Silicon Carbide for Power Semiconductor Devices

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Outline

- Introduction
- SiC properties
- 10V-300V: SiC or Si
- 300V-3500V : Unipolar devices:
- > 3500V: Bipolar devices ?
- Future Trends

What is Driving Future Power Electronics?

- Power electronics holds the key to annual **energy savings** of around $400 billion!
- **Lightweight**, high performance products such as **mobile** computing, home entertainment and power tools
- High efficiency, **high power density** electric drives in products such as air conditioning
- Proliferation of **automotive and aerospace** electronic systems
- Increased use of power electronics in transmission and distribution systems
- Energy storage systems
- …

Introduction

- Increased power densities
- Lower electromagnetic emissions
- Plug-and-go systems
- Extreme operating environments
- Higher levels of integration
- Lower cost

Moore law for power devices:
Doubling frequency and power density every 4.5 years

Why SIC ?

- Si devices are generally limited to operation at junction temperatures in the range of 200ºC.
- Si power devices not suitable at very high frequencies.
- SiC, GaN and Diamond offer the potential to overcome both the temperature, frequency and power management limitations of Si.
- At present, SiC is considered to have the best trade-off between properties and commercial maturity with considerable potential for both HTE and high power devices.

Why SIC ?

Physical properties of various semiconductors for power devices

Material	*Eg (eV) @300K*	μ_n $(cm^2/V.s)$	μ_p $(cm^2/V.s)$	v_{sat} (cm/s)	*Ec (V/cm)*	λ $(W/cm.K)$	ε_r
Si	1.12	1450	450	10^7	3×10^5	1.3	11.7
GaAs	1.4	8500	400	2×10^7	4×10^5	0.54	12.9
3C – SiC	2.3	1000	45	2.5×10^7	2×10^6	5	9.6
6H – SiC	2.9	415	90	2×10^7	2.5×10^6	5	9.7
4H - SiC	3.2	950	115	2×10^7	3×10^6	5	10
GaN	3.39	1000	350	2×10^7	5×10^6	1.3	8.9
GaP	2.26	250	150		10^7	1.1	11.1
Diamond	5.6	2200	1800	3×10^7	5.6×10^7	20	5.7

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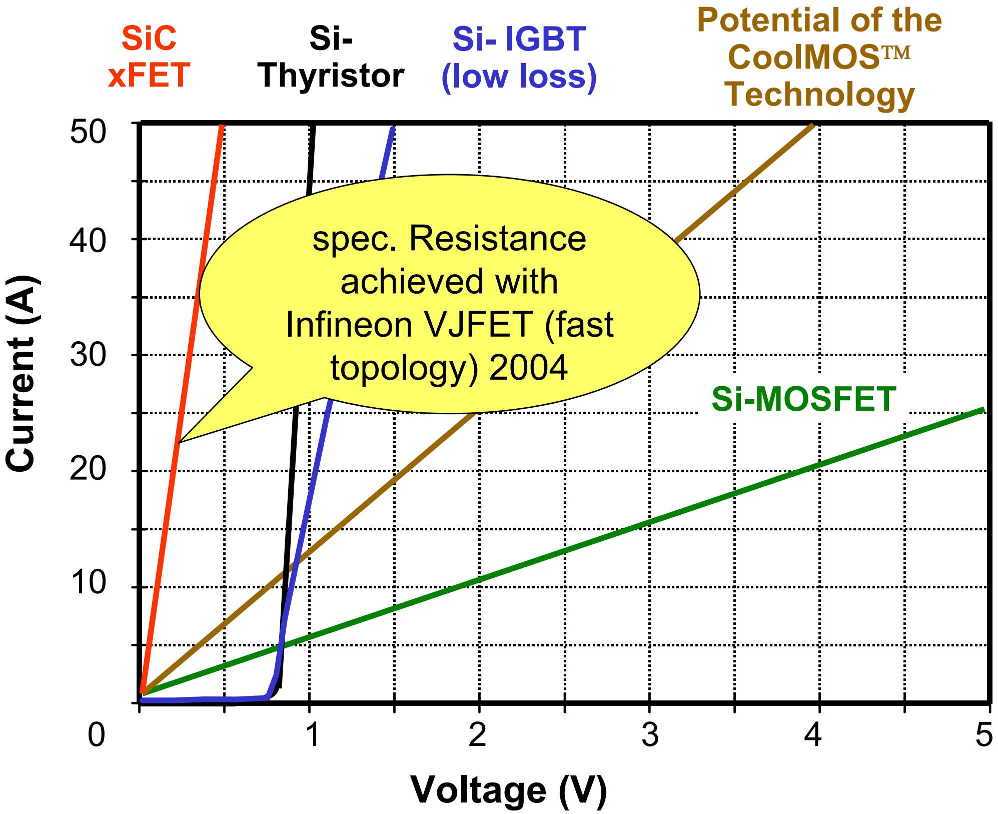
Introduction



spec. Resistance achieved with Infineon VJFET (fast topology) 2004

Blocking voltage

1000 V

Chipsize

1 cm²

Losses at 50A

P = U x I

500W

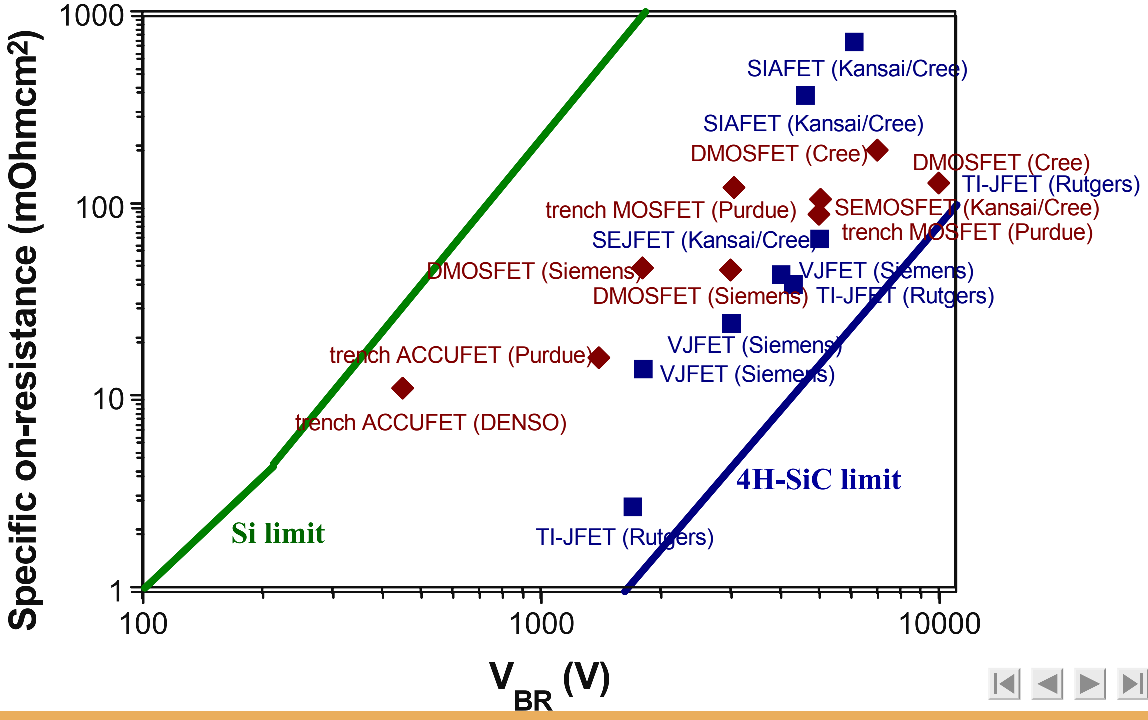
200W

75W

50W

25W

Introduction



SiC Material

- Achievements in SiC bulk material growth and in SiC process technology.
  - 3” SiC wafers with very low micropipe density (0.75 cm^{-2}) available in the market → high yield manufacturing process of large area SiC power devices.
  - 4” SiC wafers are already in the market and it is expected that the very low micropipe density target will be achieved soon.
  - 6” SiC wafers in 2008

