EPE 2005 Dresden

ESCAPEE

The achievements of the EC funded project "Establish Silicon Carbide Applications for Power Electronics in Europe" (ESCAPEE)

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Overview

- Overview of recent results from the ESCAPEE project.
- Update to the information originally presented at EPE 2003 in Toulouse.
- Key targets
- Significant scientific progresses
- Final achievements and successes.

Key research targets

(creation and introduction of SiC technology, from fundamental science through to real applications.)

- Produce improved quality of thick (>10μm) SiC epi-layer material suitable for high power devices.
- Develop device processing and fabrication technology (implantation, passivation, etching, metallization).
- Establish edge termination to enable high voltage applications.
- Develop high temperature device packaging suitable for SiC
- Use the created technology in a module introduction and end-user application in traction systems

Important scientific progresses

Significant results from the ESCAPEE project include:

- Development of new sublimation epitaxial growth technique - produces epi-layers at growth rates up to 20 times faster than standard CVD growth.
- Development of high temperature implantation equipment for SiC and the subsequent commercialisation.
- Development of surface cleaning processes and reduction of surface damage produced by high temperature annealing, for implant activation.
- Development of low resistance n-type and p-type ohmic contacts and high quality Schottky diodes.
- Design of edge termination and fabrication of thermally stable Schottky diodes with blocking voltages of up to 4.7kV and reverse leakage currents of less than 2e-7 A/cm^2 at 3.5kV.
- Increased device yield of 1.6mm $\times$1.6mm diodes from 12% to 43% using a novel polishing technique.

Significant results from the ESCAPEE project continued…

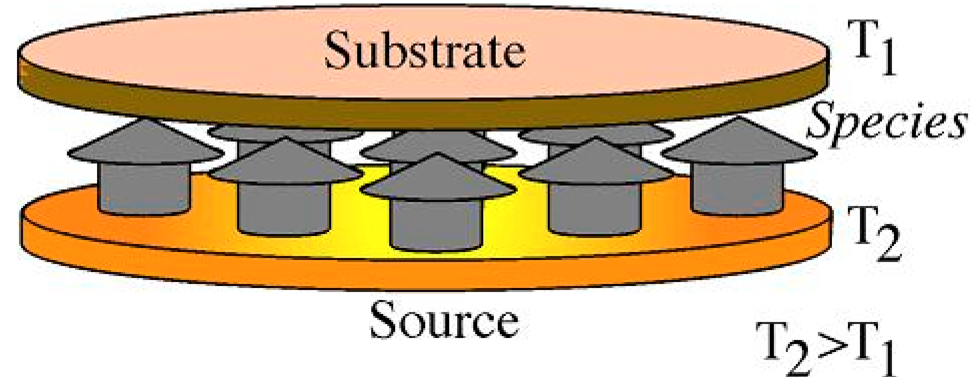
- Development of 1.2 kV MOSFETs.
- Record Field-effect mobility and drain current as a function of gate voltage for transistors with a PVT grown epilayer and a reference CVD grown epilayer.
- Design and production of specialized high temperature thermally stable packaging for high voltage SiC devices.
- Production of a demonstrator module using SiC diodes and Si IGBTs.

ESCAPEE Technological developments

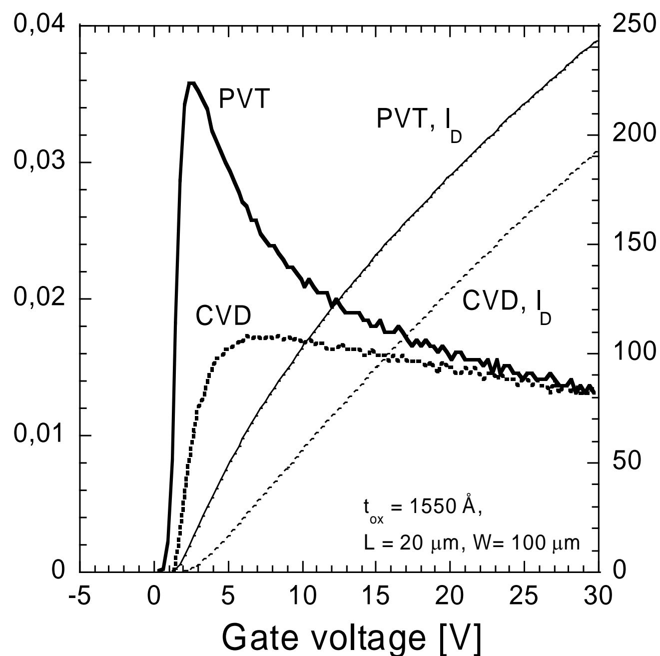
ESCAPEE's results – Material

Fast epitaxy by PVT

- Sublimation of a solid source and transport of vapor to a substrate
  - ideas based on the sublimation growth process to produce wafers but smaller distance between source and substrate
- Benefit of high growth rate from intrinsic sublimation to yield thick layers
- Develop growth conditions to achieve smooth surfaces and low doping



Achievements



- Low doping in the E15 range has been achieved
- Causes for the background doping are known and even lower doping is expected
- Higher field-effect mobility and drain current for transistors with a PVT grown epilayer than on reference CVD grown epilayer.
- A patent on the fast PVT epitaxy technology has been filed
- Discussions with partners for commercialization are in progress

ESCAPEE's results – Implantation

High temperature implanter

High temp chucks :

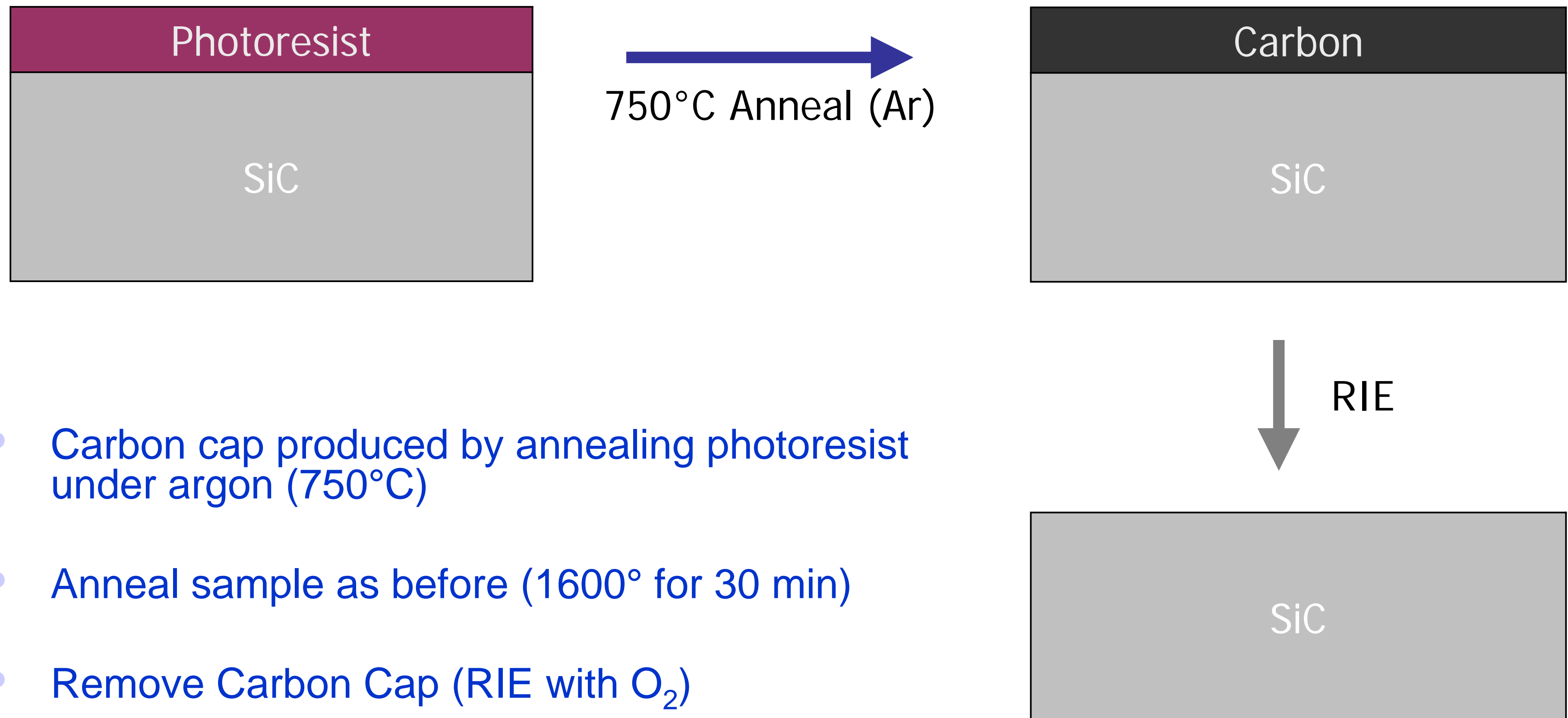
- Several versions available and already sold (Univ. Madrid, INRS Canada, LETI.)

