from industries that require devices that extend the environmental operating range of power electronic systems such as traction and aerospace. While these are significant markets they are not as big as the potential market that could result from more general energy applications. As one respondent commented, “the availability of a switching device rated at 22kV [15kV AC nominal], 150A would revolutionise Power Electronics the energy sector”.

The voltage levels required by the aerospace and traction sectors are relatively low (except in the case of marine drives), which means that the onus to develop the high voltage devices that the energy sector would benefit from is not there. Further a number of respondents expressed scepticism that SiC or GaN would be able to deliver switching voltage improvements much above a factor of 2 on what Silicon currently achieves. For example Cree have recently reported a 20kV, 25A rated PiN diode with current density of 100Acm^{-2}. However the forward conduction loss through this device was measured to be 13V, over three times more than the loss in an otherwise equivalent 10kV device they had also produced.

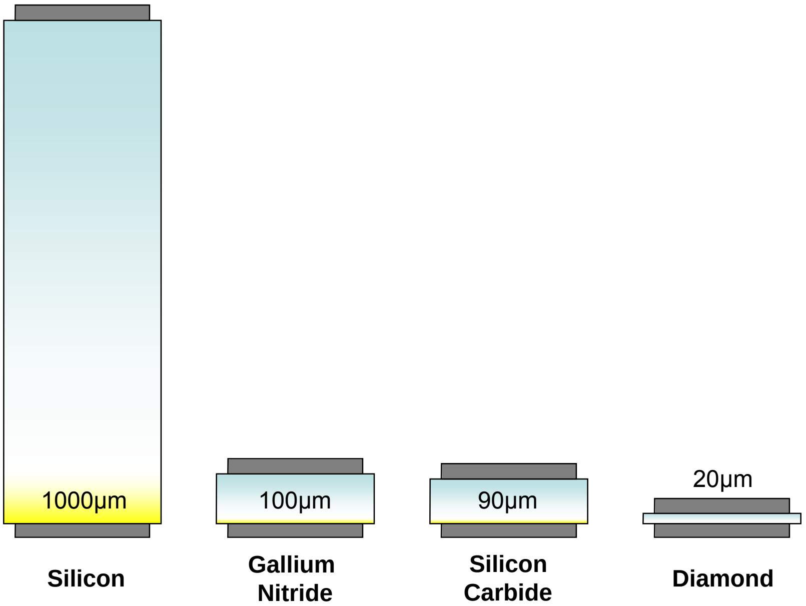


Figure 20: Comparison of depletion layer thickness necessary to achieve 10kV reverse breakdown insulation.

As the chart in Figure 20 illustrates, while SiC and GaN offer significant insulation improvement over silicon, diamond is around a factor of 5x better still. It therefore seems likely that the opportunity for diamond lies in some sort of family of devices that deliver high voltage performance. With the relatively modest current levels required this offers the prospect that diamond devices may not be as hampered by the present limitations of the current substrate technology and arrive in the market place earlier than people may expect.

3.6 Conclusion

There is a recognised growing need for a replacement for silicon in power electronic devices. The problem is that most of the markets driving that underlying need cannot generate the volumes necessary to support the investment in a new technology. SiC and GaN have risen to the fore because of their adoption in the opto-electronics sector, yet questions still remain as to whether they will deliver sufficient performance improvements to justify a move to devices based on these materials. Diamond is seen as the ultimate electronic material, but it significantly lags behind the other materials. This is partly because the pull from industry is not sufficiently strong, but also because of its association with the gem material that continues to hamper its wider proliferation.

SECTION 4 – VALUE CHAIN ANALYSIS

Today the electronics industry is a \$1300Bn market. Power Electronics though accounts for just 10% of that market. It is therefore a significant market, but one that is always likely to struggle to enjoy the benefits of volume the far larger electronics industry enjoys. The usual representation of the Power Electronics market often used by industry organisations such as Semi (the materials and equipment trade group) is shown Figure 21[18,19]. For the purposes of this study manufacturing equipment will be ignored. However what this market breakdown omits is the fact that much of the pull comes, not the people who develop Power Electronics systems but, those who integrate Power Electronics into the larger electrical or electro-mechanical systems for which they are intended. A more appropriate value chain is illustrated below in Figure 22.

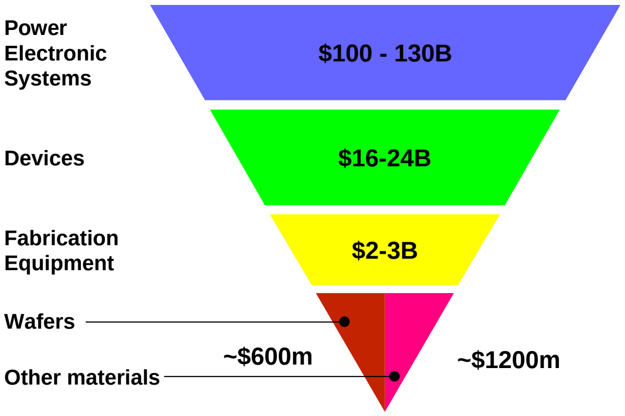


Figure 21: Estimated world market for Power Electronics in 2005

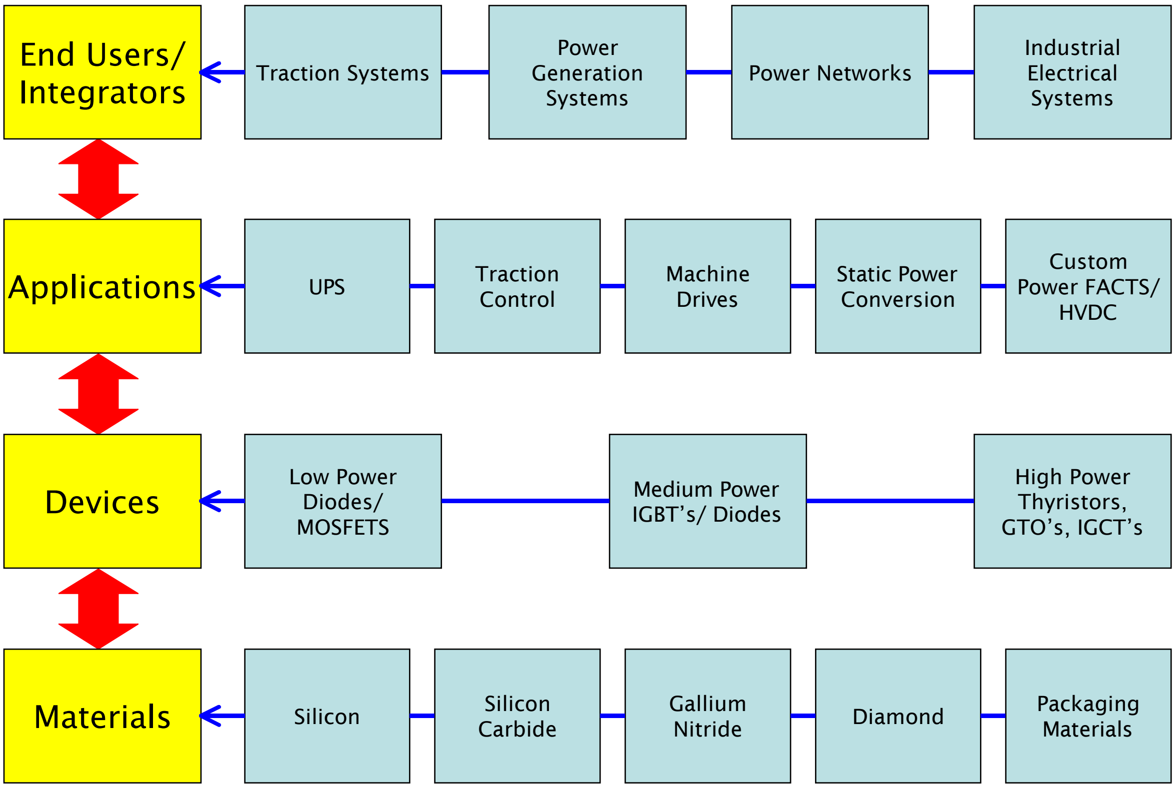


Figure 22: Value chain and options matrix for Power Electronics with specific emphasis on medium and high power energy applications

The value chain has 4 principle tiers. The top tier represents businesses who have positioned themselves to provide turnkey electrical or electro-mechanical systems that incorporate Power Electronics as part of the overall solution. At the bottom are the materials producers who provide the basic semiconductor and packaging materials. In between lie the device manufacturers and those who actually develop and realise actual Power Electronics systems.

The dynamics of the chain highlights the existence of contrasting drivers. At the integrator level, the major watchword is conservatism. This is imposed on them by the nature of the end users they themselves supply, where security and reliability are paramount. Certainly at industrial level much of the equipment is expected to operate for decades and suppliers are expected to provide legacy support during that period. The knock-on effect is that applications manufacturers also tend to be conservative – especially in the lower volume markets. Yet the industry is price driven and applications developers will embrace new technologies if they help drive down costs.

This caution in the industry is illustrated in Figure 23. New applications (and devices) often follows an adoption profile that sees an initial take-up resulting in prototypes being developed and installed followed by an evaluation period, which is typically 1-5 years. The length of this evaluation tends to be dictated by the risk profile of the end user, the more risk averse the longer the evaluation period. Once end users are satisfied, acceptance is often characterised by the emergence of competing "me too" products, rapid adoption is often the norm as a new generation of technology supersedes the old.

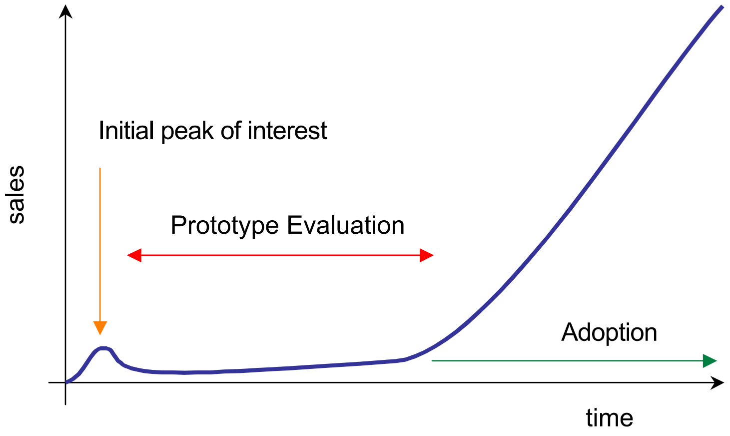


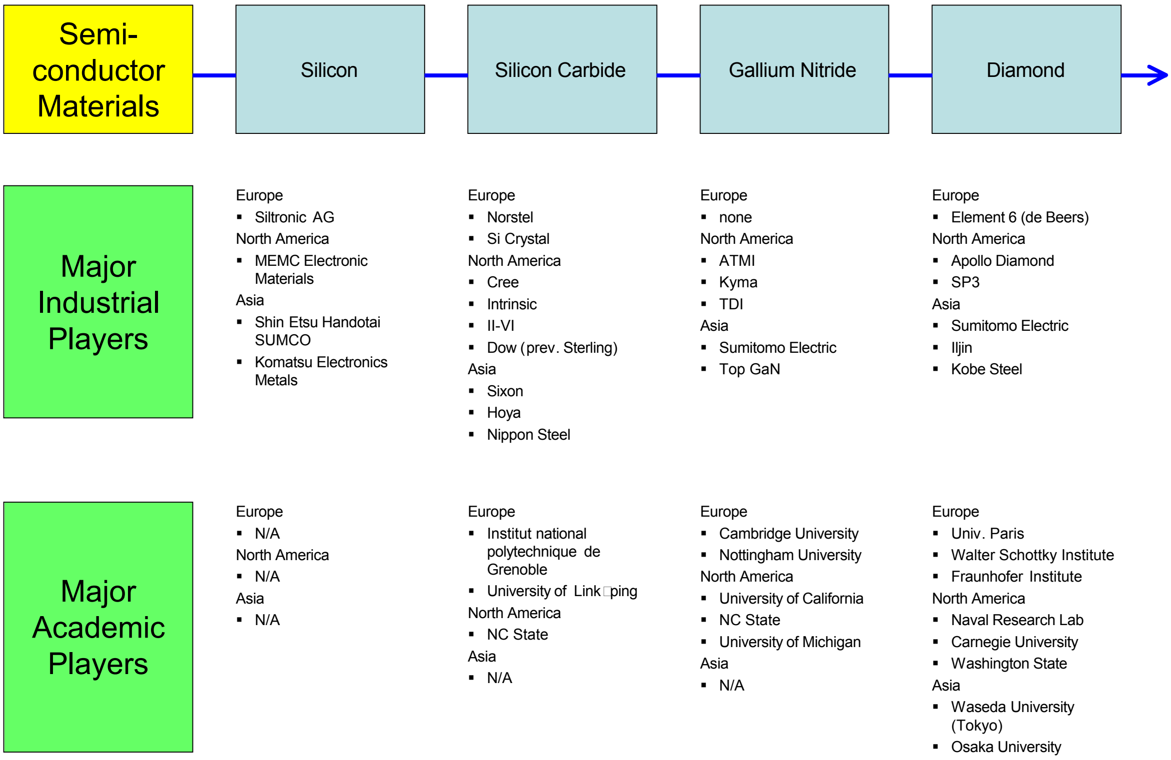
Figure 23: Typical adoption curve for new power electronic applications and devices

The one area where major change can be instigated is at device level. It is here that new devices yielding cost savings at application level or offer better efficiency can generate a technology push. A good example of this is the rapidity by which the IGBT has largely superseded the GTO within the space of a decade.