- GaN: 2” wafers (poor quality, high cost)
  Diamond: 1cm x 1cm samples

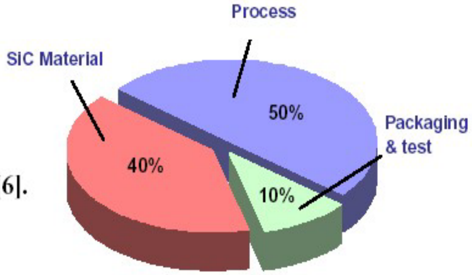
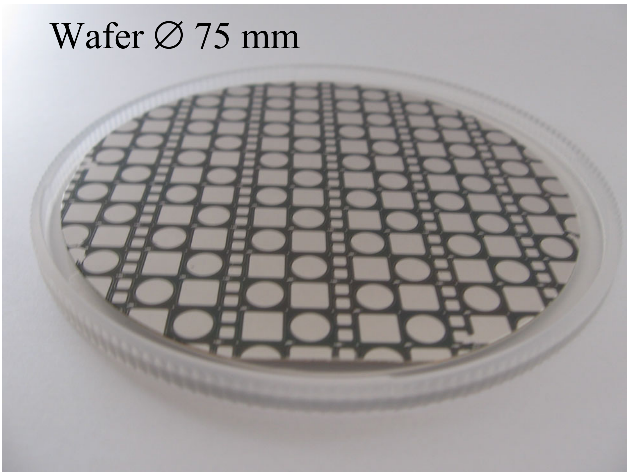
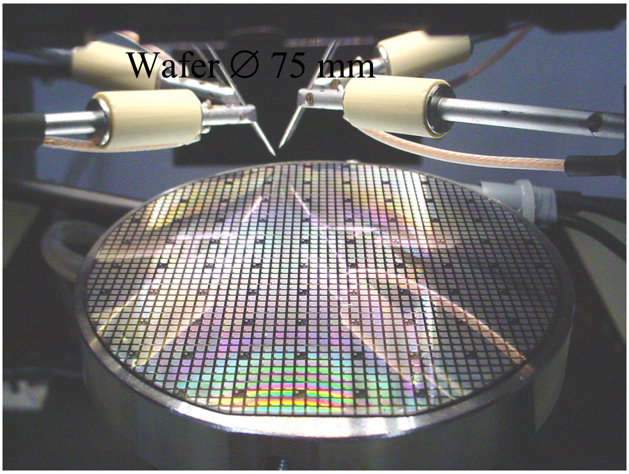


Fig. 5.8. Typical cost breakdown for SiC devices [6].

Introduction



CNM large area diodes
2.56 < diodes area < 25 mm^2



SiCED-Infineon commercial JFETs
1 < JFETs area < 1.25 mm^2

Commercially available SiC devices and testing samples

Schottky diodes, MESFETs

Schottky diodes

JFETs testing samples

JFETs and hybrid cascode testing samples

Advanced R&D programs

DENSO

Kansai Electric Power (Kepco)

Acreo

Rockwell

United Silicon Carbide Inc

Si power devices

10V – 200V : Schottky, MOSFET

300V-1000V: PiN
MOSFET/CoolMOS Fast switching
IGBT

1200V – 6500V
PiN
IGBT Gate control
GTO High current

> 6500V Serie connections

Unipolar devices: 10V-200V

Low voltage range:

10V -200V

Unipolar devices: 10V-200V

- Difficult to compete with Si
- High temperature applications could be covered by SOI

- High power - high frequency RF devices in SiC and GaN
- Low on resistance GaN switch

Medium voltage range:

300V – 3500V

- SMPS
- Motor integrated drives
- Hybrid cars (300-500V – 250C)
- More electric aircraft (270-800V – 300C)
- Space power applications

SiC Unipolar devices

SiC Schottky Diodes

- SiC SBDs commercially available since 2001. They range from the initial 300 V-10 A and 600 V- 6 A to 20 A and recently 1.2 kV.

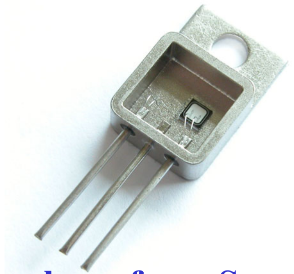
- SBDs can be advantageously applied for blocking voltages up to 3.5kV.

- Large area 3.5 kV – 10/20A SBDs demonstrated at CNM

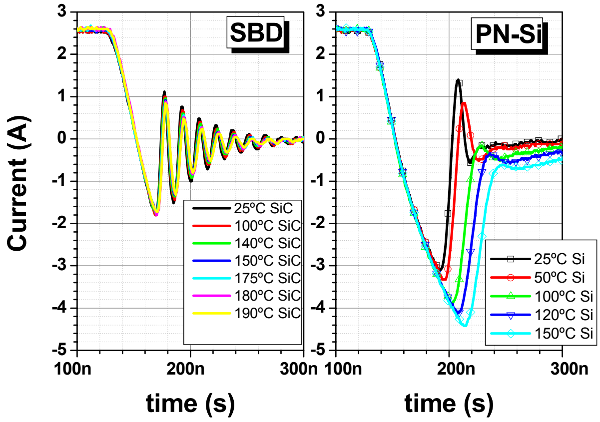
The 25 mm^2 SBDs exhibit a leakage current of 100 µA @ 2 kV.

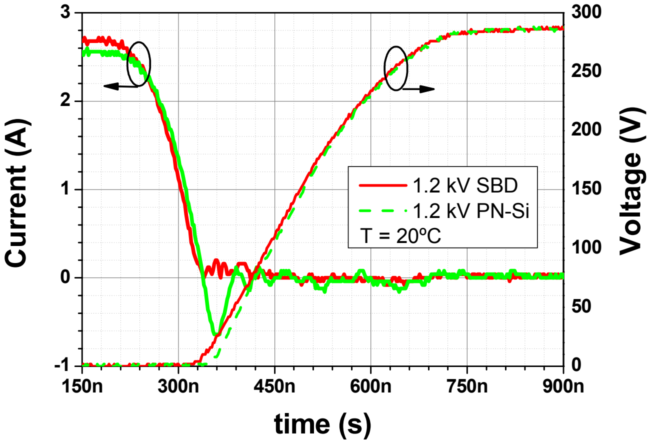
Manufacturer	V_{BR}	I_N	V_f	I_R
CREE	600V	10A	2V@175ºC	100uA
	1200V	5A	2.6V@150ºC	100uA
	1200V	20A	2.5V@150ºC	20uA
Infineon	300V	10A	1.5V@150ºC	20uA
	600V	4A,	2V@150ºC	4uA
	600V	16A	1.7V@150ºC	10uA
Microsemi	200V- 600V	1A 4A	1.6V@25ºC 1.7V@25ºC	20uA 20uA