V2 : Installed in Madrid

Proto of V3 : Installed at INRS (Canada)

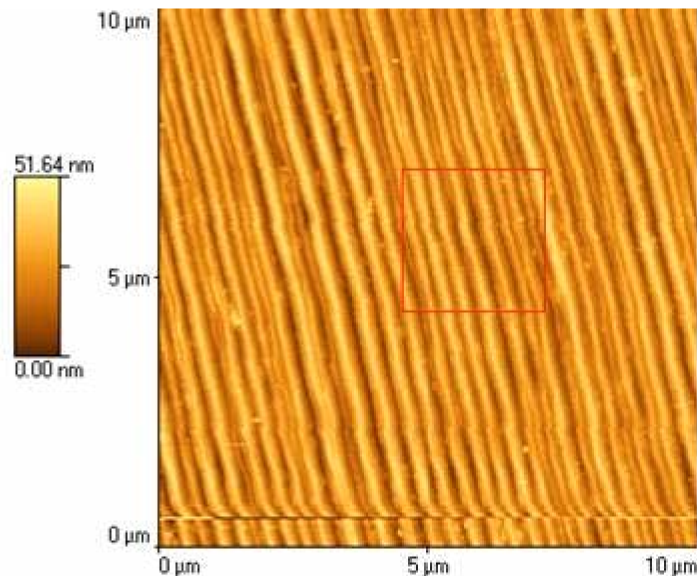
Novel process technological step

- Results using Graphite cap – surface protection process are promising.

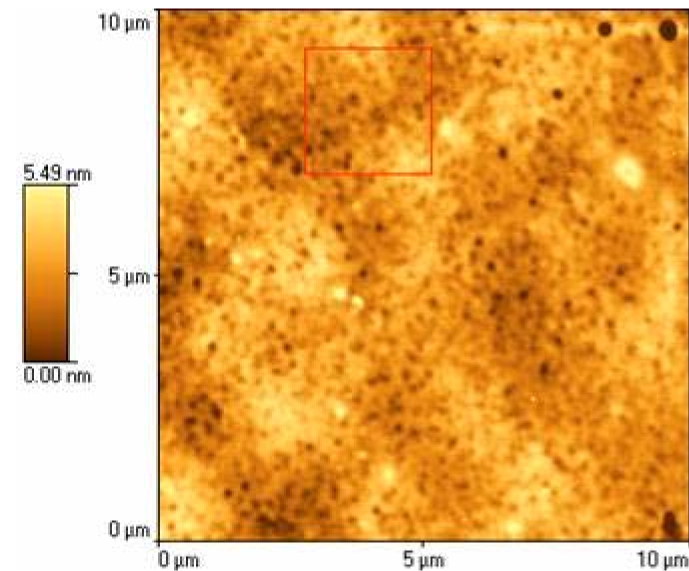


- Carbon cap produced by annealing photoresist under argon (750°C)
- Anneal sample as before (1600° for 30 min)
- Remove Carbon Cap (RIE with O_2)

Surface roughness reduced by up to a factor of 10
Improved forward I(V) characteristics
Improved reverse leakage currents