At the bottom of the chain are the basic materials suppliers. This tier applies not only to the production of semiconductor wafers but also the other materials that are required to package up a device. There is more value in the packaging of devices than the raw die (processed wafer) as companies such as Semikron exemplify. By their nature, power electronic devices push materials close to their intrinsic limits.

The Power Electronics industry is something of a series of villages with pockets of capability mainly centred in Japan, Europe (primarily UK and Germany) and the USA. Of these the main knowledge of very high Power Electronics lies with the European and Japanese players – driven primarily by the heavy engineering traditions that still exist in those countries. The US probably has the upper hand in the low power end of the market, certainly in device design and application design expertise.

4.1 The Materials Tier



Semi-conductor Materials	Silicon	Silicon Carbide	Gallium Nitride	Diamond
Major Industrial Players	Europe ▪ Siltronic AG North America ▪ MEMC Electronic Materials Asia ▪ Shin Etsu Handotai SUMCO ▪ Komatsu Electronics Metals	Europe ▪ Norstel ▪ Si Crystal North America ▪ Cree ▪ Intrinsic ▪ II-VI ▪ Dow (prev. Sterling) Asia ▪ Sixon ▪ Hoya ▪ Nippon Steel	Europe ▪ none North America ▪ ATMI ▪ Kyma ▪ TDI Asia ▪ Sumitomo Electric ▪ Top GaN	Europe ▪ Element 6 (de Beers) North America ▪ Apollo Diamond ▪ SP3 Asia ▪ Sumitomo Electric ▪ Iljin ▪ Kobe Steel
Major Academic Players	Europe ▪ N/A North America ▪ N/A Asia ▪ N/A	Europe ▪ Institut national polytechnique de Grenoble ▪ University of Link□ping North America ▪ NC State Asia ▪ N/A	Europe ▪ Cambridge University ▪ Nottingham University North America ▪ University of California ▪ NC State ▪ University of Michigan Asia ▪ N/A	Europe ▪ Univ. Paris ▪ Walter Schottky Institute ▪ Fraunhofer Institute North America ▪ Naval Research Lab ▪ Carnegie University ▪ Washington State Asia ▪ Waseda University (Tokyo) ▪ Osaka University

Figure 24: Breakdown of major industrial and academic players in the Semiconductor materials sector by materials type

The Silicon materials market is a standalone market, which, according to Semi (the semiconductor materials trade association), was worth an estimated $7.9B in 2005, producing around 4.3 million square metres of silicon. Today the market is dominated by just four producers who between them supply over 80% of demand with a further 3 players meeting much of the remainder. The silicon market is highly mature and has probably consolidated about as far as it is likely to go in the near future.

In addition to basic materials production, there is also a considerable intermediate tier populated by companies who provide wafer polishing and other prefabrication services. According to Semi, this market is worth about as much as that of the basic materials. A market also exists for resellers of basic materials that have been graded or refined to customer requirements. In Europe companies such as Okmetic (Sweden) meet this demand.

One trend that has been identified is that the existing silicon producers are not driving the emerging new wide bandgap semiconductor materials. Silicon carbide is dominated by US companies - who have benefited from significant US government support, primarily through defence research contracts. While the Japanese have a presence in the sector, companies such as Hoya have focused on the 3C polytype whereas the market seems be settling on 4H for many applications – especially for power semiconductors. The only significant European producer is Norstel (as spin-out of Okmetic) who have benefited from significant investment from the Swedish government.

Cree are the dominant company in the SiC market place. A number of respondents suggested that Cree may be keeping back their highest quality material for their own internal consumption in their gallium nitride and devices business thus creating opportunities for others. It is not clear just how large the SiC materials market is because of its use in GaN production; however it is probably in the low hundreds of million dollars. Like the silicon secondary market, intermediate service suppliers such as NovaSiC in France are starting to appear who specialise is substrate polishing and preparation.

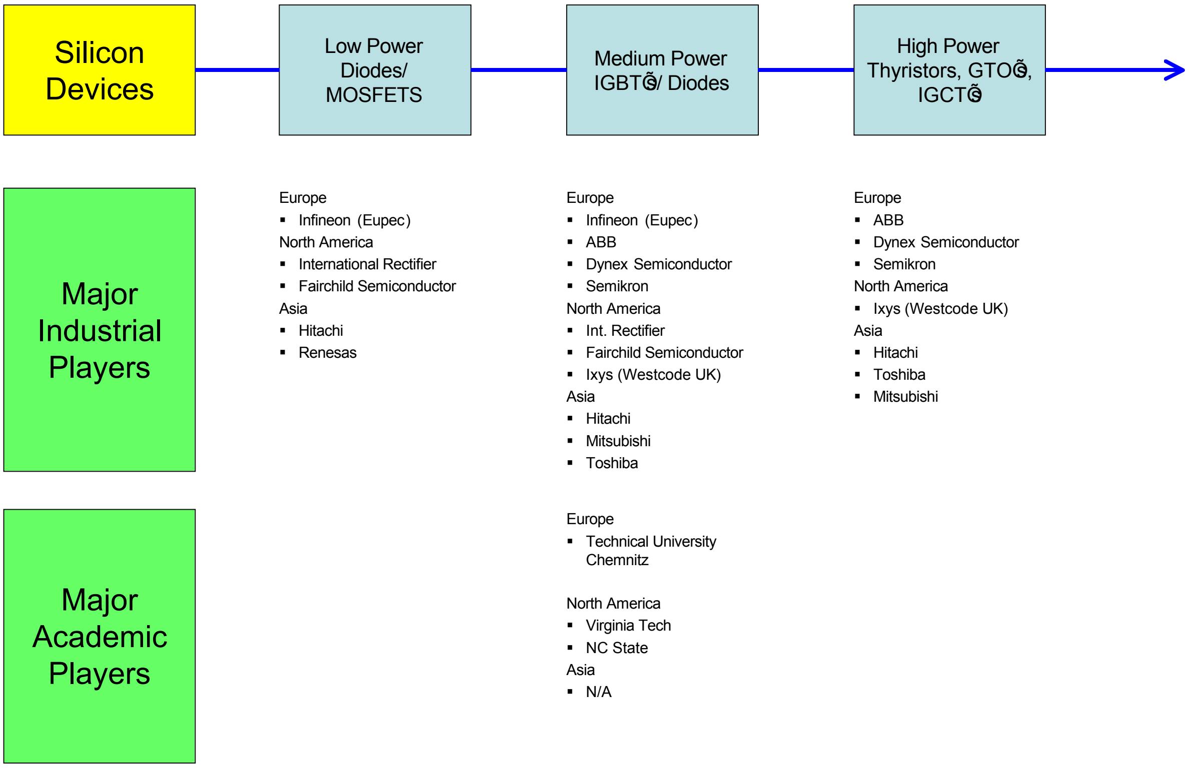
Gallium Nitride has evolved rapidly as a high frequency and opto-electronic material. Again there is very little activity in GaN from an industrial perspective in Europe. Although GaN has matured rapidly in the past 5 years, it still has to resolve many of the material quality issues – particularly the high defect count. GaN is grown on a donor substrate rather from a seed of the same material and the market remains split on those that produce the material using SiC (usually yields better quality material) or the less expensive Sapphire.

Consolidation is already occurring in the SiC and GaN materials sector. There is an industry perception that supply structures will go much the way of the silicon industry, reducing down to just a handful of players who will benefit from mass production. A good example of this is the recently announced acquisition of IntrinSiC Semiconductor by market leader Cree for $46m[20].

The diamond materials market is the one area that the UK has any sort of dominance in thanks to the capabilities of Element Six (the industrial diamond arm of de Beers). Electronic diamond is the least mature of any of the materials discussed. Less than 10% of Element Six's estimated $300M turnover in 2005 was derived from sales of high quality materials the rest being basically diamond grit. The only other major player is Sumitomo Electric in Japan, who has recently invested heavily in GaN production. Apollo Diamond in the USA punches above its weight, but it is a small company lacking the deep pockets of its competitors. With only a few highly dispersed players of major significance there is a distinct lack of competitive impetus that could drive this industry forward. This is not helped by the fact that suppliers are nervous about releasing production quality substrates for fear of allowing their competitors to make use of them in their own production. Hence Diamond stands poised at something of an impasse at the present time.

As a mature market there is little academic activity in basic silicon materials. The exception to this is ongoing work on alternative substrate materials for silicon-on-insulator (SOI) technology. This is seen as key to future generations of silicon electronics and also helping to push the operating temperatures that silicon operates at. With the growing maturity of SiC and GaN again much of the knowledge lies with commercial developers, however there is strong university expertise in the area of materials characterisation. It is only in the field of diamond is there notable basic materials research expertise with a strong but small community led by the likes of Carnegie Mellon University in the USA plus, UCL and Heriot-Watt in the UK.

4.2 The Devices Tier



Silicon Devices	Low Power Diodes/ MOSFETS	Medium Power IGBT's/ Diodes	High Power Thyristors, GTO's, IGCT's
Major Industrial Players	Europe ▪ Infineon (Eupec) North America ▪ International Rectifier ▪ Fairchild Semiconductor Asia ▪ Hitachi ▪ Renesas	Europe ▪ Infineon (Eupec) ▪ ABB ▪ Dynex Semiconductor ▪ Semikron North America ▪ Int. Rectifier ▪ Fairchild Semiconductor ▪ Ixys (Westcode UK) Asia ▪ Hitachi ▪ Mitsubishi ▪ Toshiba	Europe ▪ ABB ▪ Dynex Semiconductor ▪ Semikron North America ▪ Ixys (Westcode UK) Asia ▪ Hitachi ▪ Toshiba ▪ Mitsubishi
Major Academic Players		Europe ▪ Technical University Chemnitz North America ▪ Virginia Tech ▪ NC State Asia ▪ N/A	

Figure 25: Breakdown of major industrial and academic players in the present silicon semiconductor devices sector by major device types

The silicon power semiconductor market is a mix of large multinational players and independent manufacturers. Depending on whose marketing data you believe, the devices market is estimated to be worth between $16B and $24B. Of this around 75% of the market is at the lower power end and the remainder divided between medium and high power markets. At the higher ratings end, the market is dominated by companies who have historic links to heavy power engineering. The greatest expertise generally lies in Europe and Japan. In the UK, both Dynex and Westcode (Ixys), who have their origins with now deceased power engineering businesses also continue to survive, but lack the resources and in house-pull through that many of their competitors enjoy.

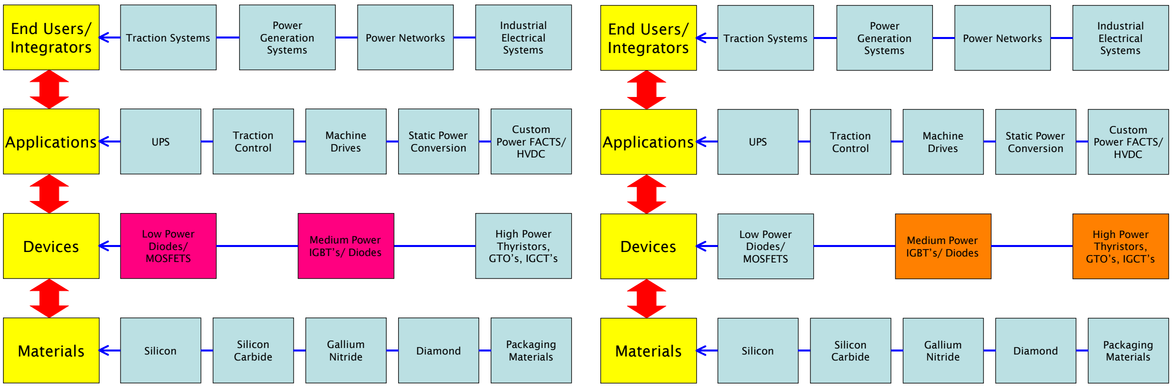
Table 5 lists the top power semiconductor companies by sales in 2004. It highlights that the lion's share of sales is dominated by transistor or MOSFET based discrete and integrated devices at the low to medium end of the power spectrum. It is also interesting to note that companies such as TI, ST Micro and Infineon also manufacture some of the industry standard control cards that many application manufacturers of medium/ high power systems use as the base for their own control software platforms. The stability and functionality of these processor cards can be just as important as the power devices themselves.

According to the DTI's trade and investment website, the UK is well positioned in semiconductor design and associated core technologies, claiming that the UK accounts for over 40 per cent of European independent semiconductor design revenue. However this largely applies to electronics and not Power Electronics where the UK is not as well served. Dynex is the only UK owned company with Westcode now owned by US company Ixys. However companies such as International Rectifier and National Semiconductor have a manufacturing presence in the UK (the latter in Scotland).