Unipolar devices: 300V-3500V



HT package from Semelab

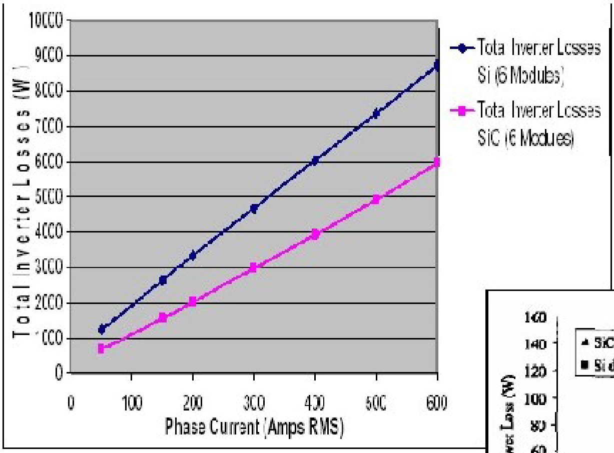


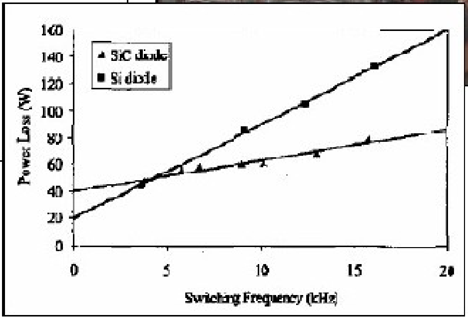


1.2kV Schottky

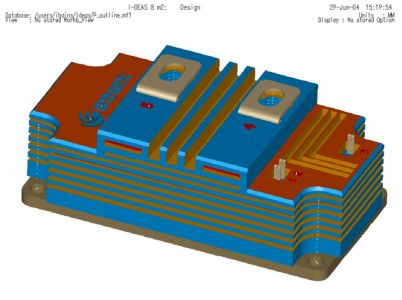
Unipolar devices: 300V-3500V

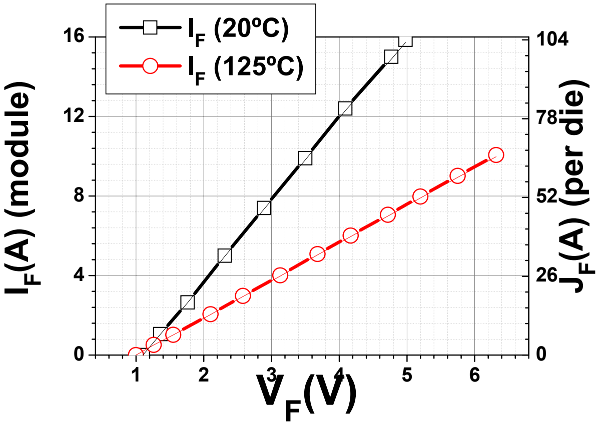
Predicted Losses Hybrid Si-SiC Inverter vs. all Si @ 12 kHz Switching Frequency, Tj=90°C

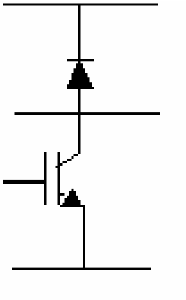


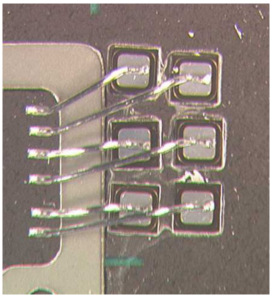


3.5kV: a limit for SiC Schottky diodes









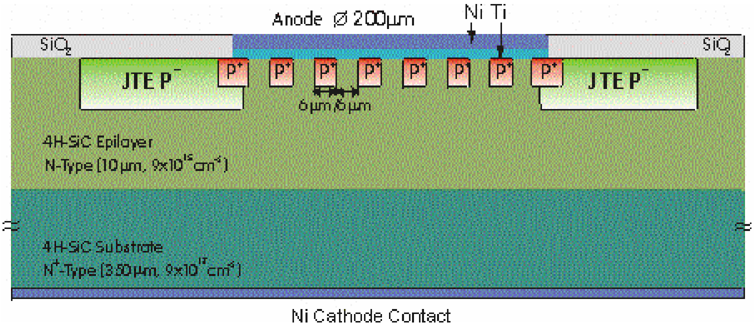
4.5kV Si IGBT + SiC Schottky module

SiC Junction Barrier Schottky diode

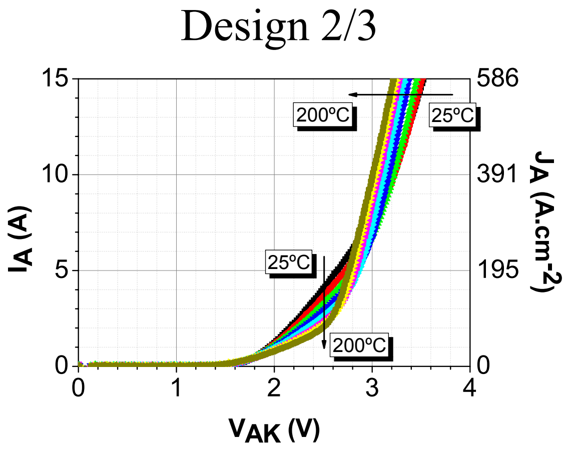
- Mixed Schottky diode + PiN diode:

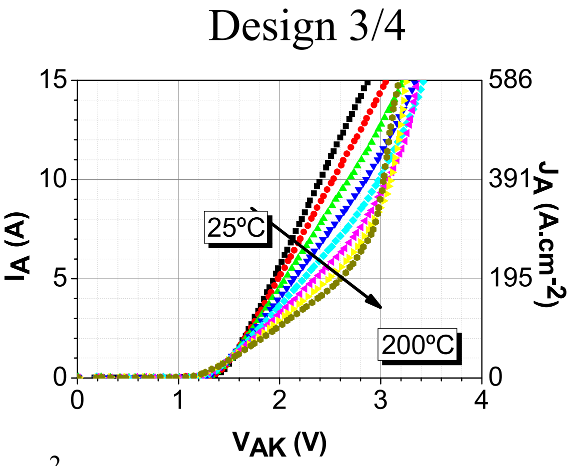
The reverse leakage well maintained closer to the PiN diode level but showing forward current densities reasonably lower (20-30%) than those of the SBDs.

In forward mode at high temperature, the bipolar mode allows a moderate current decreases unlike in pure Schottky.



SiC Junction Barrier Schottky diode

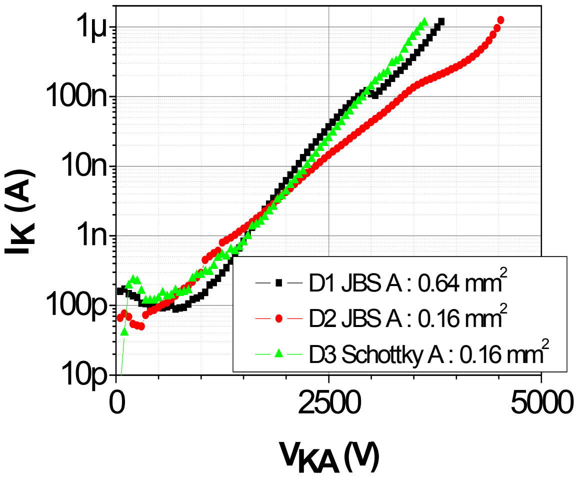




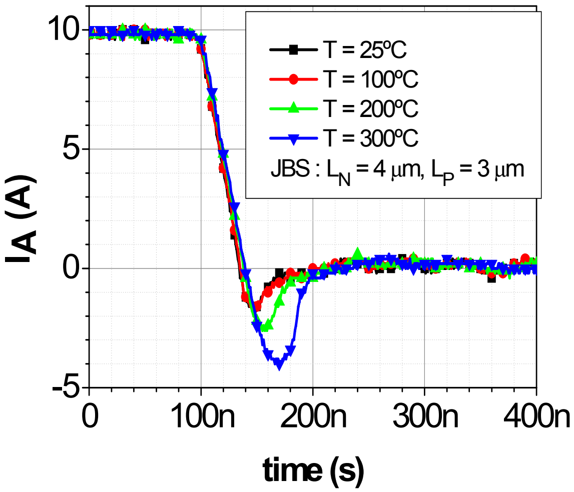
S = 2.56 mm^2

- 1.2kV - 6A packaged JBS
- Good performance in temperature
- Temperature behaviour depends of the JBS diode design
- 10 A diodes have been realised

SiC Junction Barrier Schottky diode



Reverse characteristics of the 4H-SiC JBS of various areas fabricated at CNM.