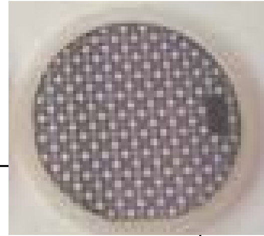
Not protected

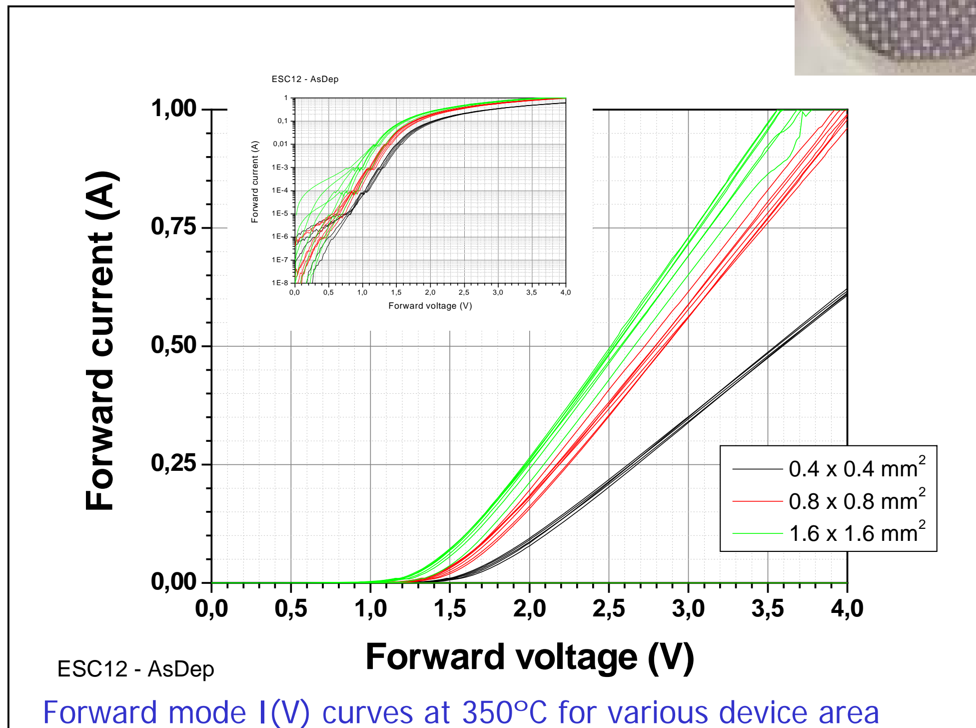


C-cap protected

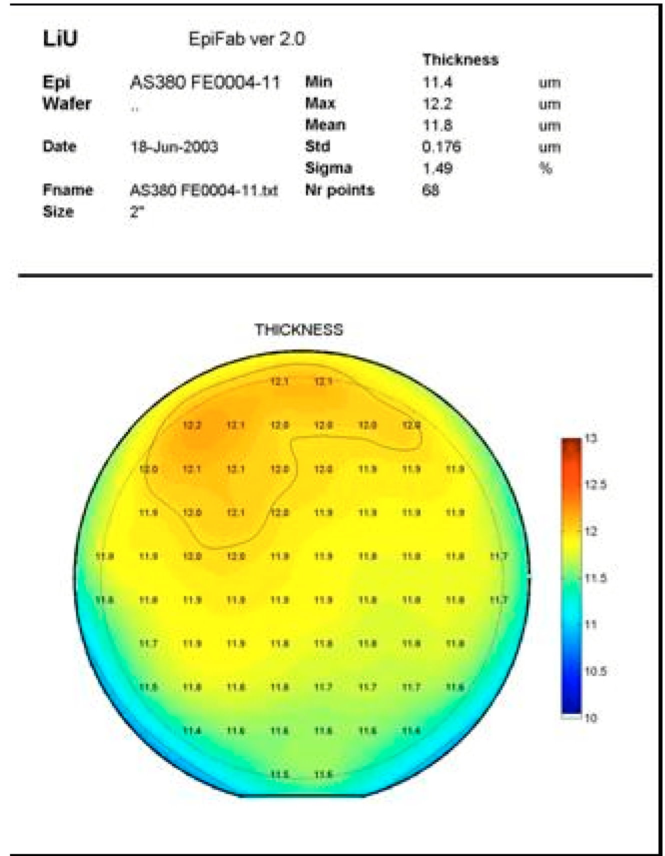
1.2 kV SCHOTTKY DIODES

1.2 kV Schottky Diodes – Area dependence and wafer uniformity



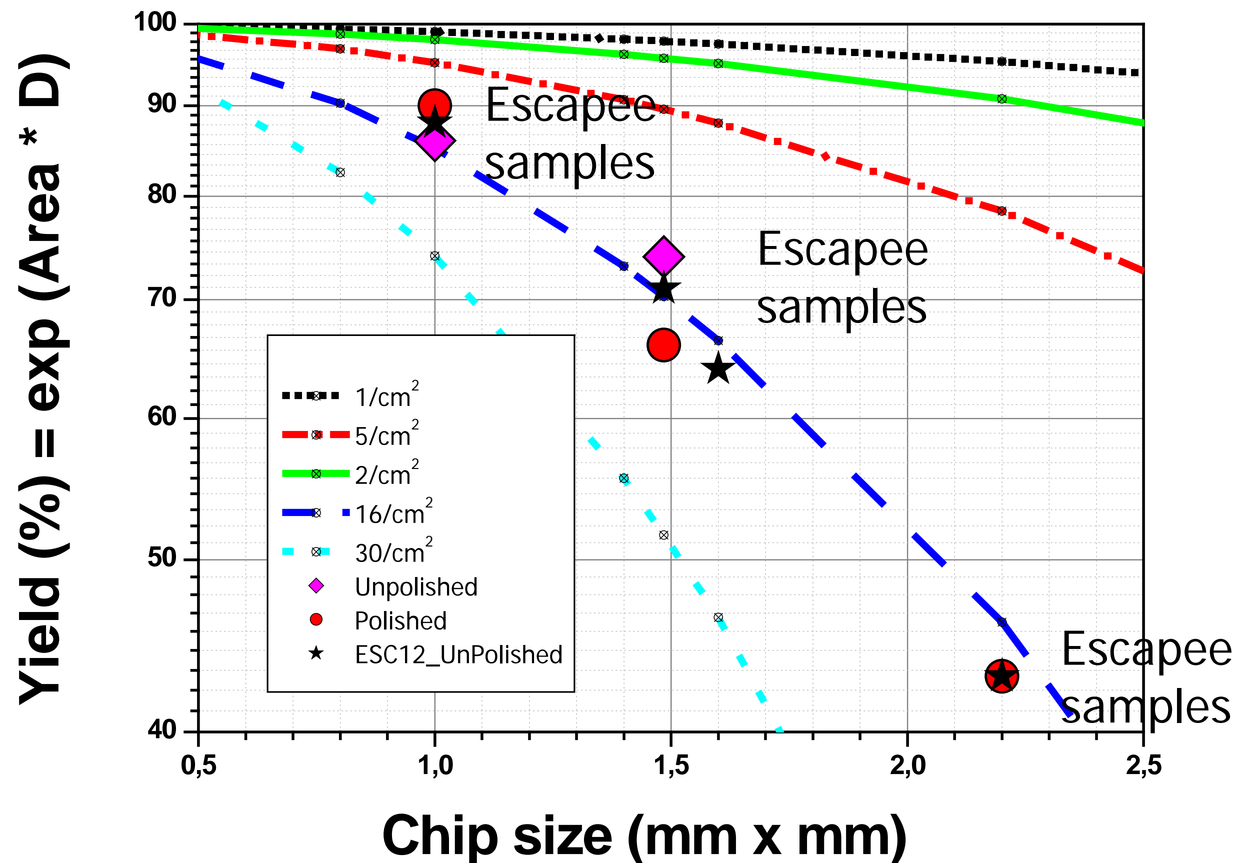


Forward mode I(V) curves at 350°C for various device area



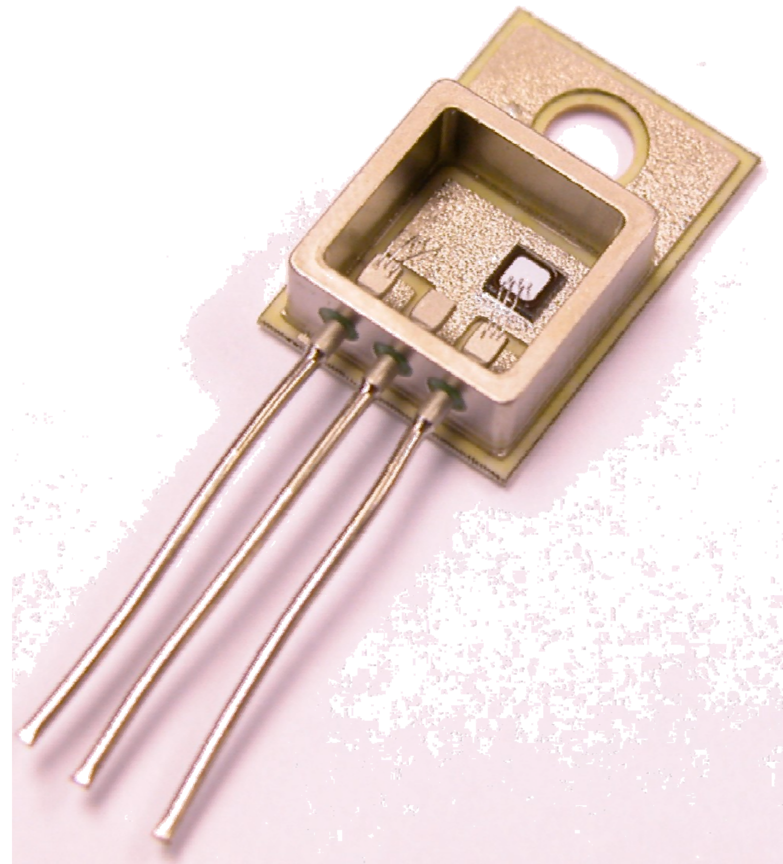
I(V) uniformity: Thickness and doping OK

1.2 kV SCHOTTKY DIODES - Yield



Discrete Package

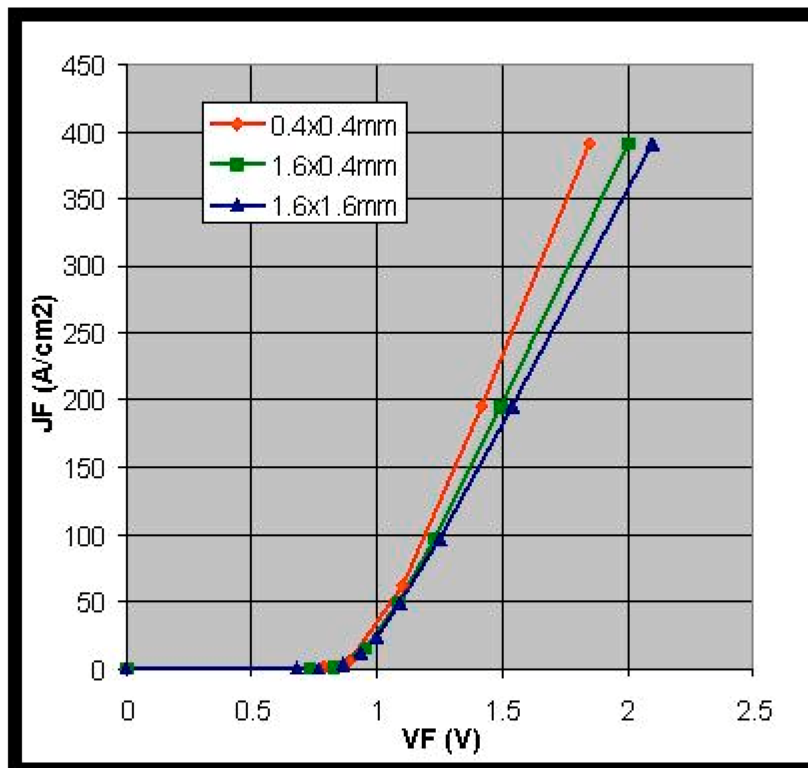
- New package uses DBC baseplate, eliminating separate copper baseplate and DBC substrate used in the conventional isolated TO-257.
- Offers reduction in weight, improved reliability and the potential to operate at elevated temperatures.
- Package successfully used to characterise 1000V ESCAPEE diodes at 225°C.
- Limited VR to 800V during hot test to avoid destroying devices.



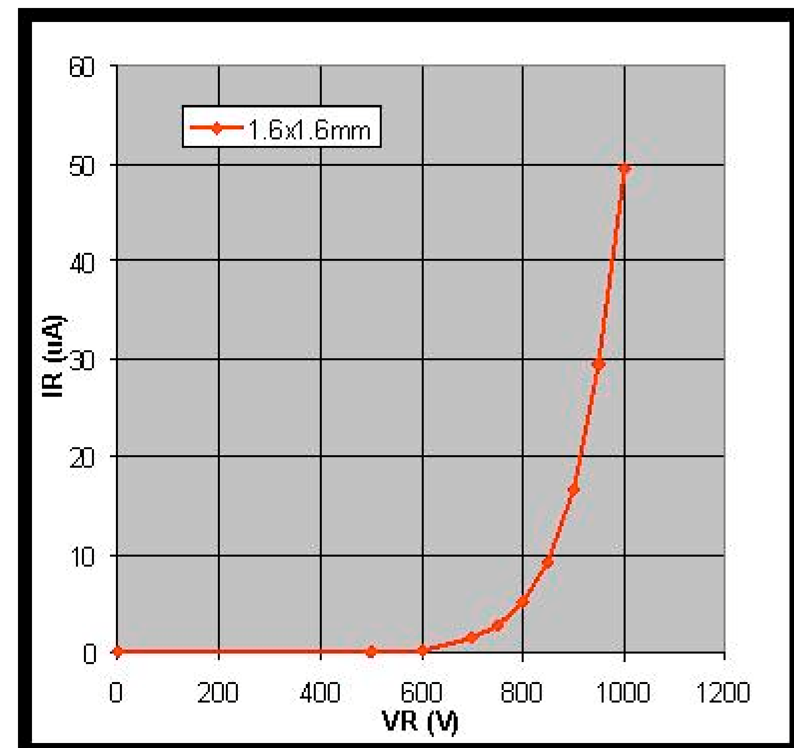
DBC TO-257 Package

Diode Characterisation

Packaged devices show little area dependence and better stability and during device testing