Power Device Sales Ranking	Company	Headquarters	2004 Power Device Sales ($M)	Overall 2004 Semiconductor Sales Ranking
1	Fairchild	USA	1130	38
2	Texas Instruments (TI)	USA	880	3
3	International Rectifier	USA	825	46
4	Renesas	Japan	805	5
5	ST Micro	Europe	790	6
6	Toshiba	Japan	750	7
7	National Semiconductor	USA	660	26
8	ON Semi	USA	805	41
9	Infineon	Europe	580	4
10	Vishay	USA	540	24
17	Semikron	Europe	~300	-
26	Ixys (Westcode)	USA (UK)	185	-
36	Dynex	UK	30	-

Table 5: Top 10 rankings of power electronic manufacturers plus major UK player rankings (overall sales rank from top 50 semiconductor companies list[21])

With the exception of companies such as ABB, who have retained a relatively small power devices manufacturing capability, few of the silicon power devices companies are vertically integrated within the Power Electronics chain. Many of these companies are horizontally integrated with substantial activities in the microelectronics sector. This integration is possibly more historical than logical since there is limited synergy between production systems needed for micro and Power Electronics. Companies also tend to specialise at one end or the other of the power spectrum as Figure 26 illustrates, highlighting that companies are either focused on the very high volume, low margin low power end of the market or, the much lower volume, higher margin medium and high power end of the market. The main area for differentiation now lies with the production of hybrid or integrated packages that lock applications manufacturers into one producer.



E.g. Fairchild and International Rectifier e.g. Dynex or Semikron

Figure 26: Examples of how various silicon device manufacturers have positioned themselves within the supply chain

As companies such as Semikron and Westcode have demonstrated, the active semiconductor dies (fabricated wafers) can be either be subcontracted to dedicated fabrication houses or even purchased in the raw from other manufacturers. The conclusion to this is that there is more value in the design and manufacture of the power semiconductor package than the actual silicon device. The fact that there are some very large manufacturers does not mean that there is room for start-ups. As Cambridge University spin-outs such as Cambridge Semiconductor (power management IC's) Enecsys (hybrid single chip converter IC's) demonstrate, there are opportunities for people with innovative technologies to make an impact in the sector. These can benefit from a fabless operating model thanks to the large number of jobbing semiconductor fabrication facilities that exist – particularly in the far east.

The picture is not the same for the wide bandgap semiconductor device sector as shown in Figure 27. The first major observation is that the traditional silicon manufacturers are not leading it. One respondent to the study observed that this quite possibly because of the sheer level of investment that they already have in silicon manufacturing. Although another reason may the desire to protect hard won reputations, as one development manager from Intel recently stated "It takes us about 10 years to evaluate a new material, we have a lot of investment in silicon and we're not about to abandon that."[22] The only notable exception to this is Infineon who have had their own very public problems with their SiC diodes. Even they have now ring fenced their SiC activity through a joint venture development company, SICED, in collaboration with ex-parent Siemens.

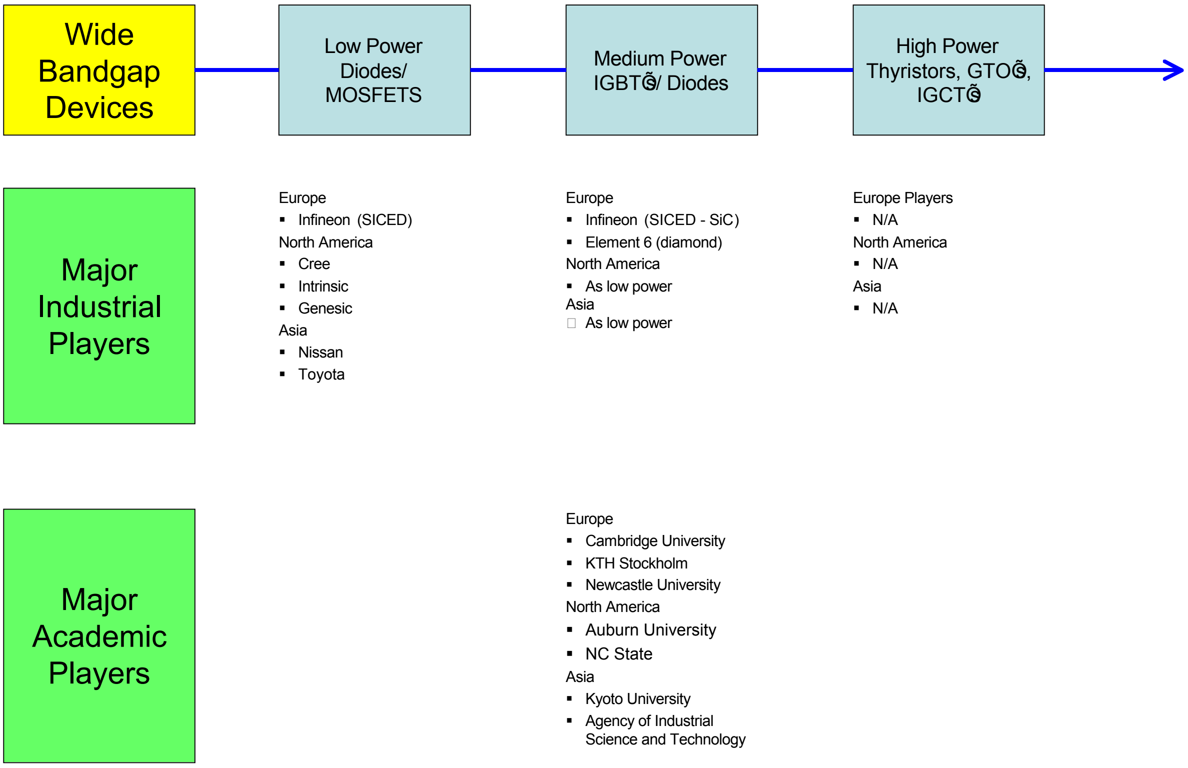


Figure 27: Breakdown of major industrial and academic players in the emerging wide bandgap semiconductor devices sector by major device types

Figure 27 also highlights another trend in the wide bandgap sector; many of the major developers are also materials suppliers. There is clearly intentional by the materials businesses to vertically integrate – something that may in part be driven by the fact that the fabrication process uses material growth techniques that are not much different from those used in its production. Another reason may be that that the equipment needed to grow substrates of the quality needed for Power Electronics does not come cheap with millions pounds of capital investment being necessary, hence a need to maximise a return on that investment.

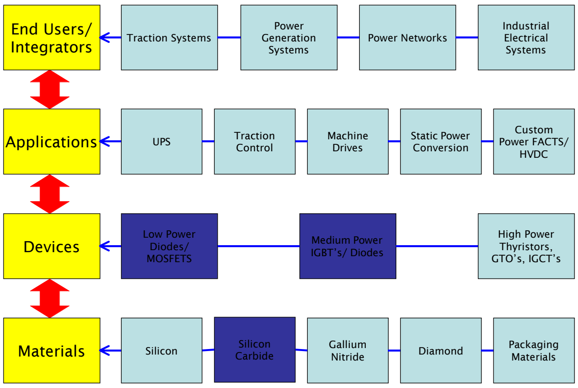


Figure 28: Cree’s positioning in the supply chain

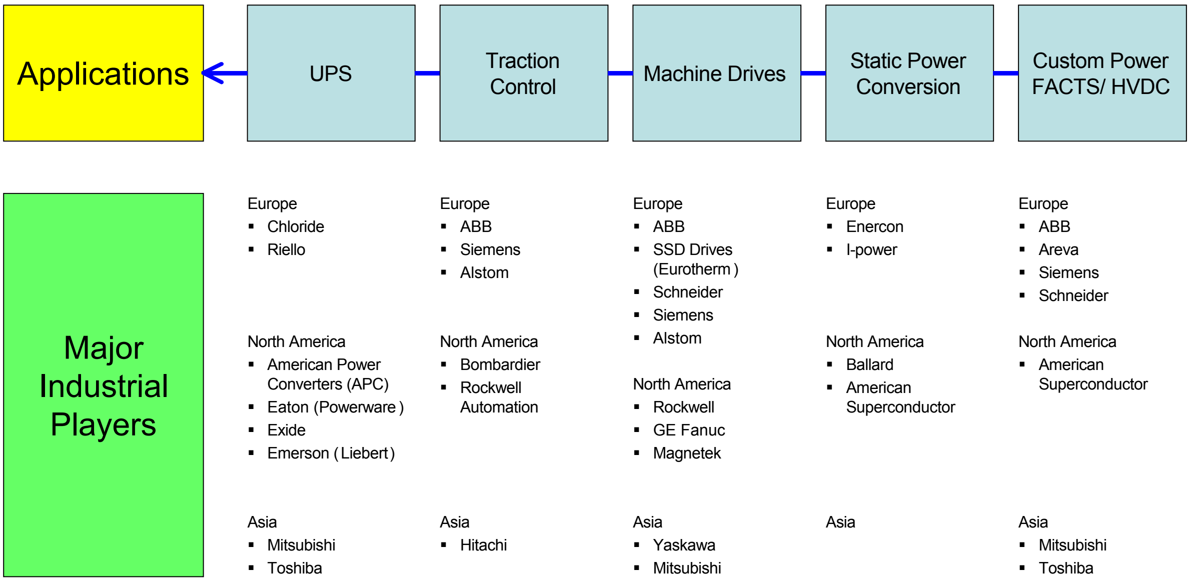
Examples of the intent to vertically integrate can clearly be seen through Cree’s acquisition of ABB’s SiC device intellectual portfolio (including 44 U.S. patents and patent applications) in 2003 for an undisclosed sum. ABB had invested heavily in SiC during the late 90’s and probably took the decision to withdraw following its financial troubles at the time of disposal. One respondent also noted that part of ABB’s problem was that they were ahead of the materials curve with what they needed to produce working commercial devices. In another example US developer Advanced Power Technology recently announced that it has entered into a license agreement with Northrop Grumman giving them access to a number of SiC patents and manufacturing methods, to enable them to manufacture proprietary devices exclusively for Northrop Grumman[23].

One popular perception of SiC is that it can be slotted into existing silicon fabrication facilities with only a few modifications whereas other materials require investment in new infrastructure. At first this would suggest that SiC should win out on economics alone, but there appear to be sufficient differences such that SiC fabrication that it will be necessary to manufacture in separate facilities. However, the opportunity for all new device developers faced with the need to invest in manufacturing infrastructure is that there remains overcapacity in the silicon industry. Coupled with the fact that all semiconductor materials basically utilise the same equipment; means that it should be possible for someone to set up a device fabrication plant based on modification of (barely) used equipment for a fraction of the cost of building a new build. It appears that companies such as GeneSiC in the US are taking such a route.

The interview process for this study highlighted a strong consensus that changes in the Power Electronics sector are likely to come from small to medium players. Yet this does not wholly reconcile with the fact that Power Electronics are expensive to develop with relatively (by electronics standards) small markets. It highly likely, therefore, that many of the larger players are playing something of waiting game. The problem is that with the trend for vertical integration they may find themselves struggling to acquire and catch up. Semiconductor history shows that it rare that companies who are dominant in one generation of technology retain that dominance with the next[24].

Designing power electronic devices has a considerable amount of know-how contained in what is a relatively small community compared with the general electronics sector. At the higher power levels Japan and Europe are perhaps better placed with greater pools of expertise in this area. However the intensive government funding being made in SiC is likely to allow the US to catch up and develop a leading expertise.

4.3 The Applications Tier



Applications	UPS	Traction Control	Machine Drives	Static Power Conversion	Custom Power FACTS/ HVDC
Major Industrial Players	Europe ▪ Chloride ▪ Riello	Europe ▪ ABB ▪ Siemens ▪ Alstom	Europe ▪ ABB ▪ SSD Drives (Eurotherm) ▪ Schneider ▪ Siemens ▪ Alstom	Europe ▪ Enercon ▪ I-power	Europe ▪ ABB ▪ Areva ▪ Siemens ▪ Schneider
	North America ▪ American Power Converters (APC) ▪ Eaton (Powerware) ▪ Exide ▪ Emerson (Liebert)	North America ▪ Bombardier ▪ Rockwell Automation	North America ▪ Rockwell ▪ GE Fanuc ▪ Magnetek	North America ▪ Ballard ▪ American Superconductor	North America ▪ American Superconductor
	Asia ▪ Mitsubishi ▪ Toshiba	Asia ▪ Hitachi	Asia ▪ Yaskawa ▪ Mitsubishi	Asia	Asia ▪ Mitsubishi ▪ Toshiba

Figure 29: Breakdown of major industrial players in power electronic applications sector

With the exception of a few major companies such as ABB and Mitsubishi, there is little vertical integration between devices and applications. This tallies with the fact that devices represent a small cost portion of the overall design. It is at this level that digital and hardware expertise is brought together. The expertise of the applications tier lies with both physical circuit and software design plus, more importantly, their integration.