Turn-off current waveforms of the JBS diode (2.56 mm², Ln=4µm, Lp=3µm) at different temperatures.

SiC Junction Barrier Schottky diode

- Interest in reverse mode (lower leakage current + avalanche mode operation)
- Interest at high temperature: on-state is lower than equivalent Schottky at 200ºC
- Interest for its surge current capability
- Interest for the 2.5-5kV range compared to pure Schottky
- Problem of forward mode degradation (Stacking faults) ??

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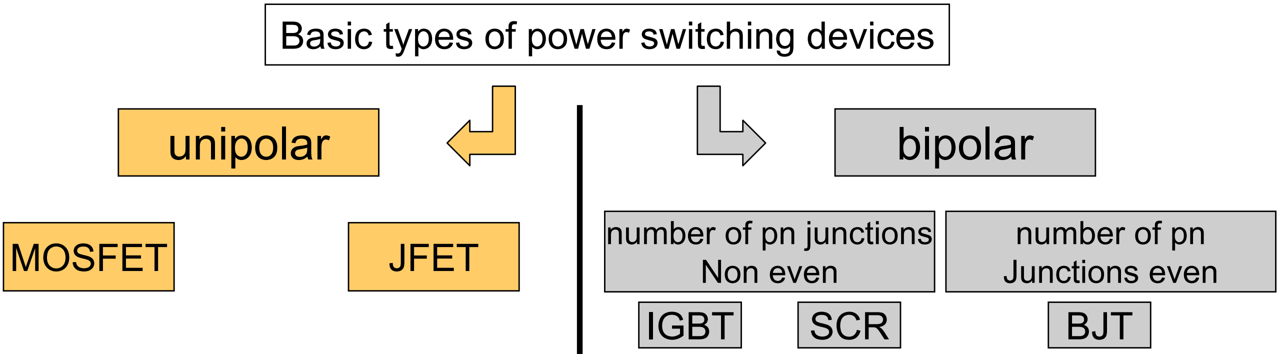
New generation of Infineon “Schottky“ diodes

SiC Power Switches



Basic types of power switching devices

unipolar

MOSFET

JFET

- ⇨ potential in SiC very high
- ⇨ fast and low loss devices possible
- ⇨ technological maturity achieved
- ⇨ applications with high volume already today visible

bipolar

number of pn junctions Non even

IGBT

SCR

number of pn Junctions even

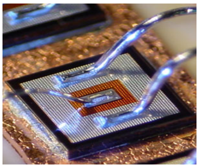
BJT

- ⇨ potential for SiC only for very high V_{br} (> 4 ... 10...kV)

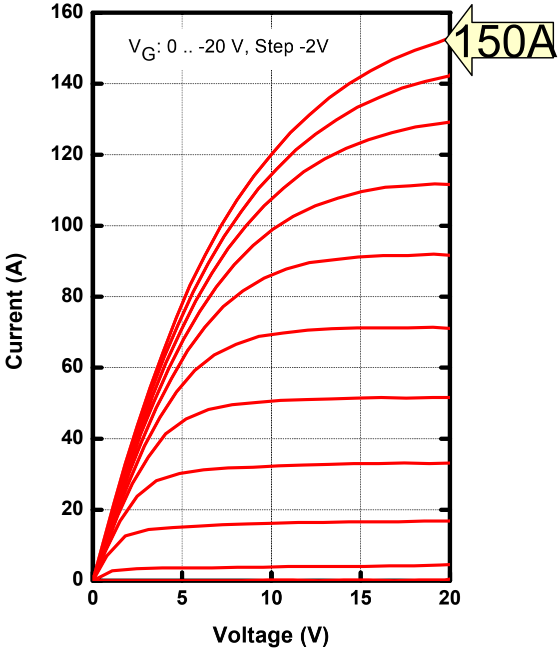
Reasons :

1. Band gap approx. 3eV
   ⇨ high threshold (IGBT, SCR , BJT)
2. P-Type acceptors with E_a >200meV
   ⇨ high p-resistivity
   ⇨ low current gain

Unipolar devices: 300V-3500V



INFINEON - SICED
50A 1200V SiC VJFET
R_{on} @25°C typ. 50mΩ



JFET

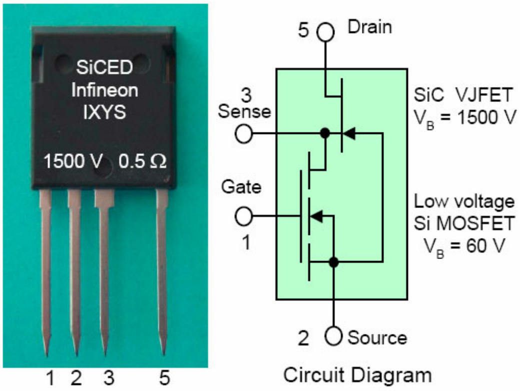
➕

- very low R_{on}-values possible
- rugged Gate-structure
- excellent short circuit capability
- high temperatures possible

➖

- unconventional technology
- normally on (?)
- new gate control

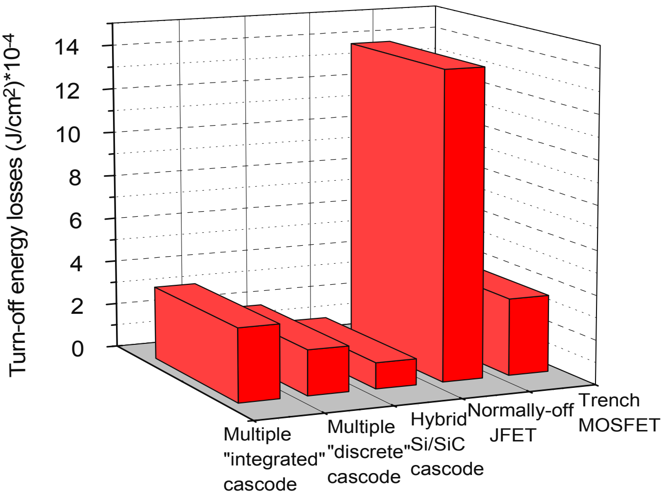
SiCED hybrid Si/SiC cascode electronic switch



Circuit Diagram

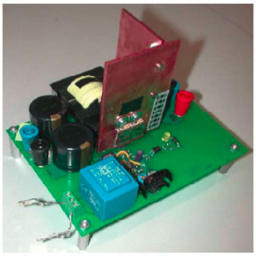
- 15 mΩcm^2 specific on-resistance (25°C)
- High short circuit capability (>200 μs)
- Power almost totally at SiC VJFET
- High T_J capability (175°C)

Single switch fly-back converter built using Si/SiC cascode



The hybrid Si/SiC cascode combination is the most efficient one

SiCED hybrid Si/SiC cascode electronic switch



Compared to a COOLMOS-based converter, the SiC-based one offers the highest efficiency (about 90%)