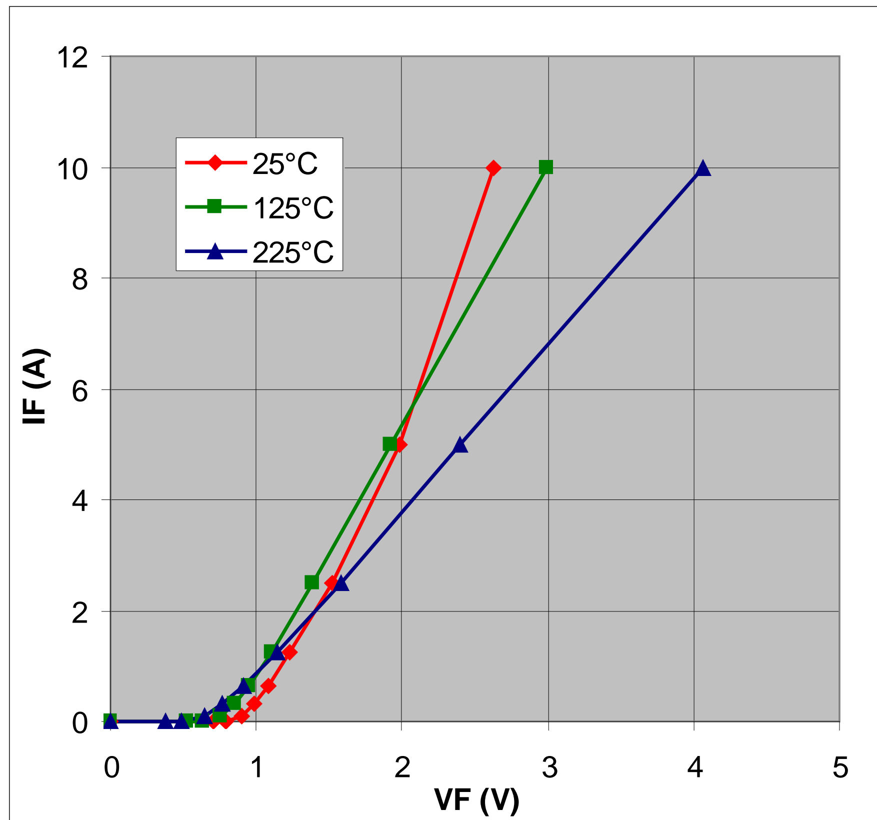


Diode Forward Characteristics

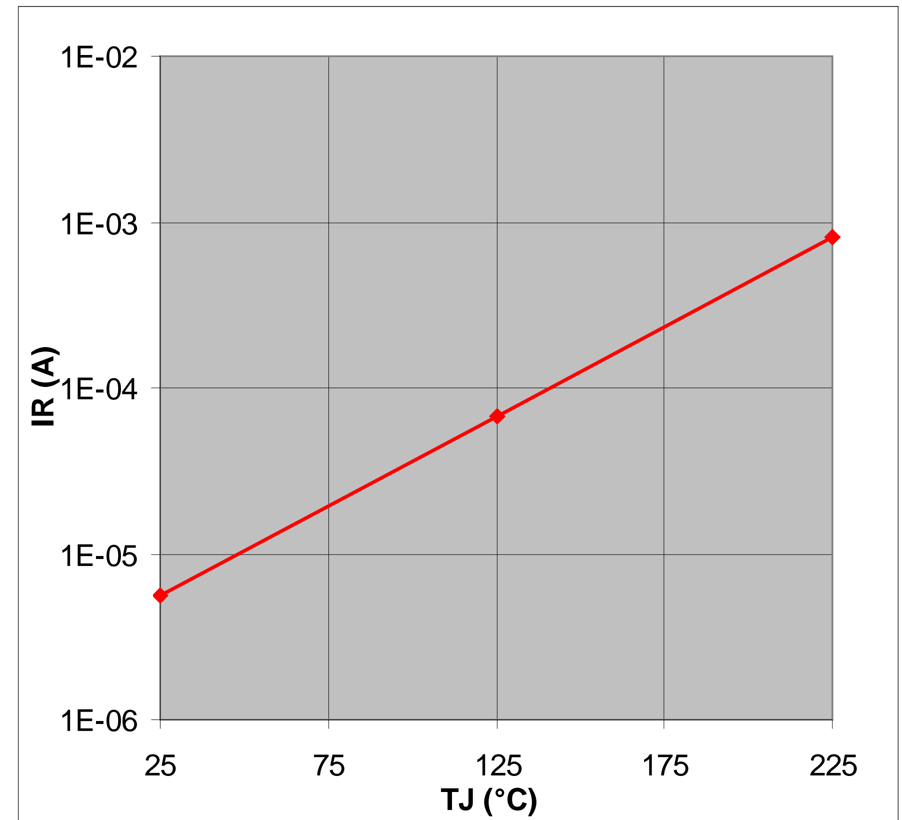


Diode Reverse Characteristics

High-Temperature Operation



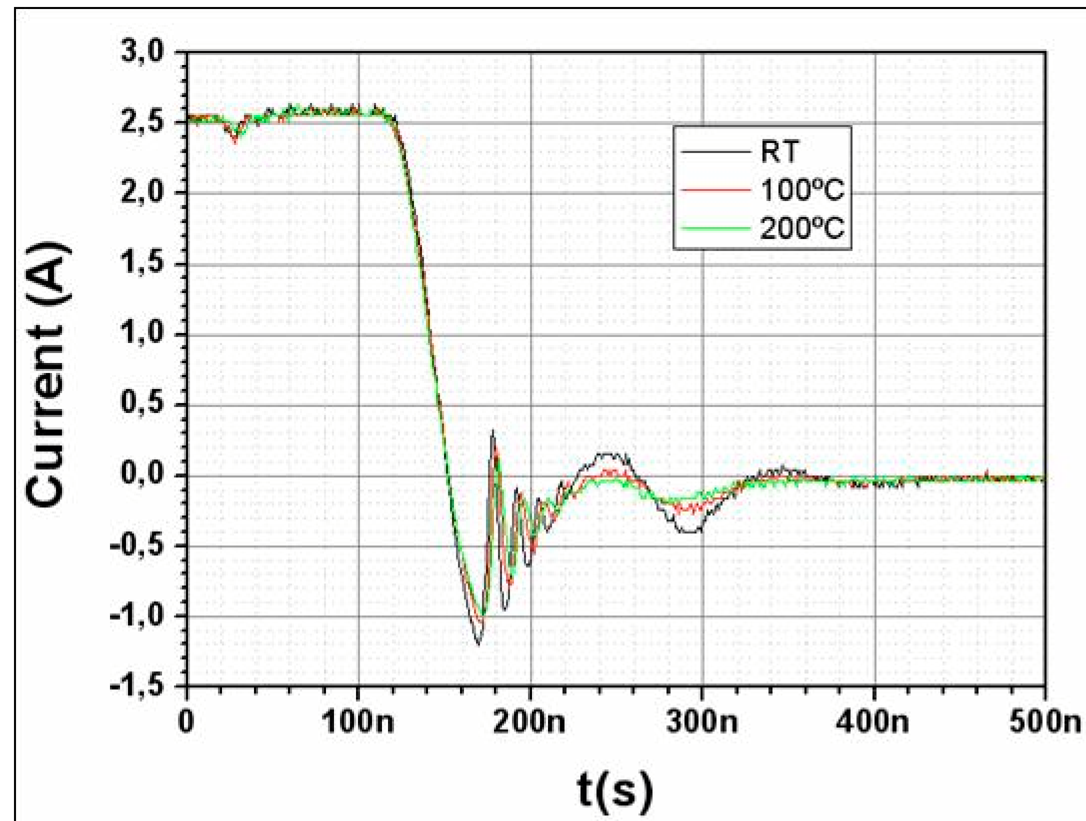
Diode Forward Characteristics



Diode Reverse Characteristics (at 800V)