Figure 29 highlights some of the major application areas that relate to energy. One area that has not been included is the power supplies sector. This is focused at the lower power consumer product end of the market, but did notch up over $14B in sales in 2004.

Uninterruptible Power Supplies have been included in the analysis because of the fact that they are the one sector who is dealing with electrical energy storage, and who also have been known to supply systems as large as 10MVA. Most of the units supplied are low voltage with 690V (three phase) being the usual maximum voltage. The UPS market is highly consolidated, in 2004 the top 15 manufacturers accounted for 95% of sales[25]. A highly competitive sector in its own right, it seems unlikely that any of these are likely to want to scale up further to embrace other energy storage systems if only because of the cost of developing techniques for operating at much higher voltages.

The other major market, in terms of sales, is the machine drives market. This is dominated by large companies, who rely on their ability to produce standard modules in bulk. There still ongoing consolidation in this sector, for example Siemens recent acquisition of US manufacturer ASI Robicon.

There is some cross-over between the machine drives and traction sectors due to the strong degree of similarity between the two. However there are differences, particularly the ruggedisation of the designs necessary to cope with the environment that most traction systems encounter. Further the traction industry tends to be a batch industry particularly in the case of rail or marine with units produced that are specific to the train or ship design in question (and hence contract sales driven). The lower volumes are therefore not particularly attractive to many of volume manufacturers and only those who are involved in the manufacture of vehicles try to exploit some synergy.

In the static power market a number of generator manufacturers have acquired or developed their own Power Electronics capability, highlighting the issue that adapting machine drives for generator interface applications is not a particularly effective option. A good example of this is I-power (formerly NADA) who were acquired by Turbogenset (the high speed generator manufacturer) to enable them design and deliver optimised Power Electronics to match their generators. Fuel cell developer Ballard have also gone down a similar route.

FACTS and HVDC are highly specialised businesses due to the fact that nearly every contract is supplied on a one-off basis. Further there is a significant element of engineering necessary to deliver these projects, since nearly every installation has to be designed to properly interface with grid system and interact in a precisely defined manner. Generally manufacturers have only been able to achieve a degree of modularity at relatively low levels in the overall implementation such as standardising the design of the valve modules. The much higher voltages that these systems operate at means that this remains a specialised industry controlled by just a handful of companies who are already dominant in the general electrical transmission and distribution sector.

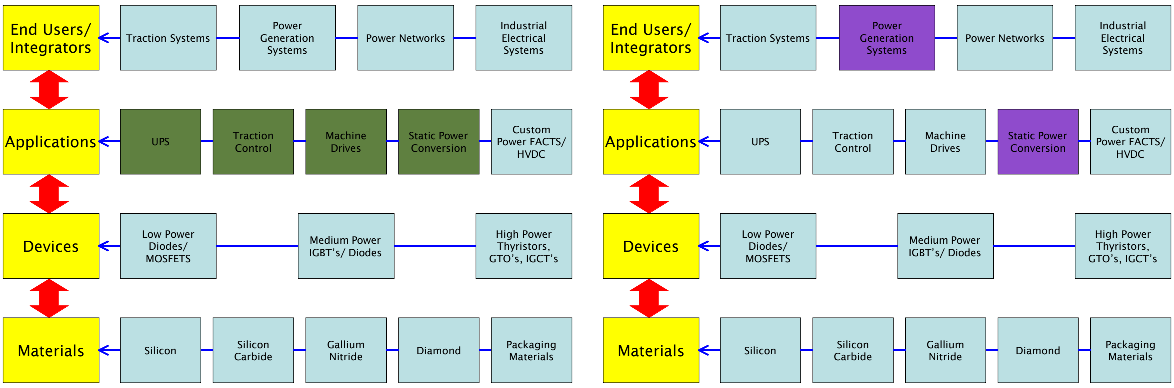
One of the key areas that link all manufacturers in the applications tier is the need for real-time software. Power electronic systems combine a need for low level supervisory routines coupled with higher level control algorithms that deliver the functionality. Managing the power flow through the electronics is not just about delivering the right volts and amps; it also requires properly responding to a number of electrical systems phenomena that impact on operation. Nearly all manufacturers have developed their own proprietary control software. This is often based on industry standard DSP (Digital Signal Processor) control boards manufactured by companies such as Texas Instruments and Infineon. Some of the larger manufacturers are only likely to use proprietary control electronics where volume can justify the cost of developing such boards. The fact that control platforms are available commercially has helped smaller manufactures to continue to compete.

The software sophistication of many systems is such that larger manufacturers are now able to supply application-editing software. This allows field installers or third party resellers to adjust major control parameters to suit a particular implementation. Access to lower level software is not given and remains a way by which competitors protect their designs.

Like several industries the significant downsizing of UK engineering activities has meant that the UK's industrial strength waned over the past two decades. Examples include the impact that Alstoms acquisition of GEC and Emerson's acquisition of Control Techniques have had. The result is that there are no indigenous globally competitive companies operating in the applications sector left in the UK.

The absence of a strong industrial base is a problem for UK universities, who do have a number of strong Power Electronics applications groups such as Strathclyde, Manchester, Nottingham and Loughborough who are capable of delivering world class research. The problem for these departments is twofold: first they do not have the resources to develop full-scale systems much above a few tens of kW; and second, they struggle to find good quality placements for their graduates in industry. This means that there is a knowledge gap – particularly regarding hardware design – between what is achieved in academic laboratories and what is achieved in industry. Consequently universities tend to be stronger on control software and circuit structures rather than practical physical design.

The UK does have pockets of excellence with companies such as Aberdeen based Masterpower and Newcastle based I-power. Both have established themselves at the bespoke product end of the market. I-power have also benefited from the acquisition of Rolls-Royce's Industrial Controls business which has given them access to the traction market. The study did highlight that one problem for these smaller companies is that of engineer retention. This is primarily due to systems integrators looking to the smaller manufacturers as a source of technically capable people who can support their own application engineering activities for bought in Power Electronics.



e.g. Masterpower, I-power

e.g. Ballard, Enercon

Figure 30: Examples of how various applications manufacturers have positioned themselves within the supply chain

One consequence of systems integrators increasing their knowledge of Power Electronics is that they are increasingly directly working with UK universities on Power Electronics development. For example, Rolls-Royce now have three tie-ups through their UTC (university technology centre of excellence) scheme with Strathclyde, Sheffield and Manchester. Similarly Smiths Industries have close ties with Nottingham and BAe Systems with Newcastle. This relationship between companies who may not necessarily enter into Power Electronics manufacture and universities appears to be borne out of frustration that applications manufacturers are not responding to requests to develop equipment that meet the needs of the system integrators.

The area now receiving the most attention from these university/ industry tie ups is in the transport sector. This covers systems for aerospace, marine, rail and automotive applications and the role that Power Electronics can play. As one respondent noted, academic focus on Power Electronics follows the money. A decade ago it was FACTS and Custom Power, before that it was machine drives. The smart money is now in transport.

4.4 The Systems Integrator Tier

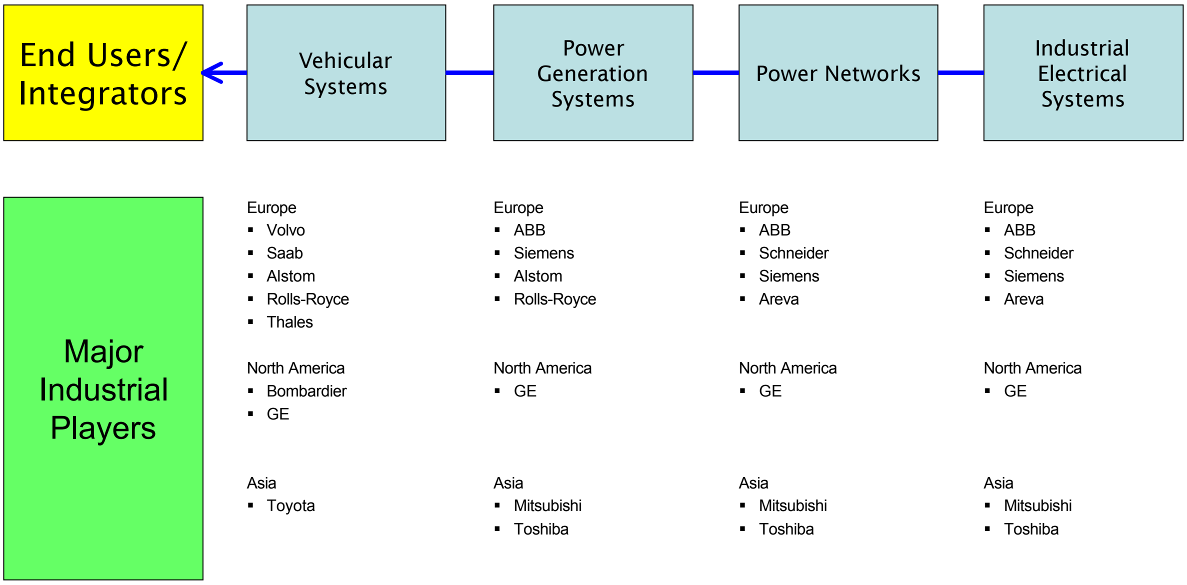
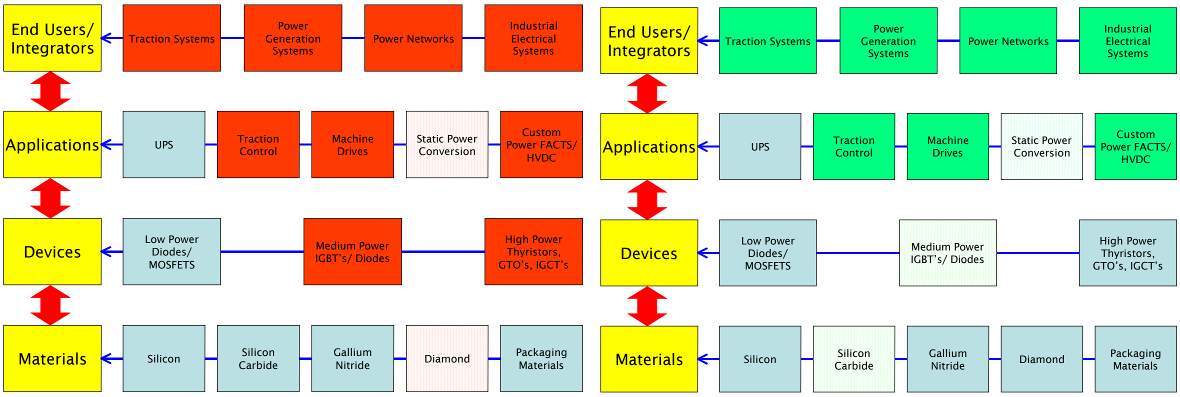


Figure 31: Breakdown of major industrial players involved in electrical system integration

Since privatisation of the utility industries there has been a trend for system operators to move to issuing increasing functional specifications for equipment to meet their needs. This has also spilled over into other industries such as ship and aircraft manufacture where responsibility for delivering non-core competence aspects for things such as the design and supply of the entire electrical system is now being sub-contracted. Systems integrators are those companies who are able to develop a turnkey solution in response to such functional specifications.

Almost by definition systems integrators are large companies who have the strength, depth and financial resources to deliver large projects on a turnkey basis. They are also the ones who ultimately determine whether or not to adopt any risks associated with new technology since they will be directly liable to the end customer for its performance. Again though there is strong competition in this sector and taking balanced risk is part and parcel of being successful.

In the electrical transmission & distribution sector, systems integrators such as Siemens and ABB have well-established businesses that are fully capable of delivering complete power systems. This includes skills from planning analysis through to manufacturing and project delivery. As the industry has consolidated through an ongoing programme of acquisitions, these companies are increasingly capable of supplying the entire project from their own in-house capabilities. The only exception to this is the civil works, which are normally sub-contracted. As Figure 32 highlights these businesses have significant horizontal and vertical integration. Companies such as ABB have maintained a power semiconductor device development and manufacture capability, while others such as Siemens are focused more on the top two tiers. While generally sticking to their core competences, these companies are involving themselves in projects further down the supply chain in a bid to gain future competitive advantage. For example ABB have collaborated with Element Six on diamond power devices and Siemens have a joint venture with Infineon to develop SiC devices.



E.g. ABB, Mitsubishi e.g. Siemens, Alstom

Figure 32: Examples of how various traditional systems integrators in the electrical power sector have positioned themselves within the supply chain. Partially shaded boxes indicate areas where they are collaborating with 3rd parties to develop new technologies.

One area to note is that while many of the larger traditional electrical companies are becoming more active in the supply of turnkey grid connections for renewable energy, they are not strong in static power conversion for emerging generator technologies. This is probably because at this time there is not sufficient volume to justify their Power Electronics businesses investing in development. As the previous section has highlighted the generator developers themselves are filling this gap.

