EPSRC Centre for Power Electronics
The Future of Power Electronics

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Transforming our future through world-leading, underpinning research, combining the UK’s best academic talent
Overview

- Acknowledgements
  - Prof Phil Mawby, Prof Phil Mellor, Prof Andrew Forsyth
  - Researchers from across the Centre!

- Overview of Challenges for Power Electronics

- Future Perspectives
  - Power Semiconductor Devices: SiC or GaN or ?
  - Component Integration: How to Handle WBG Devices
  - Converter Technologies
  - Integrated Drives
Challenges for Power Electronics

- Higher efficiency
- Increased power densities
- Lower electromagnetic emissions
- Higher reliability
- Easy-to-use “plug-and-go” systems
- Lower life-cycle costs
- Skills
What Generates Advances?

- Market pressure
  - Existing applications seeking to reduce cost and increase performance
  - New and Emerging Applications
  - Environmental legislation
- New Materials and Components
- Increased Knowledge
- Intellectual Curiosity
Devices

Si, SiC, GaN or ?
Power Semiconductor Devices

- Power semiconductors operated in switched mode lie at the heart of all power electronics
- The ideal power device:
  1. When on – zero resistance
  2. When off – support infinite voltage
  3. Switch between on and off (and vice-versa) in zero time
  4. Zero Power dissipation
  5. Small, light and cheap!
SiC vs. GaN Power Devices

- Vertical
- Homoepi
- pn junction, MOS, implantation
- Unipolar and Bipolar devices
- Oxide or Polyimide passivation
- Avalanche capable in commercial devices

- Lateral
- Heteroepi
- Heterojunction
- Unipolar devices
- SiN, SiO₂, Al₂O₃, or AlN passivation
- Avalanche not seen in commercial devices
Industrial activities on SiC
- Main stream is Schottky diode & MOSFET to 1700 V
- More and more companies (big and small) join in, including module makers
- Higher voltages are just a matter of time ... and market volume
- Plasma (bipolar) devices are on their way ...
- ... but what can SJ do? Unipolar to >10 kV?
- Energy cost of material growth a limiter?

Industrial activities on GaN
- Low entry barrier ➔ many (small) players
- Massive tail wind from opto-electronics and RF
- First commercial devices available
- Consolidation ongoing
- Generally different market segments to SiC
Next 5 years

- **SiC**
  - Schottky MPS diodes 300A, 600V – 3kV
  - PiN diodes 300A, 3kV – 25kV
  - MOSFETs 300A, 1.2kV – 10kV
  - IGBTs 300A, 10kV – 25kV

- **GaN**
  - HEMT 300A, 30V – 3kV

- **Ga$_2$O$_3$**
  - Schottky 10A, 1000V

- **Others?**
Components

Fast Switching, Passives, Integration, Virtual Prototyping
Fast switching

New wide bandgap devices are capable of switching much faster than their Si counterparts (10s of kV/μs):

- Lower losses
- High operating frequencies
- Smaller passives

However

- Parasitic circuit elements important in determining overall performance
- ‘Slow’ IGBT-based drives already require significant EMC countermeasures
- Mandates use of filters, screens etc.
Sometimes slow switching is better?

Impact of load capacitance and EMI countermeasures may outweigh other advantages
Better Passives?

Wound components and capacitors typically represent half the size and mass of the complete power electronic converter and are a significant factor in the overall reliability.

Weight breakdown for 60 kW, 75 kHz DC/DC converter:

- SiC MOSFET: 5.2 kg (48%)
- Cold plates: 1.1 kg (31%)
- Magnetic devices: 0.7 kg (7%)
- Power modules & gate drivers: 0.4 kg (4%)
- Mounting and cooling hardware: 0.3 kg (6%)
- Control and busbars: 0.05 kg (4%)
A more integrated approach?

- Meeting the challenges through concurrent electrical, thermal and reliability design
- Reduced weight and volume (fewer interconnections, less “dead” space)
- Reduced cost (smaller bill of materials)
- Optimised thermal management (not limited by standard component footprint/construction)
- Passive components located close to active devices (layout optimised for reduced parasitic inductance and low EMI)
- Integrated control and protection functions
- Suited to wide band gap semiconductors
A more integrated approach?

Virtual prototyping using multi-physics models derived from component geometry and layout

Circuit topology

Component physical models

Suite of computationally efficient component and system level behavioural models
A more integrated approach?