1.2 kV SCHOTTKY DIODES – switching T dependence

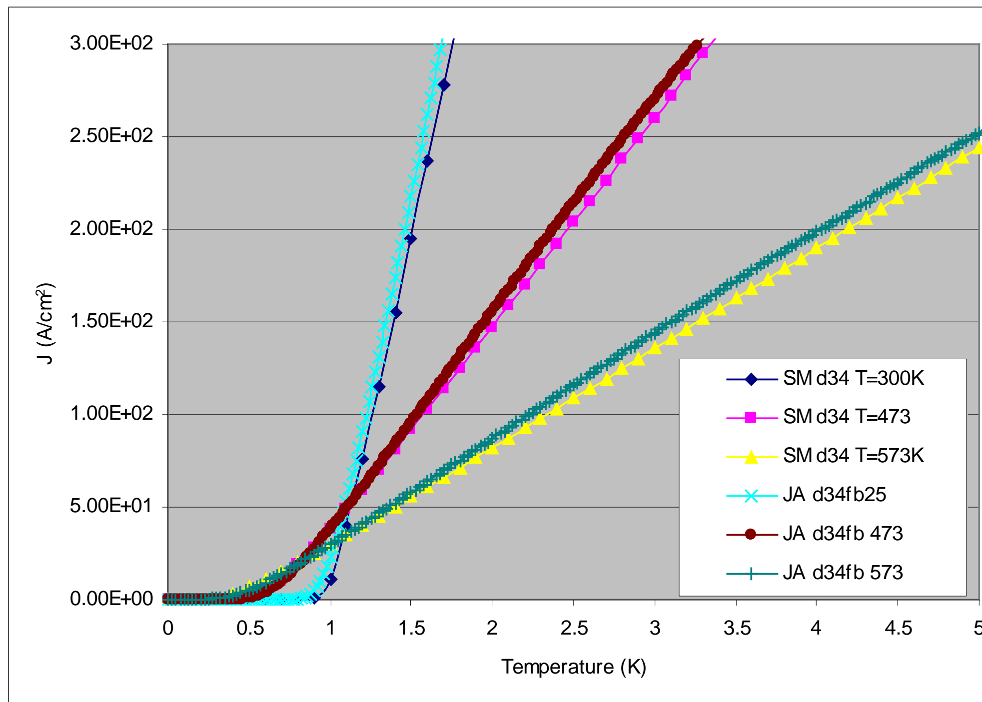
Temperature dependence on the dynamic behavior of the 2.16 mm² SiC SBD

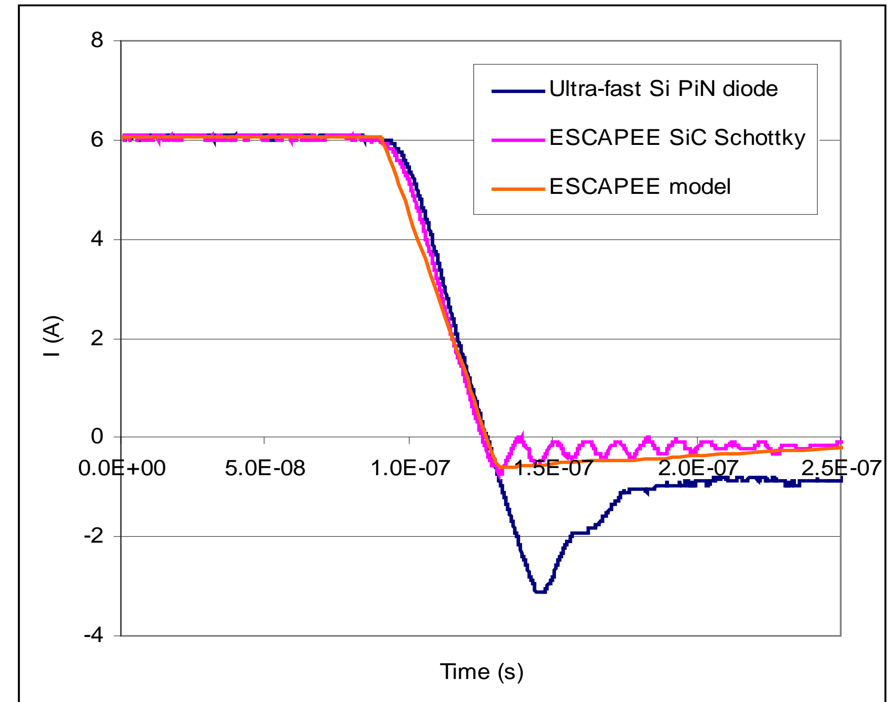


✓ **No significant impact of temperature on switching characteristics**

Compact modelling

ESCAPEE's results



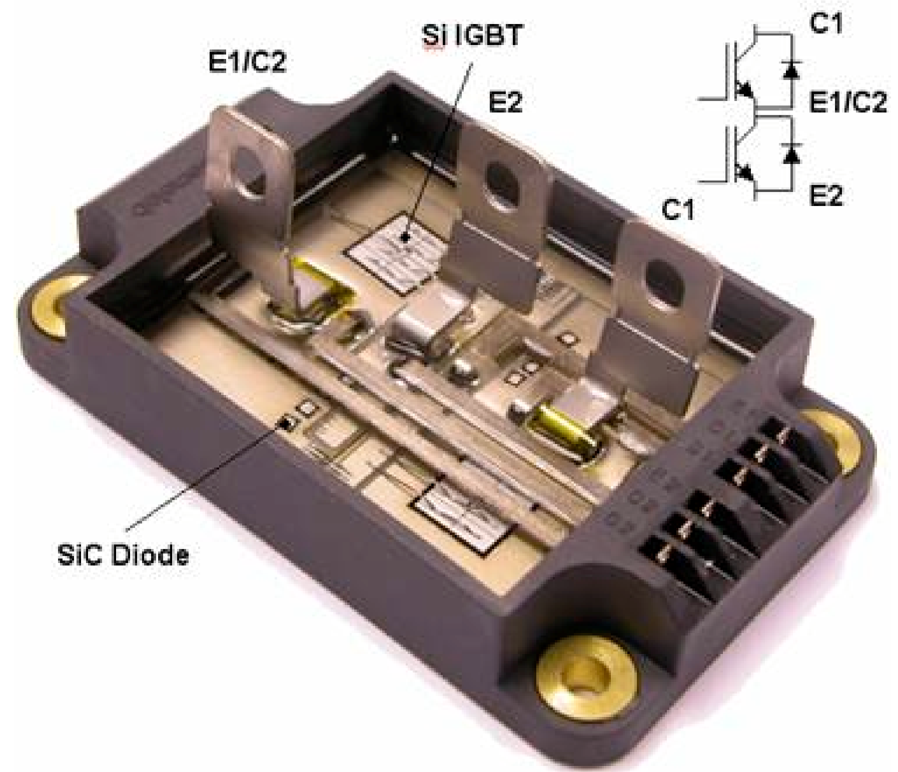


DC

Switching

1.2KV Hybrid Module

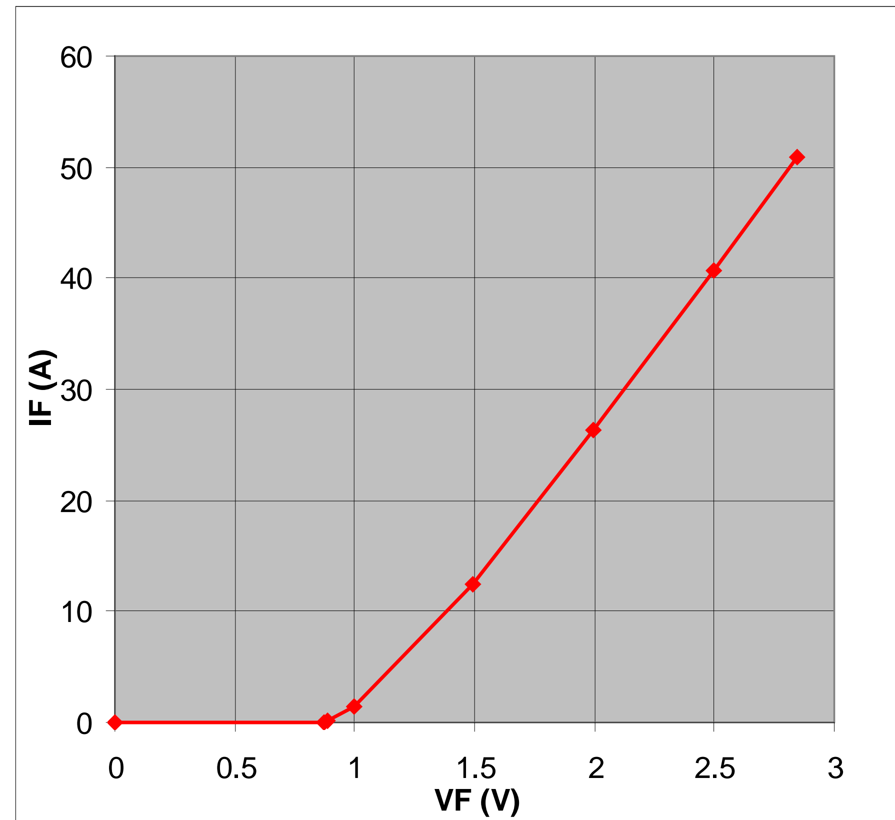
- Aerospace IGBT/diode half-bridge module.
- 150A 1200V Infineon Silicon IGBT.
- Four 1.6x1.6mm 1000V ESCAPEE SiC Schottky Diodes in parallel.
- AlSiC Baseplate, Al/AlN substrate, Cu lead-frame, PBT ring-frame and lid.
- PbSnAg solder and vacuum furnace die-attach.
- 5mil/12 mil Al wire-bonds.