The key for wider adoption of Power Electronics in the primary energy cycle (i.e. from generation through to distribution) lies with better education of the electrical utilities by the systems integrators. Only by developing a better mutual understanding of the benefits that deploying Power Electronics can bring, is there likely to be a change in standards and practices that will make them a more attractive economic proposition. One activity that is helping to advance this understanding is the EPSRC sponsored Supergen consortium. This consortium is coordinated by a number of universities including Imperial, Strathclyde and Manchester in collaboration with a number of companies and operates a number of projects looking at aspects of future network operation.

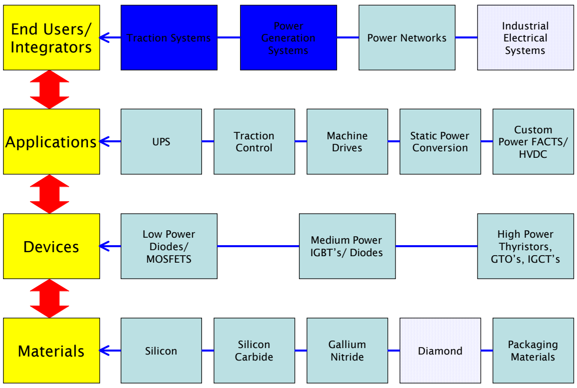


Figure 33:Example of how emerging systems integrators such as Rolls-Royce are positioning themselves in the supply chain Partially shaded boxes indicate areas where they are supporting 3rd parties to develop new technologies.

In the case of the marine and aerospace sectors each have similar visions of utilising electrical power to control all major systems on ships and planes, which are now steadily moving towards actual implementation. In the case of ships the application goes all the way through to the propulsion system, whereas on planes the main use of power will be for actuation of the controls. Common to both sectors is that the plane and ship builders are looking to sub-contract all responsibility for these electrical power systems to third parties. This has created a scramble for second tier companies such as Rolls-Royce, Thales and BAe Systems to try to occupy the role of systems integrator. This is unfamiliar territory for these companies – even though they have traditionally supplied power plant and other electrical components to these industries. The result is that these companies are very much on a learning curve with a need to quickly gain electrical systems design expertise – something that is likely to be only achieved through acquisition rather than organic growth.

One challenge for these new integrators is the need to develop a detailed understanding of operating islanded electrical networks. The fact that the network is self-contained and expected to operate under conditions not normally encountered by land based systems means there are unique issues that need to be addressed. It is clear that Power Electronics will play a key role in maintaining the stability of these networks from the prime power generation through to load control. As figure 33 illustrates, the new system integrators do not have much historical connection with any other part of the supply chain, yet one of the key success factors will be the effective implementation of power around the system. For this a systems perspective such as was discussed in Section 1 and close working relationships with applications developers is going to be necessary. Like the more traditional systems integrators have investing in (usually academic) research projects throughout the supply chain looking at future disruptive technologies. For example Rolls-Royce are collaborating in an EPSRC project with University College London looking at power electronic devices in diamond[26].

As has already been discussed these new systems integrators appear to be developing close working relationships with universities to address the gaps in the knowledge base. It is not clear, however, how the work (particularly relating to Power Electronics systems) will be transferred into commercial manufacture since these companies are not active in this sector. One activity that many of the systems integrators (new and traditional) have in common is that they are supporting developments relating to wide bandgap devices. Some of this is through academic links and some of it, such in the case of Siemens, is done through collaboration with other companies. The fact that both silicon carbide and diamond are being supported highlights that jury is still out as to which is likely to satisfy the needs of future Power Electronics based systems.

4.5 Conclusion

The supply chain is dominated by large multinationals; nevertheless there is room in the market for smaller businesses to compete at the bespoke and low volume manufacture end of the market. Much of the electronics infrastructure of today is based around silicon, but there are signs that traditional structures are about to be challenged through the emergence of vertically integrated developers of wide bandgap materials and devices, plus higher up the supply chain generator developers who have acquired their own applications capability. It is highly likely that the next decade will see considerable opportunities for smaller players at all levels in the supply chain, particularly in the sustainable generation and transport sectors. Further, acquisition and consolidation by the larger players is also likely as they look to take a stake in these new markets.

Section 5 – Intellectual Property Landscape

The Intellectual Property (IP) landscape in Power Electronics is a mixture of patents, proprietary know-how and design copyright. The profile of the IP varies according to the specific technology, but broadly falls into the categories defined for the supply chain model of the previous section.

5.1 IP Landscape for Materials

The silicon industry is highly mature with most relevant patents already granted. The one area that new IP is being developed is in the area of silicon-on-insulator (SOI) technology. A number of organisations at academic and commercial level are actively pursuing techniques to stably deposit silicon on non-silicon substrates to achieve better thermal response. The main scope of patented IP will be for techniques to ensure that the materials are matched so that they do not separate due to differential thermal expansion.

For the newer wide bandgap materials there is considerable ongoing patent activity. Silicon carbide is the most active area with market leader Cree having taken out, by far, the most patents in an attempt to raise significant barriers to any competitor who wishes to produce SiC. It appears that they now have over 200 patents covering their production process (note that as a US company many of these may be continuations i.e. additional claims relating to an earlier invention) and methods of stably doping the material. Cree will have further strengthened their production IP protection through the additional patents it will gain through its acquisition of IntrinSiC. The fact that Cree still has a number of competitors suggests that this IP is not watertight, but it does raise significant barriers to entry. Further, most of Cree’s patents relate to a physical vapour epitaxy production process, hence alternative processes such as the chemical vapour method developed by Norstel are likely to circumvent much of Cree’s patented IP.

For diamond, the major companies such as Element Six, Sumitomo and Apollo are all presently actively filing patents relating to the production of single crystal diamond films. There appears to be just one method for growing diamond (plasma assisted chemical vapour deposition) and patenting appears to be focused on methods of growing stable large films and separating grown diamond from seed diamond. However there is also other IP being developed relating to production of nanocrystalline diamond and polycrystalline diamond for other electronic, but non-device applications. Companies such as SP3, Applied Diamond and Kobe Steel are all active in this area.

For all wide bandgap materials grown from the gas state there is, as one respondent commented, a significant amount of “alchemy” is involved. Essentially the growth processes that many companies use rely on finding “sweet spots”, these are a set of conditions that lead to faster growth coupled with higher quality material. Patents do not usually precisely define these conditions, and the exact recipe is usually kept as a trade secret.

One patenting trend that has appeared in the past few years is that of materials developers taking out patents for specific ranges of materials properties, for example a substrate with particular dopant, its number density and, the resulting physical properties. These patents then go on to claim that any electronic device that utilises material within this range of properties are guilty of infringement. This is symptomatic of the desire of the new materials producers to also control the device market and represents the biggest threat to developing a healthy competitive industry for a new generation of semiconductors. What is not clear is whether these patents will actually stand-up in practice. Already there is evidence to suggest that they may not after claims in an early GE patent for synthetic diamond relating to its use in all electronic applications were successfully contested by the German Fraunhofer Institute a few years ago.

Alongside the active semiconductor materials, there still remains scope for new IP in new materials (e.g. epoxies, sealing compounds, plastics and ceramics) for use in packaging devices. It is likely that materials that offer greater stability and compatibility over a broader range of temperature, plus better dielectric performance at high voltages and frequencies will get the most attention.

5.2 IP Landscape for Devices

Patenting remains a clear area for protection of IP at device level. Much of the patenting taking place today relates to improvements to devices for example: better contacting arrangements, specific structures/ topologies of the device and, integration of functionality onto devices. For silicon it appears unlikely that any breakthrough device suitable for power applications has yet to be discovered. There may be scope for new device concepts in wide bandgap semiconductor devices, but so long as developers continue to treat the alternatives as a direct replacement for silicon breakthrough IP is unlikely to emerge.

There are several thousand patents relating to silicon devices, plus several hundred for each of SiC, GaN and diamond. One problem in assessing patents is that a large number are theoretical or apply to one-off events conducted in an academic laboratory. In particular there appears to be a considerable amount of speculation in the patent activity relating to diamond devices that have yet to be practically realised.

Highlighting the trend for vertical integration, in 2003 Cree acquired a portfolio of 44 patents and associated know-how from ABB for an undisclosed sum[27], after the later decided to pull out of SIC development. The fact that the material production processes may be potentially applied throughout the device production process means that material companies aiming to control the device tier may seek to embed aspects of materials processes in device patents.

As Section 2 has highlighted, there is probably more value in the packaging of wafers than the wafers themselves. Patenting is also active here, relating to package designs, methods of assembly and specific features of the design such as busbar structures within the package.

5.3 IP Landscape for Applications

At the applications level, IP is more about know-how and design copyright; however patents continue to be taken out relating to new converter topologies. A problem for applications developers is that circuits are likely to specific to the core devices used.

This means that while it is possible to patent certain circuit functionalities, reduction to practice tends to be kept as know-how.

Much of the novel circuit development is also conducted in universities, for example the matrix converter that was developed by Nottingham University is only now being belatedly patented after much of the basic principles have been already disclosed through technical publishing. This means that many of the fundamental circuit designs are often not well protected and it is left to reduction to practice patents to secure IP.

Power Electronics is as much about the control software as hardware design. Many companies have developed proprietary firmware and software for the control of Power Electronics. This is controlled through copyright. Echoing the problem with fundamental circuit technology, many of the basic algorithms and techniques for producing control software are in the public domain. The key again is the reduction to practice, which in many cases is also dependent upon the actual processing hardware.

5.4 IP Landscape for Systems

At the systems level IP is more about know-how and design copyright. The complexity of a system is such that it would be extremely difficult, bordering on the impossible, to patent one due to the consensual processes (often driven by national and international forums) that normally take place. In many respects the key here is the know-how associated with integrating a diverse range of components and integrating them into a functioning entity. The sheer scope for variation here means that most businesses operating at this level can, at best, try to protect specific features of an overall design rather than the whole. The key to protection here is to patent at much lower down the supply chain.

5.5 Conclusion

There is much patent activity at the materials and device level, where protecting IP this way is easiest to achieve. A major concern for the establishment of healthy competition in the emerging wide bandgap market is the moves by companies such as Cree and Element Six to erect patent firewalls that try to ensure that any competitor will be caught by possible infringements. It is likely that this will only be settled in the courts. At the applications and systems levels IP is restricted more to design copyright and know-how, however there remains continuing scope for innovation and protection of resulting IP.

SECTION 6 – AREAS OF OPPORTUNITY

Power Electronics represents a wide area going from fundamental materials issues to megawatt applications (and its associated engineering). It is also a conservative market – driven primarily by industrial sales where reliability comes a close second to price. At first glance it may appear that the market place is crowded and there is little room for emerging players. Yet Power Electronics are only applied to a minor percentage of the potential applications that would benefit from their use. Respondents to the study have all perceived a considerable need for future innovation particularly in regard to initiatives that will drive down the system cost of Power Electronics.

Power Electronics is a critical element in the blueprint for future electrical systems; facilitating better energy utilisation, more efficient generation of energy and more effective movement of energy. The study has highlighted five opportunity areas for technology development. These are:

- Hybrid Devices
- Wide Bandgap Semiconductors
- Novel Cooling and Packaging Arrangements
- Grid Connection Electronics (particularly for prime mover interfacing)
- Open Source Control Architectures

These cover a spectrum of applications from the lower power end (e.g. hybrids for use in small machine drives and micro-renewable connections), through to megawatt connection designs and software issues to reduce development costs.

To date the main driver for developments has come out of the machine drives and rail traction application markets where most uses are up to a few megawatts and generally low voltage. There is obvious scope for growth in the machine drive sector, particularly in light of greater awareness and potential incentives to invest in energy efficient designs for electrical machine driven plant, however this is likely to be met by existing players.

It seems likely that renewable and sustainable energy applications, plus associated network control devices will drive the unit power requirement for converters up. For many renewable power devices there is a tendency towards 2-4MW as being the economic unit size. To compete at this level, Power Electronics will need to be capable of direct connection to the grid, which means that design of high voltage converters will become a key piece of know-how. At the lower level, energy efficiency of white goods coupled with moves towards hybrid automobiles will create greater opportunities for high volume converter products. Further adoption of micro-power generation could also generate a considerable market for 10-100kW rated converter systems suitable for connection to the domestic mains grid.

Underpinning some of these conclusions is an assumption that there will be considerable change in energy policy and public attitudes to energy in the coming years. However as one respondent observed, "*the growth of renewables will be stunted if countries shift to a nuclear option. In this case it is likely that largely wind turbines alone will meet renewable targets. Given the level of penetration that will occur (less than 20%) it is likely that the current technology is likely to suffice, creating little need to innovate much further*".

Also with energy security becoming a major issue in particular with relation to gas (& slightly further out, oil) there may be a knock on effect on micro-generation such as Stirling engines or micro-turbines (both of which require power converters to interface with the mains). The only market that is likely to see change under any scenario is the automotive industry where a change in fuel is seen as inevitable – but even this will be subject to a battle as to the best candidate replacement for the present fuels.

Yet one look at energy growth statistics such as those produced by the IEA[28] suggest that, even if a pessimistic forecast is used, sustainable energy will be a major growth area. Should Power Electronics became the universal interface method for renewable energy systems, this should would rapidly create a device market with a potential value in excess of $800M per annum and an applications market worth probably around 10 times that.