All SiC sparse matrix converter: 100KHz – 1.5kW – efficiency 94%

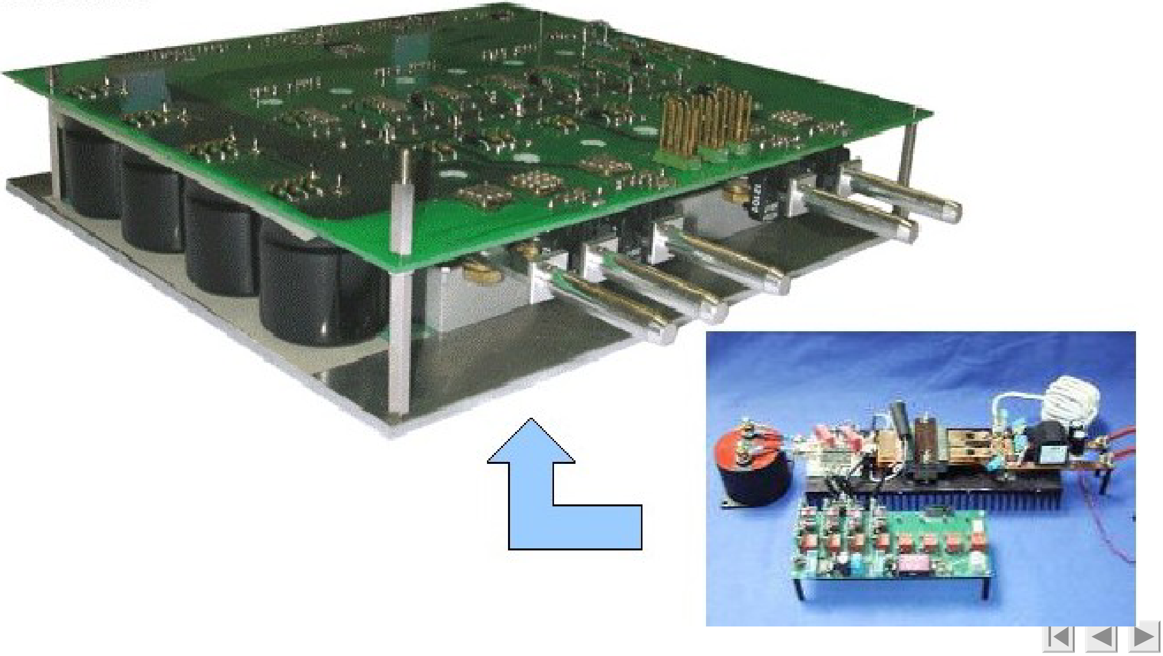
1300V 4A SiCED Cascodes + 1200V 5A CREE Schottky diodes

More Electric Aircraft: 3 phases PWM rectifier 10kW – 500KHz – 480V

CoolMOS + SiC Schottky diodes : efficiency higher than 96%

Volume: 30% power circuit + cooling / 30% electrolitic capacitors / 30% EMC filter

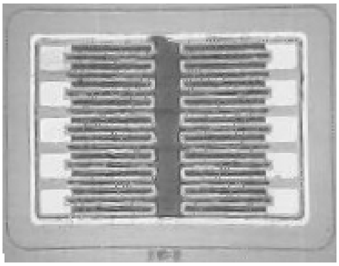
Hardware design study: Propulsion inverter approx 20 kW using SiC power elements from industrial preassembly process line

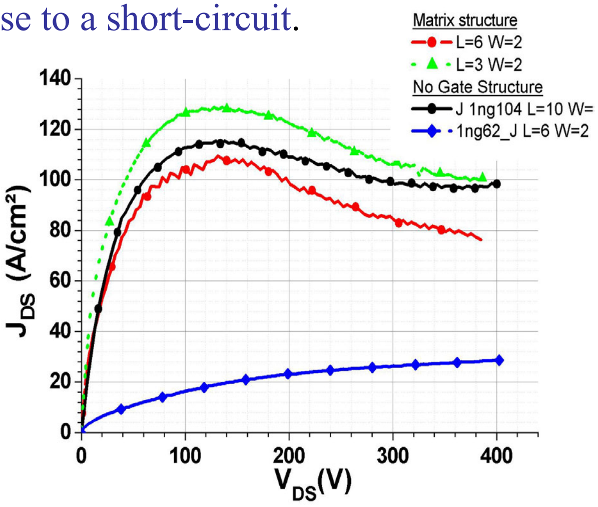


JFETs for Current Limiting for Power System Protection

- Efficiency of both devices checked under working conditions: connected to the mains.
- The current limiter is plugged in series with the power supply and the load (230V/5w bulbs).
- SiC VJFET experimental response to a short-circuit.

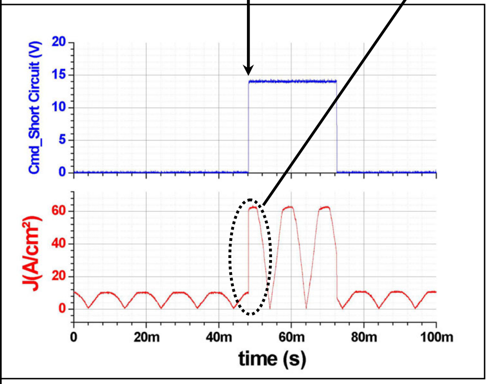
CNM VJFET

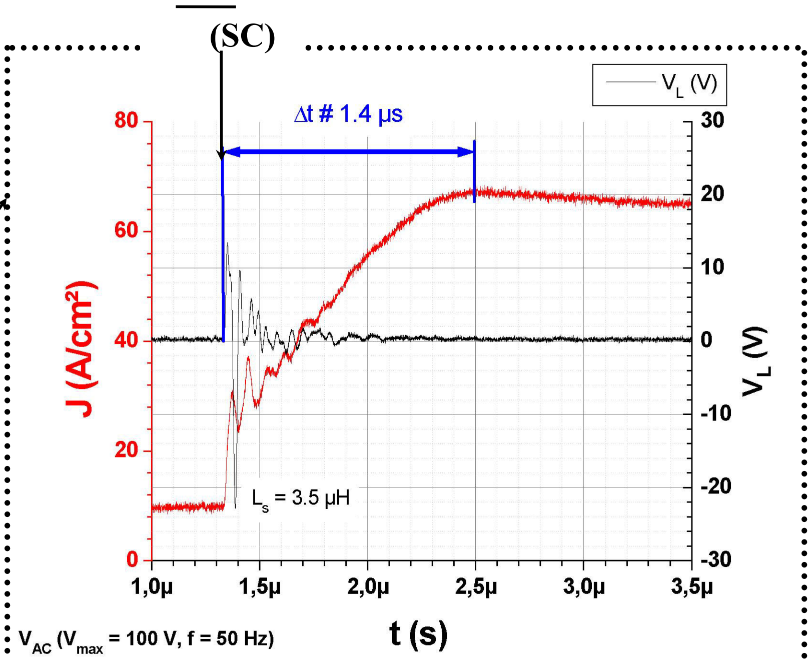




Short circuit protection demonstration :Transient wave form (measurements)

Short circuit (SC)