Si IGBT/SiC diode hybrid module with lid removed

Hybrid Module Characterisation

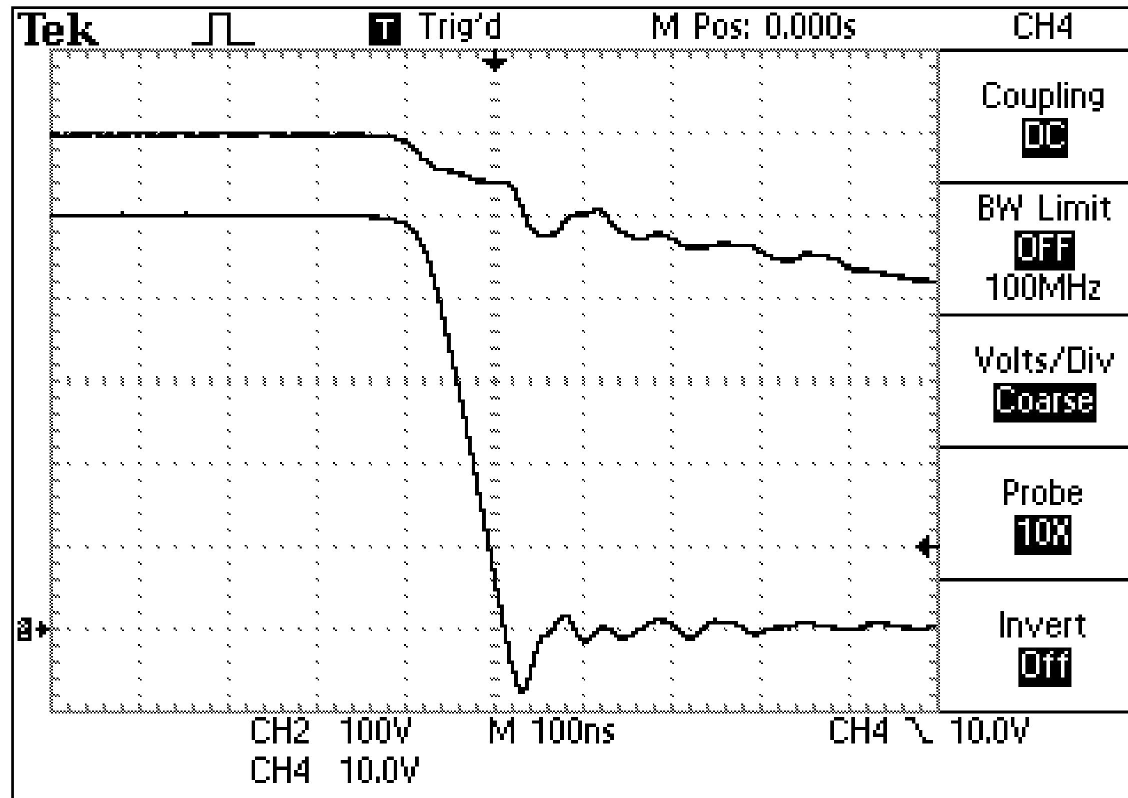
- Three IGBT/diode substrates exhibited IR<300uA at 1000V.
- One IGBT/diode substrate suffered fractured breakdown characteristic above 600V.
- VF < 3V at 50A, 25°C.
- Module successfully switched 25°C, 50A, 600V, 500A/us.



Hybrid Module SiC Diode Forward Characteristics

Hybrid Module Switching

lts



Si IGBT/SiC diode hybrid module inductive-load switching at 25°C, 50A, 600V, 500A/us.

3.5 kV SCHOTTKY DIODES

Diodes fabrication for module

- 4.5 kV ESCAPEE Schottky diodes fabricated at CNM for hybrid module

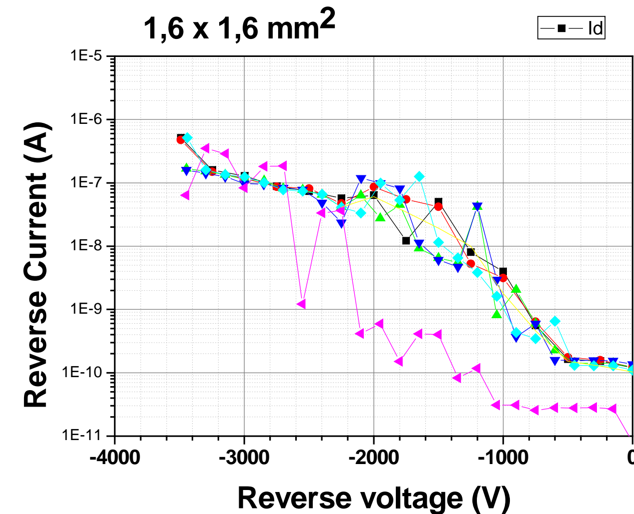
- Good current density uniformity vs diodes size
- R_{ON}= 40mΩ.cm^2 close to theoretical expected value (31mΩ.cm^2).

- Ni used as Schottky contact - stability demonstrated up to 200°C

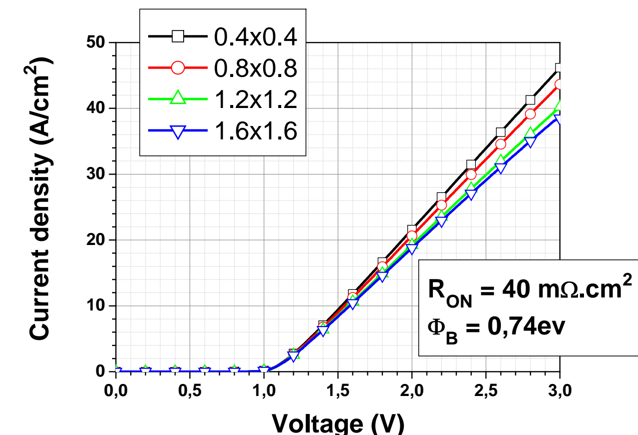
- Very low reverse leakage current density (JR<10 µA/cm2 @ 3.5kV)

- No breakdown differences between measurements made in the air and inside galden on polyimide passivated devices.

4.7kV Breakdown voltage measured = termination efficiency of at least 80%

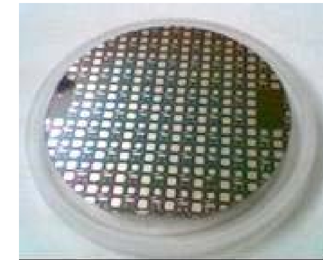


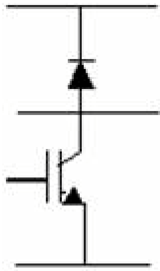
Schottky diode reverse characteristics

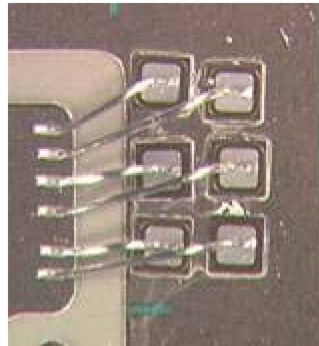


Schottky diode forward characteristics versus size.

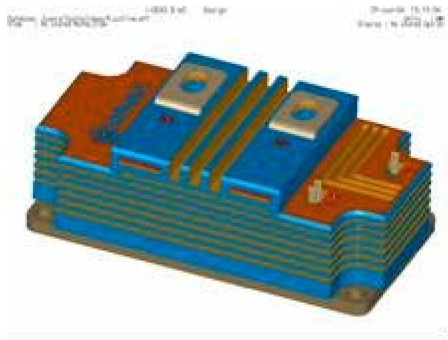
4.5 kV- 8A Module fabrication







Arm electrical equivalent circuit, packaged diodes



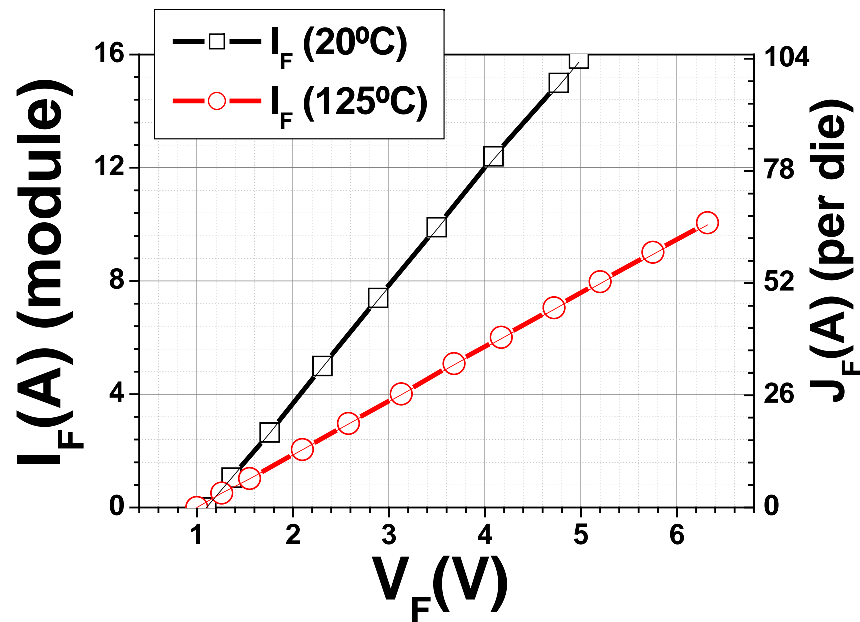
3D-High voltage module CAD view.