6.1 Hybrid Semiconductors

A market for hybrid semiconductors already exists, with a number of manufacturers offering modules that incorporate a number of preconfigured devices in a single package. These offer savings in terms of reduced part count and more compact designs, as well as simplifying the design process by helping to eliminate parasitic circuit effects. At present many of these are in generic configurations, but there is an emerging market for bespoke designs. There is an established model in the industry that allows second tier manufacturers to purchase raw dies (processed devices that are still on their wafer) and integrate them into their own packages. One of the emerging challenges is integrating elements of the control electronics into the same package, or even onto the same wafer.

Companies such a Cambridge Semiconductor or Enecsys (both spin-outs from Cambridge University), are examples of fabless companies who are designing hybrid devices for power management applications. In CamSemi's case the focus is on energy management applications. However Enecsys's focus is on integrated modules for low power energy systems such as photovoltaics, where the converter design can play a key role in overall efficiency and output from the solar cells.

There are a number of other applications that could benefit from this approach, which all lie in the 1-50kW power range including low end machine controllers, automotive and micro-generation applications where integration and high volume manufacture could be justified. For each of these the key know-how is a combination of packaging expertise and software design to create intelligent embedded controllers. The predominant market for Power Electronics will continue to be for low power consumption applications (<1kW). For the majority of these markets silicon will continue to dominate the sector due to the fact that no other materials technology will be able to meet the price levels demanded by this sector.

Such businesses are likely to be relatively investment businesses since they can operate on a fabless basis. This means, at most, they may only need limited clean areas for final packaging – which could also be sub-contracted but preference may be to keep this activity in-house.

6.2 Wide Bandgap Semiconductors

The difficulty for wide bandgap semiconductors is that they have to offer performance advantages that enable applications where silicon cannot directly compete. The key differentiators here are: greater thermal, power density, voltage and frequency performance. Such markets do exist such as: aerospace, power conversion for renewable and sustainable energy systems, defence and automotive applications. All of these markets require devices that deliver a better level of performance than silicon can currently deliver.

For energy applications there is one clear requirement, which is higher voltage operation. As Section 2 highlighted, major savings in high power converter costs will only become possible when a device capable of switching at the utility distribution voltage becomes available. The target voltage rating for such a device is therefore going to be 22,000V (15kV AC). However, in terms of current, it is likely that a rating of as low as 150A could meet a number of wide ranging applications. With current densities of around 100Acm^{-2} being achievable from wide bandgap materials this means that the device is physically quite small and therefore does not require very large areas of high quality materials to manufacture such devices.

The question is which material is likely to yield devices that will meet a practical operational rating of 22kV. The consensus appears to be that, while Silicon Carbide may get there, the only material with the inherent intrinsic properties that meets this requirement is diamond. The UK capability in most wide bandgap semiconductors is limited, with UK plc basically competing against large government programmes that have been ongoing in the US and Japan for well over a decade. However when it comes to Diamond the UK does have world-class capabilities, most notably the fact that the worlds leading materials business in this field (Element Six) is based in the UK. Further with the US and to a lesser extent Japan placing greater emphasis on the other wide bandgap technologies there is a gap that the UK/ Europe could enter.

The problem for kick-starting diamond is two-fold:

- Lack of competition/ impetus in the materials sector
- Overcoming the doping problem and developing credible devices

As SiC and GaN have demonstrated the devices market will only take off when the materials technology starts to proliferate. While Element Six is the acknowledged world leader they continue operate on a basis that is more focussed on defending the status of diamond as a premium material rather than exploiting its potential applications. It is likely that the only way this will be overcome is by creating a doorstep competitor. Here Scotland does have some expertise in the shape of the diamond materials group at Heriot-Watt. It is conceivable that by attracting one of the other players to establish a development facility in Scotland healthy competition could be stimulated which in turn could capitalise on the expertise that exists in the UK and Europe.

With regard to devices, a number of groups are starting to produce some interesting devices, yet it is likely that the true breakthroughs in Diamond will result from techniques that make use of the fact that diamond is just one of two states of carbon. It is therefore highly likely that Diamond based devices will have no parallel with devices made in other materials.

To support a business in this sector Scotland already has an overcapacity of clean room space following the withdrawal of several of the Silicon Glen manufacturers. It is highly likely that device developers could benefit from access to redundant equipment and facilities. On the materials side however, considerable investment (several £M) in capital would be required to purchase the gas phase growth reactors.

6.3 Grid Connection Electronics

The grid connection standards for generators are more onerous than for loads due to the legacy of standards based on rotating generation plant. This means that while commercial machine drives can be utilised and adapted for generation applications they are not ideal. First and foremost they are rarely optimised to the prime mover resulting in poor conversion efficiencies. Further most machine drives are designed to operate in controlled industrial environments, whereas many generation applications will be required to operate in far more hostile conditions. Therefore for power generation applications there may be opportunities for developers of converter systems specifically designed for grid interfacing.

The consensus appears to be that renewable applications will settle at into broad bands centred around 10-100kW for domestic and small distributed generation and between 1-4MW for larger bulk generators such as units for wind or tidal farms. At the latter power level connection will need to be at the distribution 11-15kV level. While considerable knowledge rests with the larger manufacturers it is likely that opportunities will exist for companies willing to rewrite the rulebook on converter design for connection applications. In terms of academic infrastructure, Scotland has a strong capability in Power Electronics design, most notably at Strathclyde University. Yet a problem remains with the gap between the modest voltage and current levels that universities tend to work with and the physical design issues associated with engineering larger systems.

6.4 Novel Device Packaging & Cooling Technologies

Heat will continue to be the major problem for Power Electronics systems – particularly the removal of heat from the devices themselves. As power density becomes an important issue for a number of applications such as aerospace and automotives there will be a growing demand for more effective materials to support the removal of heat from the substrates. This is not a simple as it looks since materials need to be electrically and mechanically compatible with the application.

With regard to cooling the most common way of removing heat is by forced heat flow, but this not the most efficient was of removing heat. Liquid cooling has not really evolved, yet developments in micromachining could lead to heat spreading or more efficient heat removing approaches that partly use liquids or rely on the better movement of air.

Other phenomena merit further exploration for their exploitation potential such as Peltier effect cooling substrates or heat pipes. There are therefore opportunities for people wishing to develop new materials or approaches to packaging that could be sold or licensed to larger manufacturers.

6.5 Open Source Architectures

There is a clear discontinuity between university activity and industry. In the UK, while the former has some notable centres of excellence, there is not similar quality in terms of UK industrial capability. That is not to say that UK industry lacks pockets of excellence, it is rather that the UK does not have the industrial competence that exists in Germany (Siemens), Switzerland (ABB) and Japan (Mitsubishi, Toshiba & Hitachi) when it comes medium and high power electronic applications. Yet there is a clear need in the UK for access to cheaper Power Electronics, particularly by the renewable energy community.

One way that this could be achieved would be to take a leaf out of the open source movement. Power Electronics is 25% hardware, 25% software and 50% engineering. The software to control Power Electronics is quite complex, requiring it to be able to respond in real time to a number of local and system issues. Local issues will vary according to hardware design, but are generically the same i.e. monitoring of switches, parallel and series sharing algorithms and issuing of firing commands. Likewise system issues are fairly generic such as coping with grid faults, zero and negative phase sequence, islanded operation etc.

By addressing the software component it should be possible to create generic open source control algorithms that can be implemented on the commercially available generic digital control boards supplied by a number of manufacturers. It would also capitalise on the major strength in universities and hence be driven by them. By making the software subject to improvement by a larger community, yet leaving actual implementation to profit making entities the opportunity exists to kick start companies interested in grid connected electronics by defraying some of their software development costs helping to drive down the price per KW by tackling the biggest component of larger Power Electronics applications, that of human resource. Further open standards could help to drive connection standards making it easier to gain certification for systems for grid connection.

6.6 Exploitation of Opportunities

The five areas that have been discussed in this section represent identified market needs where good innovations coupled with appropriate resource could lead to the emergence of strong world-class technology companies. The problem for Scotland is that it is presently not strong in Power Electronics. However it does have pockets of notable excellence at applications level, most notably with Strathclyde University and Masterpower. Nevertheless this is not likely to be sufficient to create a strong Power Electronics industry in Scotland, particularly with the absence of commercial enterprises at other levels in the supply chain to pull technology through.

The only practical option therefore is to look at attracting companies with an interest in Power Electronics to Scotland. There are two fundamental challenges to this:

- Creating incentives that are more than financial to attract companies to Scotland and ensure that they become embedded into the economy
- Creating a cluster of companies that encompass the supply chain and become self-sustaining as well as globally competitive

The first incentive can, to a certain extent, be addressed by the second challenge. Respondents have noted that although Power Electronics is an international market, it is actually a series of local markets. What would therefore attract companies would be the knowledge that other companies with connected, but separate, aims may be proximately located. The challenge therefore would be to attract companies on the basis of working loosely together to address known technology gaps in the market place (e.g. effective prime mover interface for renewables). The added value element from ITI Energy would be to steer these companies towards these visions, while accepting that not all companies will deliver their pieces of the jigsaw at the same time.

Building such clusters is only the beginning. The more important part is ensuring that these companies become embedded into Scotland. One way this can be achieved is by incentivising companies to work with Scottish universities. This will focus academic effort and create a positive feedback loop that, in turn, will create suitably qualified graduates and possibly lead to further spin-outs. An important criterion for success will be that developers (commercial and academic) have a locally receptive market that is willing to pull through innovation and technology.

SECTION 7 - CONCLUSION

7.1 POTENTIAL AREAS FOR TECHNOLOGY DEVELOPMENT

Key areas of technology development that were identified, include:

1. Hybrid semiconductors
2. Wide bandgap semiconductors
3. Grid connection electronics
4. Novel device packaging & cooling technologies
5. Open source architectures

7.2 ITI ENERGY AREAS OF INTEREST

ITI Energy considered the above identified technology development opportunities and investigated how they best fit with our current R&D portfolio and strategy. Our conclusions are that there are 2 broad areas with considerable opportunity for new technology development in Scotland:

1. Smart Silicon Hybrid Devices
2. New Material Devices with characteristics that go beyond what Silicon devices can achieve

7.2.1 – Smart Silicon Hybrid Devices

With Silicon devices reaching the limits of their capabilities in high power applications, potential significant gains can still be made by integrating Silicon technologies on one chip, thereby reducing space, increasing speed and efficiency of the device. Important markets for this technology include electric vehicles and micro-power generation. The key drivers for this technology therefore are: cost, weight, reliability, volume, low component count, low power losses and high conversion efficiency.

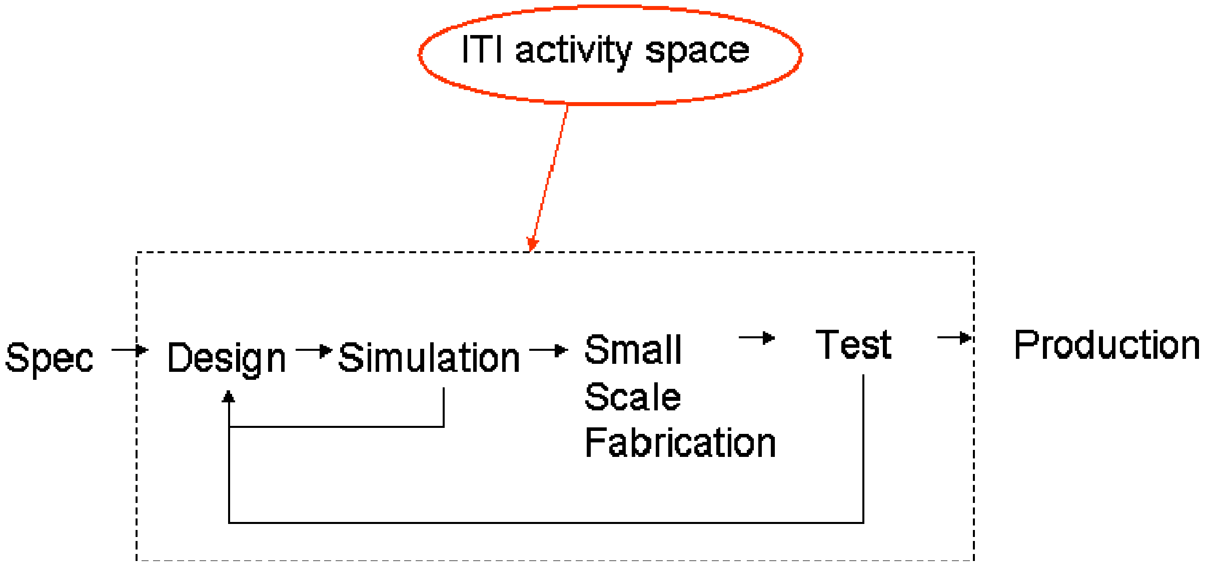


Figure 1: Overview of the technology development phases for a typical Power Electronics Programme

Skill sets that are required to develop new technologies in this area include:

- Converter design (control & hardware)
- Power Electronics device design
- Modular packaging
- Software design (embedded)
- Test/realisation skills

ITI Energy intends to launch a programme in this area in 2007 and we are currently developing a more specific scope of work, as well as identifying potential collaboration partners.