- Integrated, flexible platform for implementing multi-phase inverters and dc-dc converters
- Multiple stations for half-bridge cells, input filter etc. with integrated liquid cooling
- Half-bridge cells: SiC JFETs with integrated dc-link decoupling, gate drives and output LC filter
- Cell interconnections, control and input filtering on separate power plane – different configurations to suit application

3-phase converter configuration
Many challenges need to be addressed if the full ambitions of ‘more’ and ‘all’ electric systems are to be met

- Lower-cost, high-performance semiconductors
- Delivering the potential of wide bandgap devices
- Integrated, modular, scalable design for cost reduction
- Passives are a major obstacle to volume and weight reduction: new materials, higher frequency?
- Higher temperature operation; components and packaging
- Better thermal management and loss extraction
- Improved reliability modelling, operational diagnostics
- Advanced tools for concurrent electrical, thermal and reliability design
Converters
Background

- Power electronics converter market predicted to grow by 7% pa, reaching $250b by 2020
- Driven by
  - Transport electrification
  - Energy applications
  - Increasing automation

Power density
Cost
Efficiency
Reliability
Converters

- Rapid transformation of:
  - High voltage grid converters
    » Advanced topologies
    » Health monitoring and management
    » Redundancy
  - Compact converters
    » Advanced topologies
    » Integrated design techniques
    » Assembly methods
    » Integration and new manufacturing techniques

» Claims of over 100kW per litre
High voltage converters

- Health management techniques
- Reconfigurable systems
- Higher efficiency
Topologies for compact converters

- 5-100 kW, mainly exploiting WBG devices
  - Modular / interleaved systems
    » Increased ripple frequency and reduced filter requirements
    » Integrated passive components
    » Reduced manufacturing costs
    » Multilevel techniques
    » Soft-switching techniques
Converter Assembly techniques

- Planar interconnect
  - Reduced parasitic inductance
  - More compact
  - Straightforward assembly
Drives

Motors; Control; Reliability; Integration; Applications
Motors – future trends to increase power density

- Higher speeds
- Mechanically stronger
- Lower losses at high electrical frequency
- Magnetic bearings
- Higher conductivity – superconducting or carbon nanotubes?
- Better insulators
- Better thermal management
Control

- Imagine if all drives in a large system have instantaneous access to all others. e.g. all cars in a traffic system.
- Very fast controllers and faster switching
- Potential for major advancements in system behaviour
- Increased system reliability
Reliability

- Increased automation must be hand in hand with increased reliability.
  - Are we happy to use drives of standard reliability to steer our future driverless cars?
  - We need to increase reliability by at least one order of magnitude

- Key enabling technologies
  - Rapid advances in sensing, monitoring and self-learning/Artificial Intelligence
  - Incorporate lifetime model and fault tolerance
  - Conditioning monitoring, diagnostics and prognostics
  - Accurate, advanced knowledge of failure
Manufacturing and Integration

- Integration
  - Advanced packaging
  - Modularity
- Customisation
- 3D Printing/additive manufacturing
  - New complex geometries
  - Better space usage
New Applications

● Transport
  » Electric and hybrid aircraft
  » Predict 3 billion cars by 2045. At a drive cost of £200 per car and a lifetime of 10 years, that’s a world market of £60 billion per annum.

● Increased Automation
  » e.g drones, logistics, self driving cars, automated manufacture.

● Renewables

● Healthcare and an Ageing Population
  » Assisted living aids – smart homes
Automotive

**US DoE Targets**

**2012 Electric Drive System**
- $30/kW, 1.1 kW/kg, 2.6 kW/L
- 90% system efficiency (on-road status)
- Discrete Components
- Silicon Semiconductors
- Rare Earth Motor Magnets

**2022 Electric Drive System**
- $8/kW, 1.4 kW/kg, 4.0 kW/L
- 94% system efficiency (R&D target)
- Fully Integrated Components
- Wide Bandgap Semiconductors
- Non-rare Earth Motors

4x Cost Reduction
35% Size Reduction
40% Weight Reduction
40% Loss Reduction
Electric and Hybrid Aircraft

- Needed to meet future emissions targets
- Electrical generators
- Electric drives for distributed propulsion
- 50 MW power system
- Power density of >40kW per kg
Summary

- Very strong market growth, especially transport
- Increased
  - Power Density
  - Efficiency
  - Reliability
  - Controllability
  - System gains
- Reduced
  - Cost
- Very exciting new applications
It is a very exciting time to be working in power electronics.