- Power Modules have been constructed integrating Si IGBTs and SiC Schottky diodes in chopper configuration

- High voltage 4.5 kV SiC diodes have been successfully assembled with high-voltage Si IGBTs into modules and characterized by Dynex Semiconductor.

High voltage packaging technology successfully applied to Si/SiC hybrid module fabrication

Module characterisation



Schottky diode forward characteristics. Module I(V) left, Die J(V) right, at 20°C and 125°C

- The measured on-resistance of the diode is lower and nearer to the theoretical value when measured on packaged devices.
- SiC Schottky diodes show excellent behaviour in forward mode up to 125°C

Module characterisation

	Diode arm	IGBT arm
Forward 20 °C	50A/cm2 @ VF=3V	
Forward 125 °C	26A/cm2 @ VF=3V	
Reverse @3.1 kV, 20°C	8µA	3µA

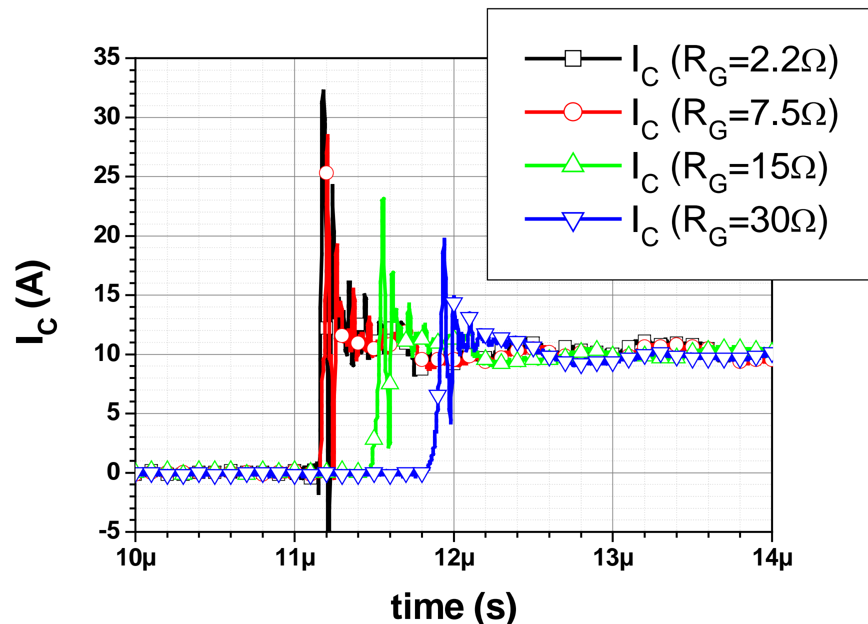
Experimental SiC-Schottky diode and Si-IGBT modules forward characteristics and reverse leakage current at 3.1kV reverse bias.

- very low leakage current values have been measured at 3.1kV (curve tracer limit) in the reverse mode.
- diode arm leakage current (8µA @ 3.1kV) is in the same range than that of the Si-IGBT arm.

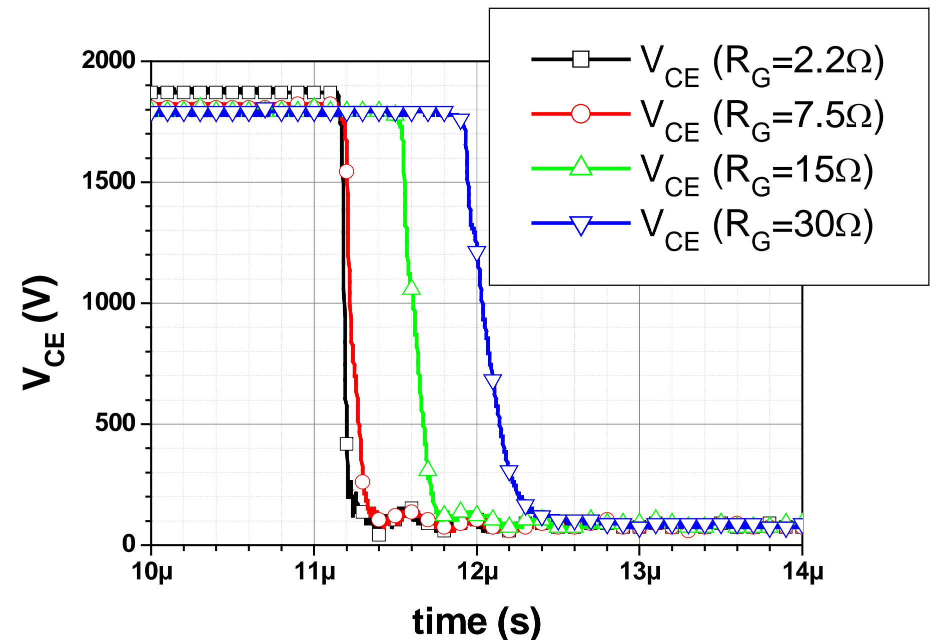
SiC Schottky diode leakage current level compatible with Si-IGBT

Module dynamic switching

Dynamic switching has been performed at 125°C



Current waveform versus gate resistance at 125°C (VCE=1.8kV)



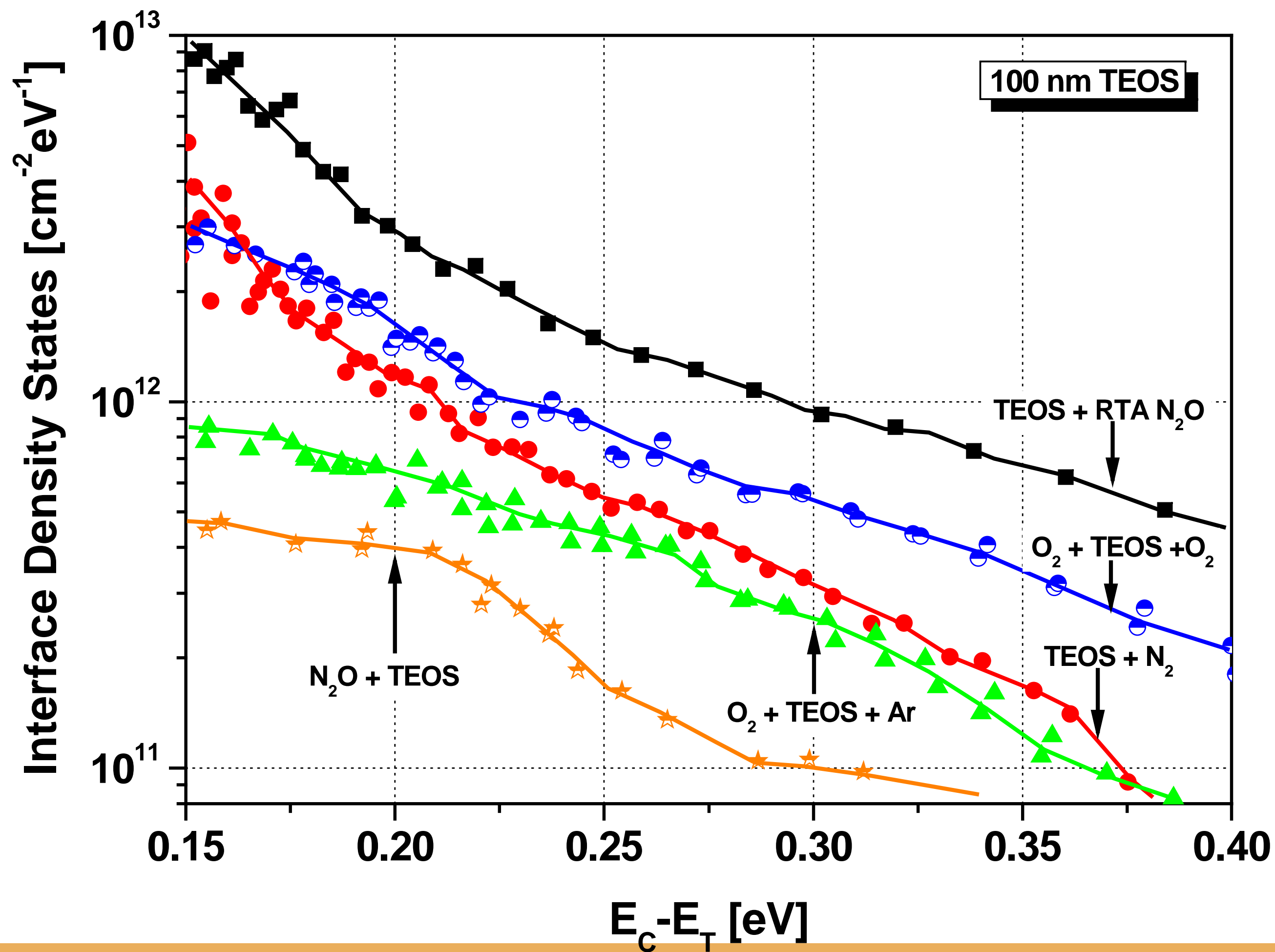
VCE fall time versus gate resistance at 125°C