7.2.2 - New Material Devices

Due to its physical limitations, Silicon-based technology cannot provide all the solutions that are required in the power markets. ITI Energy identified the following specific areas where new materials may provide a better alternative:

- Medium Voltage (10 – 15kV) AC device
- Extended temperature operational range higher than 150 degC and/or lower than -30 degC
- Ultra high reliability – in terms of radiation hardness, robustness, etc.
- High frequency

Again, these improved performance characteristics will need to be delivered at acceptable cost.

Potential market applications for new material devices include:

- Distributed power generation direct grid interface at greater than 5MW, for instance wind turbines
- Rail System 25 kV single phase
- Machine Drives
- HVDC (High Voltage DC)
- FACTS (Flexible AC Transmission Systems)
- Aerospace power systems
- Marine power systems

The first of these development opportunities can be further qualified as a switch that can operate at 22 kV and 500A with a forward voltage drop of less than 10V.

ITI Energy is exploring this opportunity further with the aim to launch a R&D programme in 2007. In particular, a choice needs to be made between the leading two new materials, Diamond and Silicon Carbide. For this programme we will also look for relevant skills and expertise first, before a detailed project definition can be established.

7.2.3 Open Skill Architecture

Lastly, we also considered the need for Open source architectures. These codes are proprietary for devices made by large manufacturers such as ABB and Siemens. The opportunity is to define an Open source architecture that fills the gap (red box in picture overleaf) and that will be made publicly available. As software makes up approximately 33% of total device cost, this will allow for smaller applications to be developed more economically. We support this view; however ITI Energy's investments are not geared towards supporting this kind of opportunity.

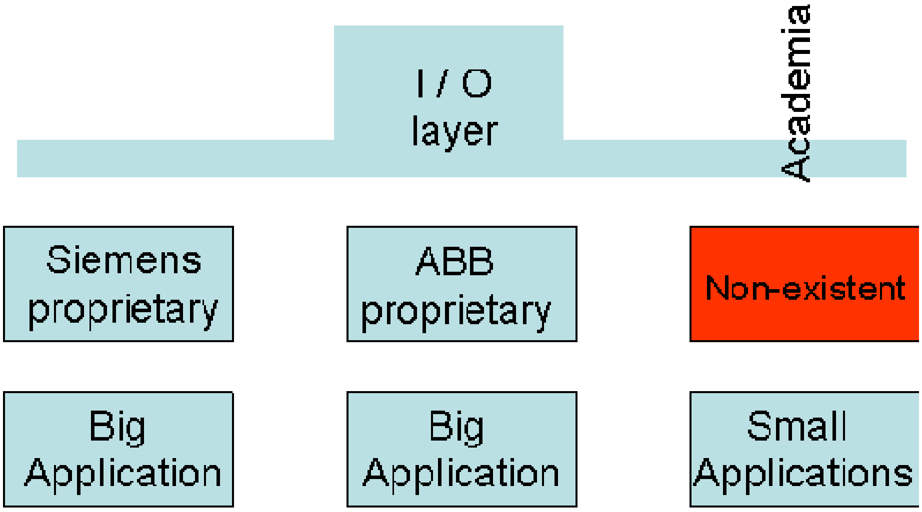


Figure 2: high level overview of Power Electronics application interface control codes, indicating the lack of a standard, publicly available code for smaller applications.

7.3 NEXT STEPS

Over the next months ITI Energy will further define the potential for a programme in the two identified key opportunity areas. We will be proactively seeking related relevant technical skills via public calls. But we also encourage Universities, R&D organisations and companies to come forward with technology development proposals in this area, independent of calls. If you would like to discuss this further, please contact Chris de Goey on chris.degoey@itienergy.com

APPENDIX 1 – RESPONDENTS TO THE STUDY

The following were interviewed either by telephone or face to face meeting. The author wishes to extend his thanks for the time that they gave to this process.

Prof. Gehan Amaratunga, University of Cambridge

Prof. J Baliga, North Carolina State University

Dr Mike Barnes, Manchester University

Dr Roger Bassett, Areva T&D Ltd

Prof. Janusz Bialek, University of Edinburgh

Derek Boyd, National Microelectronics Institute

Dr Stephen Finney, University of Strathclyde

Dr Bo Hammarlund, TranSiC

Prof. Philip John, Heriot-Watt University

Prof. Mark Johnson, Sheffield University

Dr Tony Lakin, I-Power Ltd

John Masterton, Masterpower Ltd

Dr Asim Mumtaz, Enecsys Ltd

Dr Mark Osborne, National Grid Transco

Prof. John Wilson, Heriot-Watt University

Other respondents:

Dr Richard Jackman, University College London

APPENDIX 2 – USEFUL WEBSITES

Device Manufacturers

Siicon:

ABB	http://www.abb.com/semiconductors
Dynex Semiconductor	http://www.dynexsemi.com/
Fairchild Semiconductor	http://www.fairchildsemi.com/
Hitachi	http://www.pi.hitachi.co.jp/pse/
Infineon	http://www.infineon.com/power
International Rectifier	http://www.irf.com
Mitsubishi	http://www.mitsubishichips.com/Global/index.html
Semikron GMBh	http://www.semikron.com
STMicroelectronics	http://www.st.com
Toshiba Mitsubishi-Electric Industrial Systems	http://www.tmeic.co.jp/global/index.html

Wide bandgap:

Velox Semiconductor (Gallium Nitride)	http://www.veloxsemi.com/
TranSiC (Silicon Carbide)	http://www.transic.se/
SICED (Silicon Carbide – Infineon/ Siemens JV)	http://www.siced.de/
GeneSiC (Silicon Carbide	http://www.genesicsemi.com/

Semiconductor Materials Suppliers

Trade organisation	http://www.semi.org

Silicon:

Komatsu Electronic Metals	http://www.komsil.co.jp/en/
Shin-Etsu Handotai	http://www.sehe.com/
MEMC Electronic Materials	http://www.memc.com
Siltronic AG	http://www.siltronic.com

Silicon Carbide:

Cree	http://www.cree.com/
Dow Corning	http://www.dowcorning.com/content/compsemi/
SiCrystal	http://www.sicrystal.de/content/ENG/start.html
Norstel	http://www.norstel.com/
II-IV	http://www.ii-vi.com/
Sixon	http://www.Sixon.com/

Diamond:

Apollo Diamond	http://www.apollodiamond.com/
Element 6	http://www.e6.com/
Iljin	http://www.iljindiamond.co.kr/en/en_index.html
Sumitomo Electric	http://www.sumitomodiamond.com/

Applications

UPS:

Chloride	http://www.chlorideups.com/
Riello	http://www.riello-ups.com/english/
American Power Converters	http://www.apc.com/
Eaton Powerware	http://www.powerware.com/
Emerson Liebert	http://www.liebert.com/

Traction Control:

Bombardier	http://bombardier.com/
Alstom	http://www.transport.alstom.com/home/
Siemens	http://www.transportation.siemens.com

Machines & Drives:

ABB	http://www.abb.com
GE Fanuc	http://www.gefanuc.com/en/
Magnetek	http://www.magnetek.com/

Masterpower	http://www.masterpower.co.uk/
Rockwell Automation	http://www.rockwellautomation.com/
SSD Drives	http://www.ssddrives.com
Siemens	http://www.automation.siemens.com/
Static Power Conversion:	
Enercon Wind Turbines	http://www.enercon.dk
American Superconductor	http://www.amsuper.com/
Ballard	http://www.ballard.com/
Turbogenset (I-power)	http://www.turbogenset.com/
FACTS/ Custom Power:	
ABB	http://www.abb.com
Areva	http://www.enercon.dk
American Superconductor	http://www.amsuper.com/
S&C	http://www.sandc.com/products/powerquality.asp
Siemens	http://www.energy-portal.siemens.com/
Toshiba	http://www.toshiba.co.jp/f-ene/tands/english/system/index.htm

Other useful websites

EPSRC Supergen Project	http://www.supergen-networks.org.uk/
European Center for Power Electronics	http://www.ecpe.org/
Semiconductors Information website (very general but many links)	http://www.semiconductors.co.uk/
Compound Semiconductor online magazine	http://compoundsemiconductor.net/
Power Electronics Technology online magazine	http://powerelectronics.com/

APPENDIX 3 - POWER CONVERTER BASIC PRINCIPLES

A Power Electronics engineer was once overheard to describe their discipline as "the art of staying 1 microsecond ahead of disaster". The basic principles the voltage converter (the heart of most power electronic systems) are fairly straightforward, the art is in making the designs work in practice. To do so requires careful attention to the physical, electrical and mechanical design of the circuits. Very often these have been hard and expensively learnt lessons.

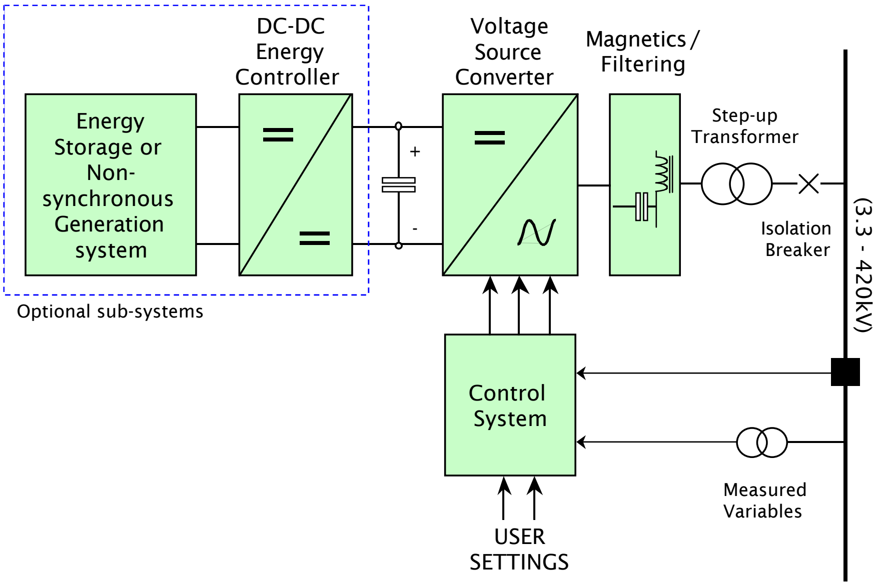


Figure 34: Basic building blocks of a grid connected voltage converter

In essence the voltage converter converts DC to AC or AC to DC in a controlled manner as illustrated in Figure 34. What it is important to remember is that in a voltage converter the power electronic device is essentially a switch and as such has two operating conditions, i.e. on or off. The aim of the conditioner is to generate a waveform that looks like an AC waveform (i.e. a sinusoid). Thus a major aspect of the design lies in the methods by which a sinusoid (or its approximation) is generated.

Figure 35 illustrates the two basic converter topologies. Figure 35a illustrates the most basic design known as a two level inverter, while Figure 35b illustrates the basic principle of a three level inverter, which can have increasing levels (in increments of 2). The multilevel inverter has the advantage of creating an improved waveform; however this is at the expense of an increasingly complex circuit and busbar arrangement.

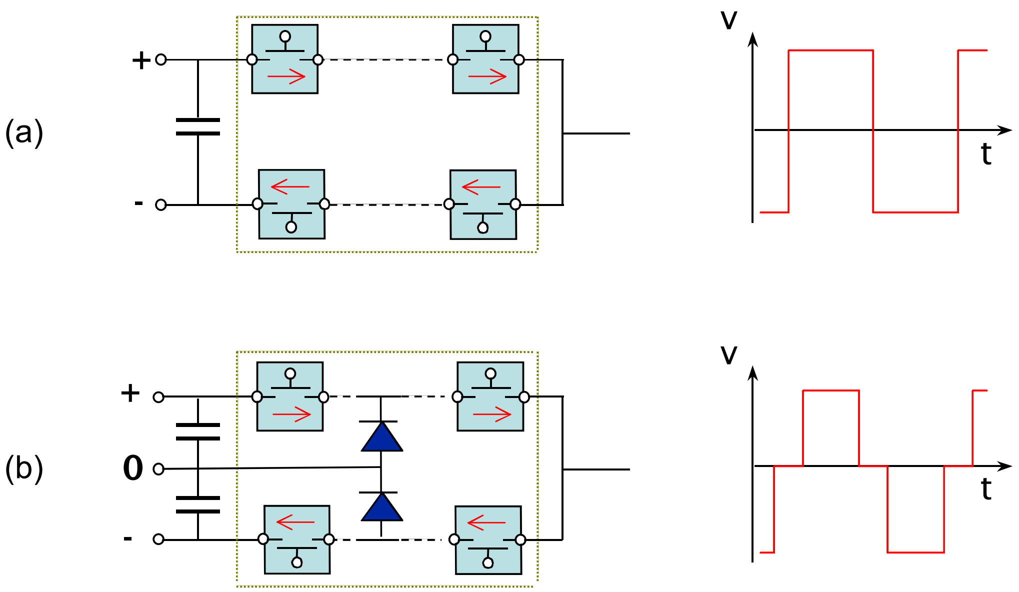


Figure 35: Basic voltage converter (inverter) topologies

As the above figure illustrates neither arrangement produce anything that looks like a sine wave. However there are a couple more strategies that the Power Electronics engineer can use to achieve a better approximation of a sine wave. The cheapest option is to use the inherent fast switching speed of power electronic devices to generate an output using pulse width modulation (PWM). PWM is a technique whereby the switching devices are operated at a higher frequency than the desired output frequency, by varying the switching times during each cycle a better approximation to a sine wave is achieved (see Figure 36).