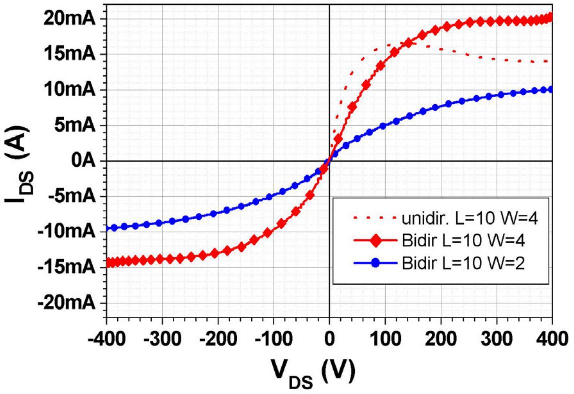


Fast current stabilisation : 1.4 µs

Unipolar devices: 300V-3500V

INTEGRATION

2D-Directional current limiter made of two devices monothically integrated



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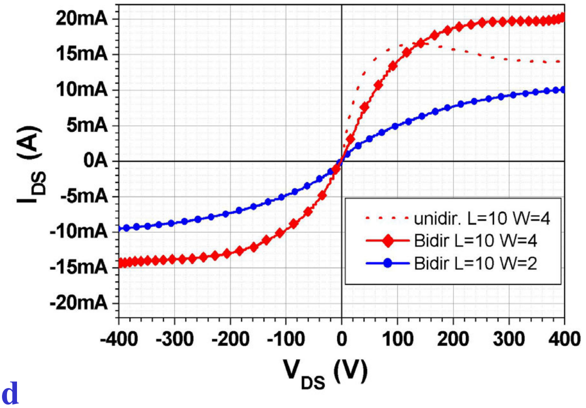
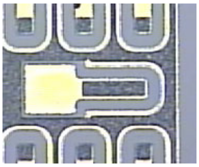
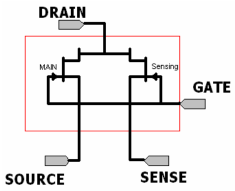
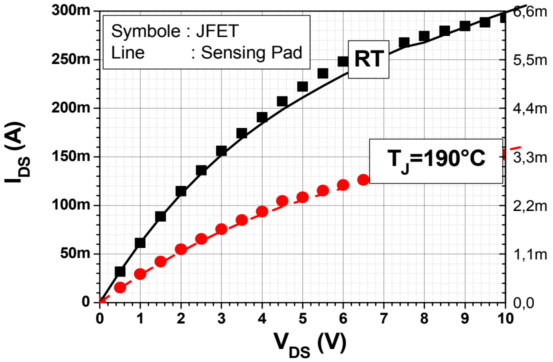


Current sensor integrated with VJFET





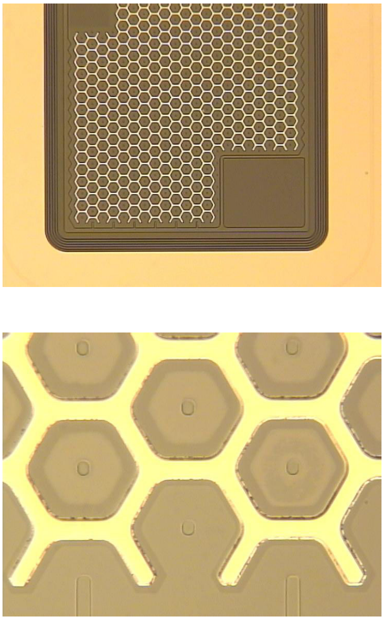


Current sensor reflect perfectly the main current of the JFET

Current sensor can be also used as temperature sensor

Unipolar devices: 300V-3500V

MOSFET



CNM 3.5KV MOSFET

+

- Simple planar structrue
- Voltage gate control
- Extensively used in Si technology
- Normally off

−

- Low channel mobility in SiC
- High temperature operation ?
- Gate reliability ?

SiC Power MOSFET

CREE:

- **2.3KV-5A R_{on}=0.48 ohm** (25ºC) 13.5mohm.cm^2 , I_r=200uA

C_{in}=380pF, C_{out}=100pF, reverse transfer C=19pF (V_{gs}=0, V_{ds}=25V, 1MHz)

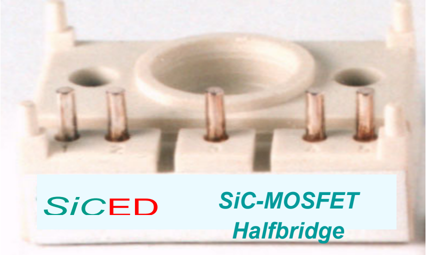
Infineon:

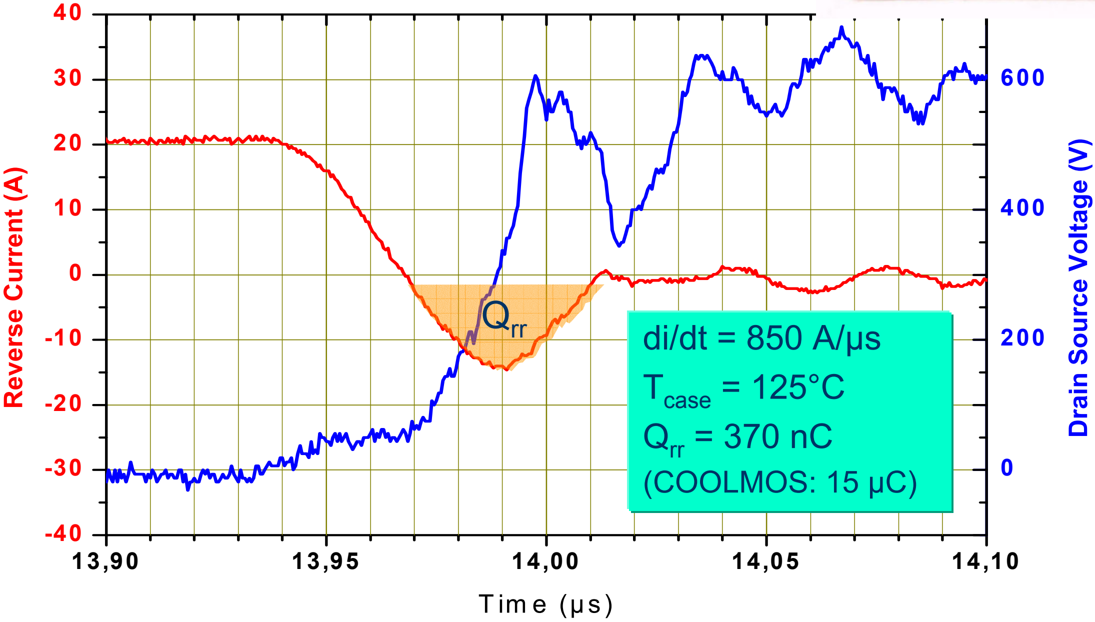
- **1200V-10A, R_{on}=0.27 ohm** (25ºC) 12mohm.cm^2

Denso:

- **1200V-10A, 5 mohm.cm^2** (25ºC),
- 8.5mohm.cm^2 (150ºC)

1200 V MOSFET (SICED): Built-in Diode Turn-off





di/dt = 850 A/µs

T_{case} = 125°C

Q_{rr} = 370 nC

(COOLMOS: 15 µC)

Bipolar devices: 3500V-6500V

> 3.5 KV

- Utilities / Power distribution
- Military platforms
- Traction / Transport

Bipolar devices ?

SiC Rectifiers-PiN Diodes

- **Main problem**: reliability due to V_F drift created by stacking faults

SiC Rectifiers-PiN Diodes

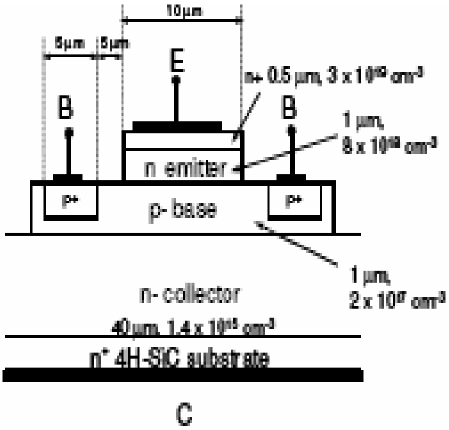
- **Main problem**: reliability due to V_F drift created by stacking faults
- The state-of-the-art device is a Cree 4.5 kV 4H-SiC PiN diode:
  - $V_F = 3.2$ V at 180 A (100 A/cm^2)
  - $I_R = 1$ µA @ 4.5 kV
  - Chip area = 1.5 cm × 1.5 cm
  - At a dI/dt = 300 A/µs, the diode shows a reverse recovery time of 320 ns.