- **10A, 1800V switching at 125°C**
- **4.5kV-8A SiC-Schottky diodes allow significant switching loss reduction and higher temperature working operation in comparison to Si-PIN diodes**

Power MOSFET Fabrication

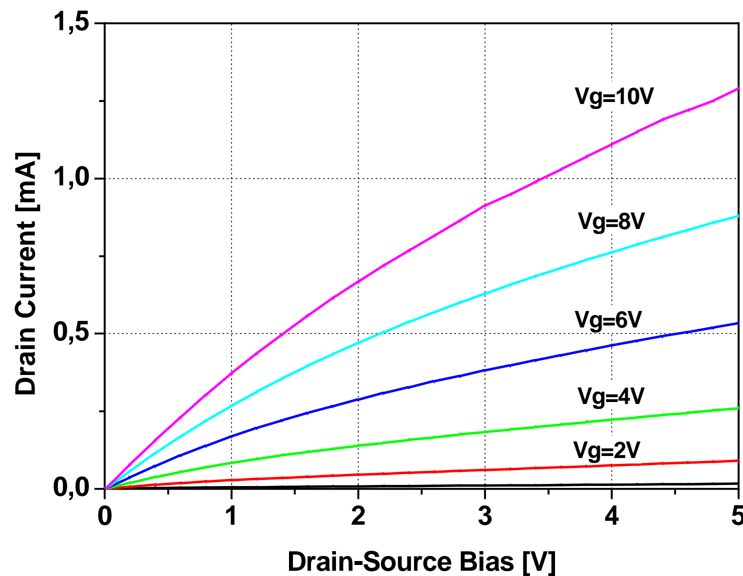
Gate oxide capacitances

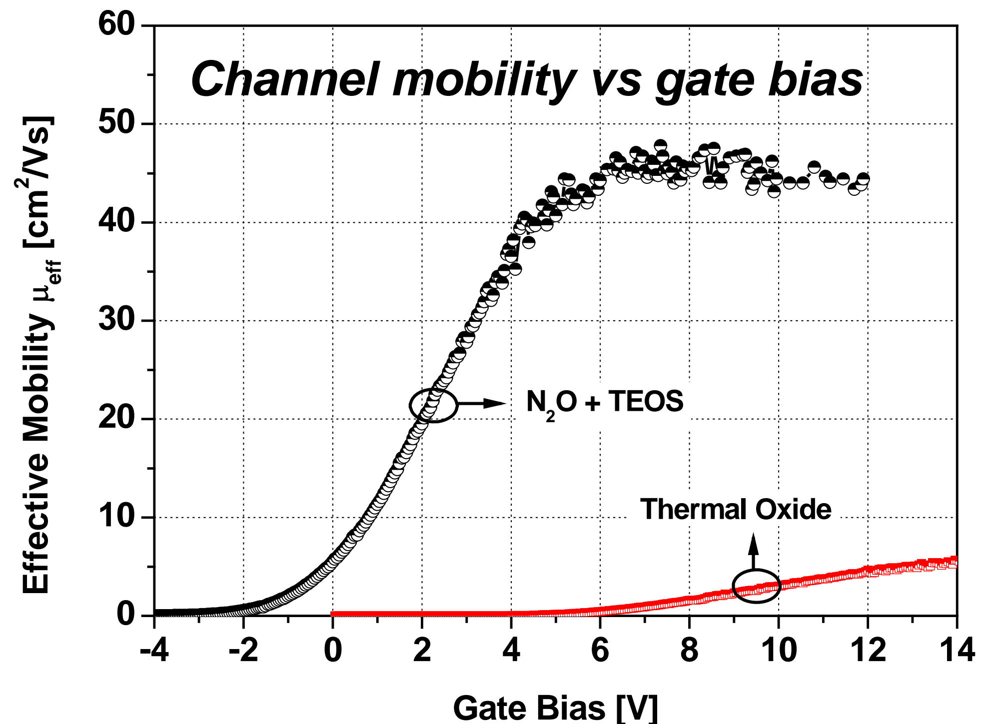
Interface density state in the SiC gap near the conduction band



Lateral N-MOSFET test structure

N-MOSFET on 4H-SiC: **Thermal N_2O /100nm TEOS / 950ºC O_2**





- Current higher than usual (x4 compared to LiU S230)
- Threshold voltage: in the range –1V / 0.5V (short/long channel)
- Channel mobility: 40- 45 cm^2/Vs (on epilayer layer annealed at 1600°C)
- Stable up to 15V

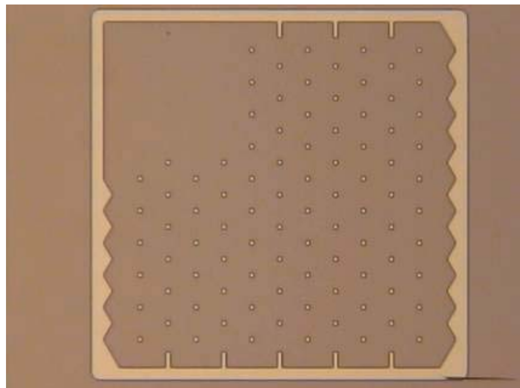
ESCAPEE CURRENT STATUS:

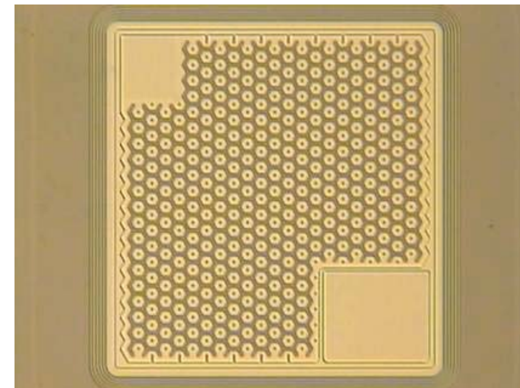
1.2 kV Schottky diodes process stable with good yield

3.5 kV Schottky diodes process repetitive: yield depends on wafer quality

Gate dielectric with channel mobility on implanted layer: 50 cm^2/Vs

1.2 kV and 3.5 kV Power MOSFETs in processing





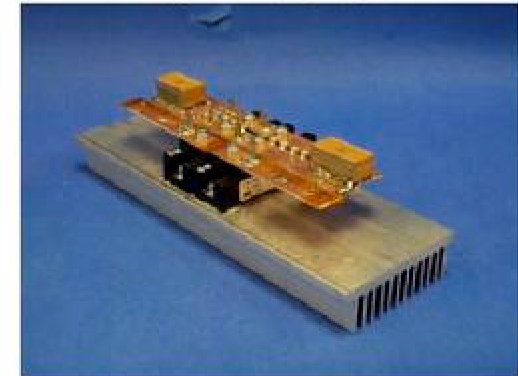
Si/SiC hybride modules

GE/Powerex Si IGBT/SiC Diodes:
Si Powerex PT IGBT: 600V/1200V, 75A
Single Chip
SiC GE Diode: 600V, 20A, 6 Dies in ||
Each Die is a 5µm Epi, Medium Size
800µmx800µm

Application benefits ...

Si/SiC Inverter

All Si Inverter



DC Bus Voltage	100V	150V	200V	250V
Load Input Power	114W	250W	440W	690W
Hybrid Si/SiC Efficiency	**90.6%**	**96.3%**	**97.5%**	**97.8%**
All Si Inverter Efficiency	**92%**	**92.7%**	**95.5%**	**97.1%**

DARPA/GE SiC Megawatt