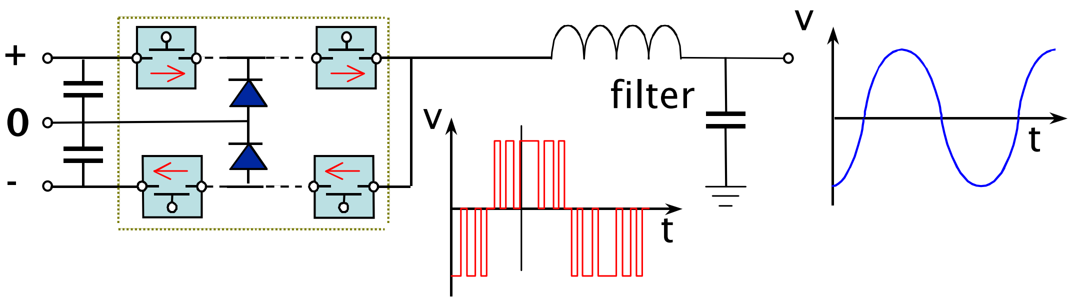


Figure 36: Illustration of pulse width modulation.

Clearly for a PWM system the higher the switching frequency the better the approximation to a sine wave can be achieved. It is here though that the amount of power being switched dictates the choice of power switching device and from that the acceptable operating frequency that the converter can be operated at. This frequency is not dictated so much by the switching speed limitations of the device, but by the acceptable amount of loss you want to incur as a result of switching. For low power applications MOSFETs are ideal and can be operated at speeds up to a Mhz, but for applications much above 200V it is necessary to look to devices like IGBT's which can only switch at up to a few KHz. This means that inverter design becomes more complex with the need to look at multi-level or staggered parallel systems. At the very high end PWM is not an option for devices such as GTO's and IGCT's. This means that other strategies are needed, which are very costly.

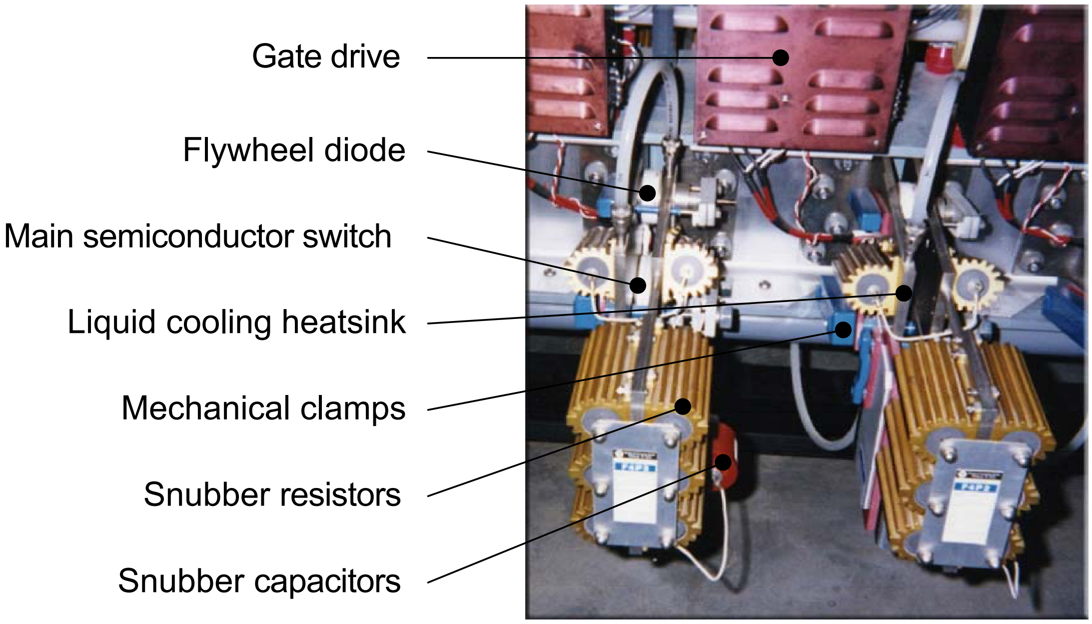


Figure 37: Example of just some of array of components and physical construction needed to get a semiconductor switching device to operate in a practical application

The other thing about power converters is that the switch is only one component, to make the switch operate reliably requires not only additional components. As Figure 37 illustrates this can be quite a number of components. Further care is needed in the physical design to prevent introducing additional stray electrical effects and a cooling system is needed to dissipate the energy lost in switching. As Figure 21, (p. 58) shows the outcome of this is that the cost of the actual power devices represents less than 10% of the system cost, yet the limitations of the devices in turn account for almost 70% of the overall system price.

Figure 37 also highlights a disparity in the development of high power converter systems. The fact is that the design of such systems is complex and expensive and the expertise to design large converter systems lies with a handful of manufacturers such as ABB, GE, Siemens, Mitsubishi, Toshiba and Hitachi. This is means that there is a considerable disconnect between what is achieved by academics and lower end manufacturers and what is actually state of the art. The reason is simple - only people with deep pockets can afford to make mistakes.

APPENDIX 4 – SEMICONDUCTOR MATERIALS COMPARISON

Some of the key electrical and physical properties of the leading proposed semiconductor materials are compared in Table 6. It should be noted that some of these properties, in particular the mobility's, are not definitive since the values reported may not necessarily be based on the purest high quality form that the material could take. The properties listed mean various things, in summary this is what they mean:

- **Lattice constant** - this is a measure of how far apart the atoms are in the crystal structure of the material, the higher the value the less tightly packed the atoms will be. This is partly determined by the size of the constituent atoms, but also the physical chemical bonds in the material. For materials such as diamond the small lattice constant means that it is very difficult to insert foreign atoms other than adjacent elements into the crystal structure to cause semiconductor doping.
- **Thermal expansion coefficient** - this indicates by how much a material will physically expand under the influence of heat. This has implications on packaging design whereby it is important to ensure that materials used to complete a device package are similarly matched otherwise differences in characteristics may cause the device to mechanically fail at operational temperatures.
- **Bandgap** - the bandgap indicates the amount of energy that is required to force the pure material into conduction. The higher the bandgap the greater the applied energy needed to force the material into conduction.
- **Mobility** - is a measure of how readily charge will move in a semiconductor material. It's basically a measure of inertia - the higher mobility the easier it is to get charge to move and also the quicker that charge will recombine, which is important for bipolar devices when turning off.
- **Saturated Electron Velocity** – this is rather like terminal velocity in air for falling objects, there is an upper limit for the speed that electrons can move within the semiconductor material. Clearly the higher the saturation velocity the better since this increases the frequency that the devices can be operated at. For instance on paper the mobility of the carriers in Silicon Carbide doesn't look any better than Silicon, however the saturated velocity is twice that of Silicon, greatly extending the frequency range that the material can operate at.
- **Dielectric constant** - is a figure that broadly indicates the amount of electrical energy that can be stored in a material. The biggest effect of dielectric constant is that the higher the constant the more susceptible devices made in that material are subject to high frequency limitations due to capacitive effects.
- **Thermal Conductivity** – is the measure of how effectively a material conducts heat, clearly the higher the conductivity the better a material is capable of dissipating heat to the external environment.
- **Critical Field** – is the measure of how effectively the material can act as insulator. The higher the value, the higher the voltage that can be held-off

across a junction of the same dimension. Since junction thickness has a direct impact on switching speed, the thinner you can make a junction the better.

- **Resistivity** – is a measure of the off-state resistance, which is important for determining the potential leakage current through the device in the off-state. Clearly for isolation a material should be as close to a perfect insulator as possible in this condition.

Perhaps an easier way of comparing materials is look at performance factors. Several of these have been proposed in relation to determining the relative suitability of materials to power applications. Some of these figures of merit are summarised and compared for the most likely candidate materials in Table 7 – which are normalised relative to silicon. Each figure of merit looks at differing performance parameters for a power device and in each case the higher value thee better the performance. The various figures are:

- **Johnson Figure of Merit (JFM)** – was the earliest proposed evaluation method in 1963. The JFM had its grounds in bipolar device technology and proposed that the most effective power devices could be made from materials that exhibited the highest critical breakdown field (E_c) and the maximum speed of charge movement through the material (ν_{sat}).
- **Keyes Figure of Merit (KFM)** – was proposed later 1972 based on the idea that the limit on bipolar device performance was actually a thermal one based on the ability of the device to conduct heat away as it was generated.
- **Baliga Figure of Merit (BFM)** – was proposed in the 1980's and was more focused on the notion that unipolar FET devices were the route for power switches based on the need to reduce power losses from switching and on-state conduction. This was perceived to be a critical issue particularly at low power end of the market. Indeed the thermal issues of device performance are now the major limiting factor in increasing the power density of power electronic systems.
- **Baliga High Frequency Figure of Merit (BHFM)** – was an extension to the BHFM considering also the performance of devices at high frequencies – in particular losses associated with switching.
- **Shenai Quality Factors (QF1 & QF2)** – were further factors proposed by a then colleague of Baliga at GE's R&D centre who proposed that the thermal limitations of the material should also be taken into consideration. Hence QF1 compares the thermal effectiveness of the material in conducting heat away and QF2 introduces the further benefit of operating at higher voltages (which of course reduces the amount of current that needs to flow).

Properties	Silicon	GaAs	3C-SiC	4H-SiC	6H-SiC	GaN	Diamond	AlN
Lattice constant (Å) (room temp.)	5.43	5.65	4.36	3.07 10.5	3.08 15.11	4.51	3.57	3.11 4.98
Thermal expansion (x 10^{-6} °C)	2.6	5.9	4.7		4.2 4.7	5.6	0.08	4.5
Density (g cm^{-3})	2.328	5.32	3.21	3.21	3.21	6.15	3.515	3.255
Melting point (°C)	1420	1238	2830	2830	2830	2500	4000	3000
Bandgap, E_g (eV)	1.1	1.43	2.39	3.26	3.02	3.45	5.45	6.2
Saturated electron velocity, v_{sat} (x 10^7 cms^{-1})	1.0	1.0	2.2	2.0	2.0	2.2	2.5 (n) 2.7 (p)	1.84
Carrier mobility μ ($cm^2V^{-1}s^{-1}$)								
Electron, μ_e	1500	8500	1000	1000	370	1250	2200	
Hole, μ_h	600	400	50	50	90	250	1600	14
Breakdown Field Strength, E_c (x 10^5 Vcm^{-1})	3.7	6	20	30	32	>50	100	>50
Dielectric constant, ε	11.8	12.5	9.7	9.6 - 10[1]	9.6. – 10[1]	9.7	5.5	10
Resistivity, ρ (Ω cm)	10^3	10^8				10^{10}	10^{13}	10^{13}
Thermal conductivity, λ($Wcm^{-1}K^{-1}$)	1.5	0.46	3.2	4.9	4.9	1.3	20	3.0

Table 6 - Comparison of Semiconductor Properties at 300K (27°C)

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[1] *Varies with frequency*

Properties		Silicon	GaAs	3C-SiC	4H-SiC	6H-SiC	GaN	Diamond	AlN
Johnson Figure of Merit	$\mathrm{JFM} = \frac{E_c^2 \upsilon_{sat}^2}{4\pi^2}$	1	11	110	410	260	790	5330 (n) 6220 (p)	5120
Keyes Figure of Merit	$\mathrm{KFM} = \lambda \left[\frac{c\upsilon_{sat}}{4\pi\varepsilon_r}\right]^{1/2}$	1	0.45	5.81	5.06	5.11	1.76	31 (n) 32 (p)	2.62
Baliga Figure of Merit	$\mathrm{BFM} = \sigma_A = \varepsilon\mu E_c^3$	1	28	40	290	90	400	14860 (n) 11700 (p)	390(μ=14) 31670 (μ=1090)
Baliga High Frequency Figure of Merit	$\mathrm{BHFM} = \mu E_c^2$	1	16	12	34	13	44	1080 (n) 850 (p)	14 (μ=14) 1100 (μ=1090)
Shenai Quality Factor 1	$\mathrm{QF1} = \lambda\sigma_A$	1	9.4	130	950	300	400	198100 (n) 155990 (p)	660 52890
Shenai Quality Factor 2	$\mathrm{QF2} = \lambda\sigma_A E_c$	1	16	550	9630	2440	4490	5784410 (n) 4554840 (p)	25520 2058620

Table 7 - Comparison of Figures of Merit Relative to Silicon[29,30]

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