  - 57% of diodes show no measurable increase in V_F following a 120 hours DC stress at 90 A.

SiC Bipolar Transistor

- Unlike Si BJTs, SiC BJTs do not suffer from secondary breakdown.

- State-of-the-art BJT [S. Krishnaswami et al., ISPSD'2006, pp. 289-292]
  - 4 kV, 10 A BJT
  - $\beta_{\mathbf{max}} = 34$
  - Chip area = 4.24 mm × 4.24 mm
  - I_R =50 µA @ 4.7 kV
  - turn-on time = 168 ns @ RT
  - turn-off time = 106 ns @ RT



It will take some time to industrialize HV bipolar SiC switches

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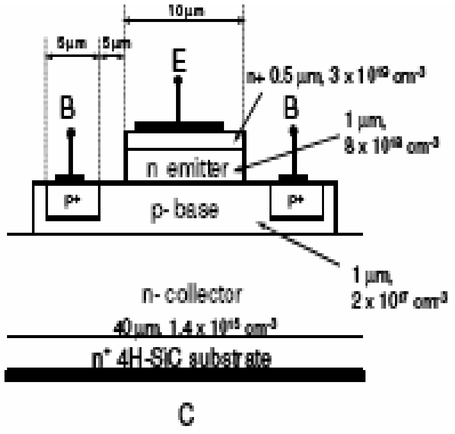
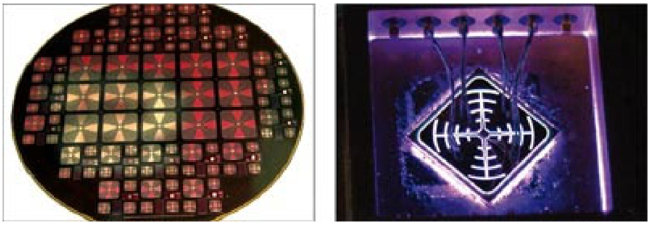


– β ⇓50% under forward stress: stacking faults in the base-emitter region

It will take some time to industrialize HV bipolar SiC switches

SiC Thyristor

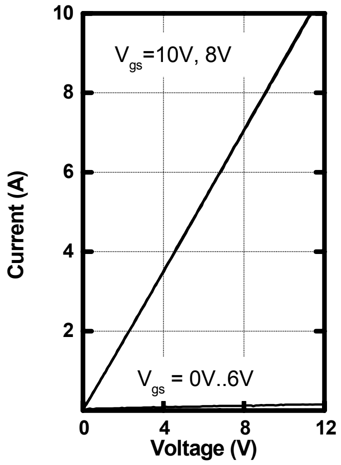
- State-of-the-art SiC Thyristor
  - 4.5 kV, 120 A SICGT (SiC Commutated Gate turn-off Thyristor)
  - Chip area 1cm x 1cm
  - $I_R < 5\times10^{-6}$ A/cm^2 @ 4.5 kV and 250ºC
  - turn-on time = 0.2 µs - turn-off time = 1.7 µs
  - Coated with a new high heat resistive resin capable of operating at 400ºC

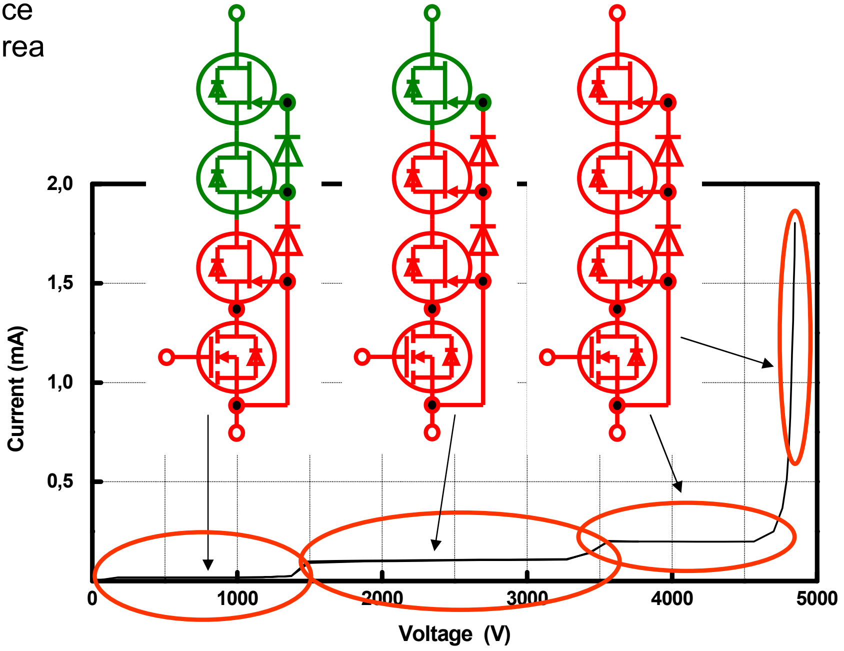


- 110 kVA PWM 3 phase inverter demonstrator using six SICGT modules (one SICGT + two 6 mm × 6 mm SiC pn diodes in a metal package). 2us turn-off time – No snubber

SiC JFET Multi-cascode

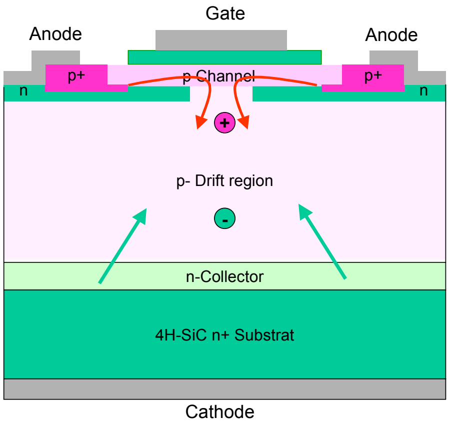
Example: 4.5kV, 3-stage device ((1.15 Ω) 8,2mm² active SiC area in each stack, ECSCRM 02)

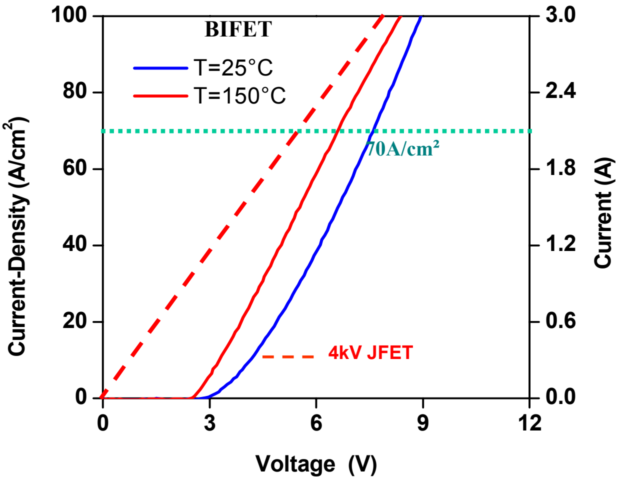




Semikron switch: 8KV – 10A – 2 ohms

SiC Bipolar-JFET





Carrier lifetime in p - epilayers has to be increased well above 1 μs to reduce the forward voltage

Tail current turn-off behaviour shows a long relaxation time increasing with temperature due to the not yet optimised gate control region.

10kV SiC Power MOSFET

- State-of-the-art SiC power MOSFET [S-H. Ryu, et al., ISPSD'2006]

10 kV, 5 A 4H SiC power DMOSFET

- 100 µm thick n-type epilayer (6×10^{14} cm^{-3})
- Thermally grown gate oxide, NO annealed
- Peak effective channel mobility: 13 $cm^2/V.s$
- Active area: 0.15 cm^2
- R_{on} = 111 $m\Omega.cm^2$ @ RT and V_G = 15 V

Bipolar devices: 3500V-6500V

SiC IGBT ???

Problems of MOSFETS (Channel mobility, reliability)
+ Problems of Bipolar (current gain, degradation (stacking faults)
+ Problems of highly doped P substrate growth

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September 2006: CREE 10kV P-channel IGBT

- 3V + 20 mΩ x cm^2
- V_F =3.9V at 10A instead of 4.4V for the VDMOS
- Improvement of channel mobility and conductivity modulation possible

Future Trends

Question was: Will SiC be useful for power electronics ?

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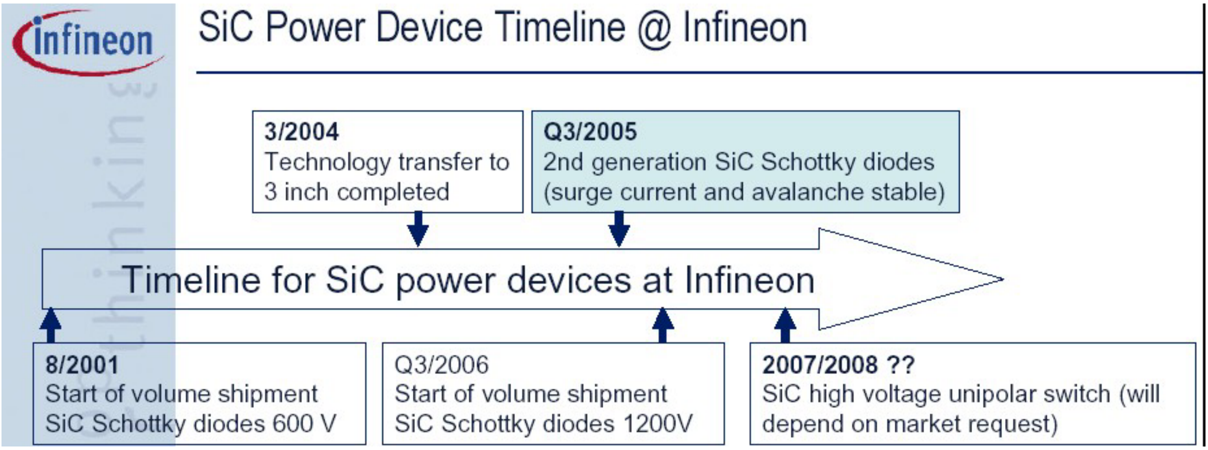


SiC Power Device Timeline @ Infineon

Timeline for SiC power devices at Infineon

8/2001
Start of volume shipment
SiC Schottky diodes 600 V

3/2004
Technology transfer to
3 inch completed

Q3/2005
2nd generation SiC Schottky diodes
(surge current and avalanche stable)

Q3/2006
Start of volume shipment
SiC Schottky diodes 1200V

2007/2008 ??
SiC high voltage unipolar switch (will
depend on market request)

Source: ECPE "Sic User Forum" march 2006 – Complete presentation available

Future Trends

Question was: Will SiC be useful for power electronics ?

Question is: When SiC will enter in power electronic ?

Expected roadmap: > 3.5 KV

1 cm^2 10kV IGBT and PiN Diode chips affordable for prototypes will be available by 2008
Production of degradation-free bipolar SiC devices by 2009
Stabilised production grade SiC devices available in 2010

Source: ECPE “Sic User Forum” march 2006 – Complete presentation available

Future Trends

SiC rectifiers

- Schottky and now JBS diodes are commercially available up to 1.2 kV.
- PiN diodes will be only relevant for BV over 3kV.
  - Need to overcome its reliability problem (forward voltage drift) before commercialisation

Future Trends

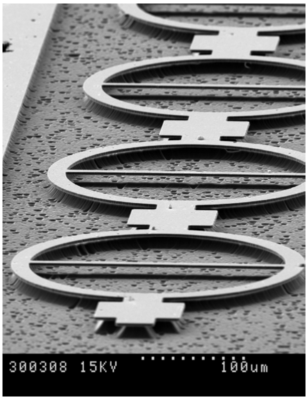
SiC Switches

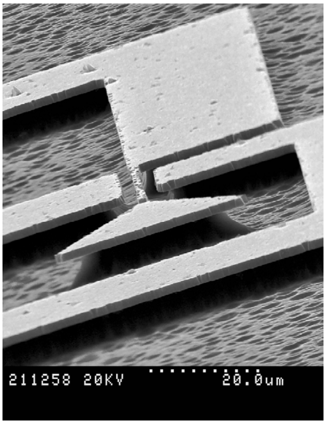
- Commercialization of the cascode pair (a high-voltage, normally-on SiC JFET + a low-voltage Si MOSFET).
- BJTs/Darlingtons are promising, they also suffer from reliability problems.
- A normally-off SiC switch is expected. It could be the SiC MOSFET (<5kV) or the SiC IGBT (>5kV).
- A normally-off SiC power transistor commercially available within next two years in the BV range of 600V-1200V.

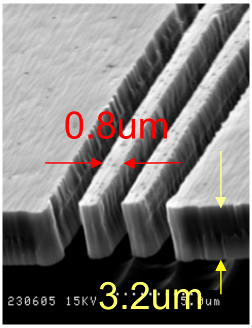
Future Trends

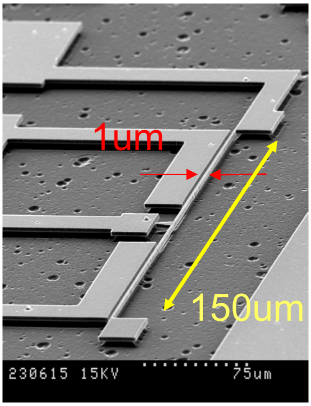
SiC MEMS

Higher young modulus (x3)
Higher yield strength (x3)





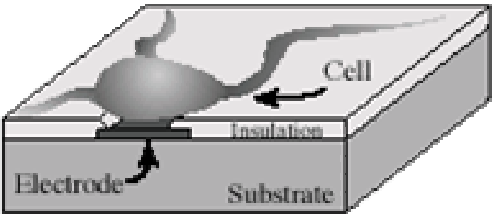


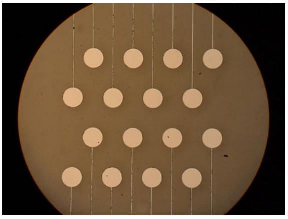


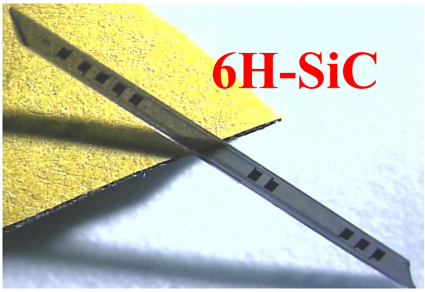
Future Trends

SiC advantages for biomedical devices

Biocompatibility – higher hardness – higher resistivity transparency







In-vivo measurement of impedance and pH of tissues in organs

Conclusions

Conditions affecting the market volume for SiC power devices:

+ Technical advantages and realised device performance

+ Improved system efficiency by using SiC power devices

− Higher device costs (mainly dominated by substrate costs)

− New packaging development (material, technology & reliability)

− Application of new circuit concepts

+/− Silicon answers to the challenges of SiC (CoolMOS; Trench IGBT…)

The development of future power electronics with higher power densities will cause an increasing market penetration of SiC power devices.

ECSCRM 2008

7th European Conference on Silicon Carbide and Related Materials

Barcelona
September 7th – 11th 2008