Status of SiC high voltage device technology

Mikael Östling,
KTH Royal Institute of Technology, Sweden

Outline

1. Introduction

2. Device Review (JFET, MOSFET, BJT)

3. 6 kV-Class BJTs

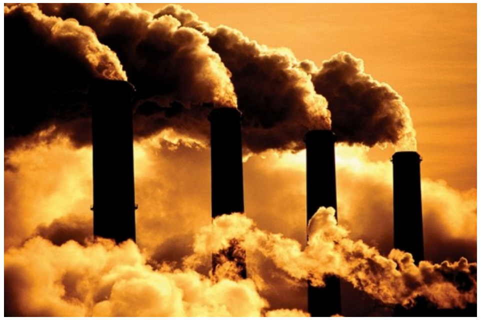
4. 15 kV-Class BJTs

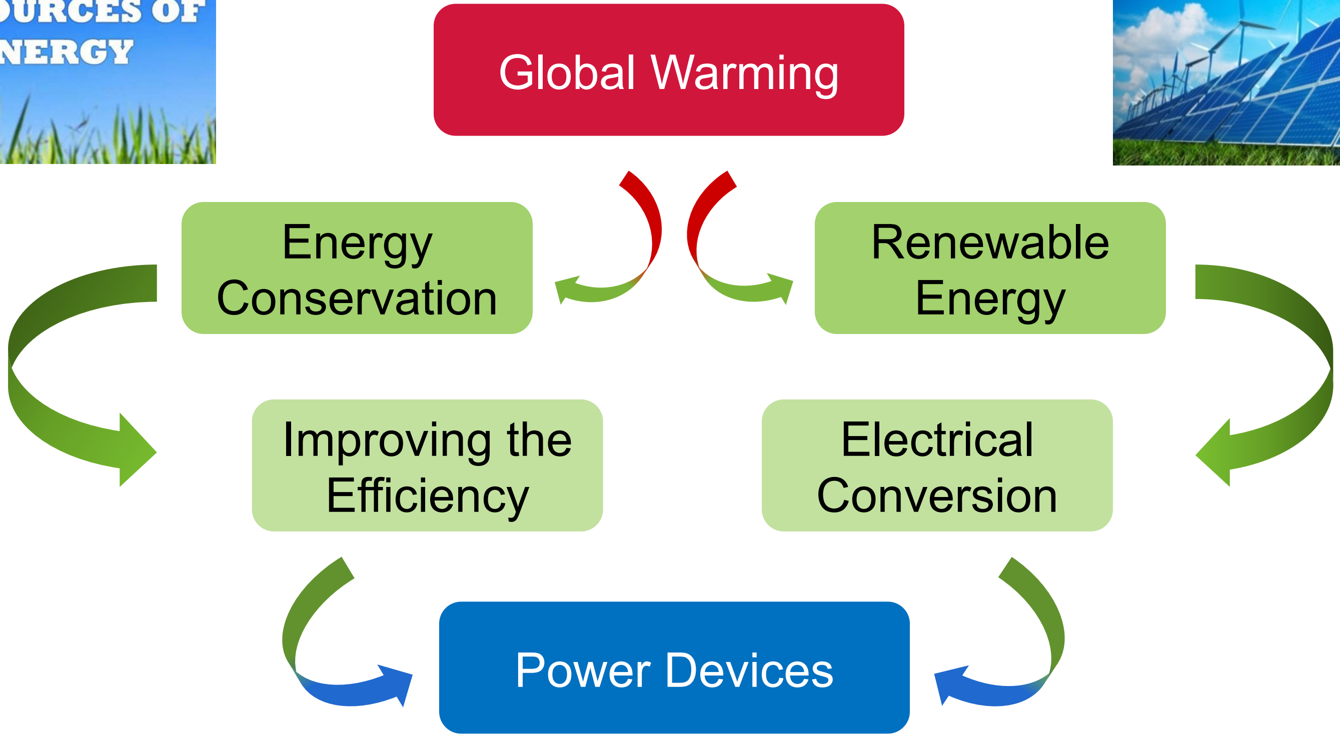
5. HT & harsh environments

6. Summary

Outline

1. Introduction
2. Device Review (JFET, MOSFET, BJT)
3. 6 kV-Class BJTs
4. 15 kV-Class BJTs
5. HT & harsh environments
6. Summary

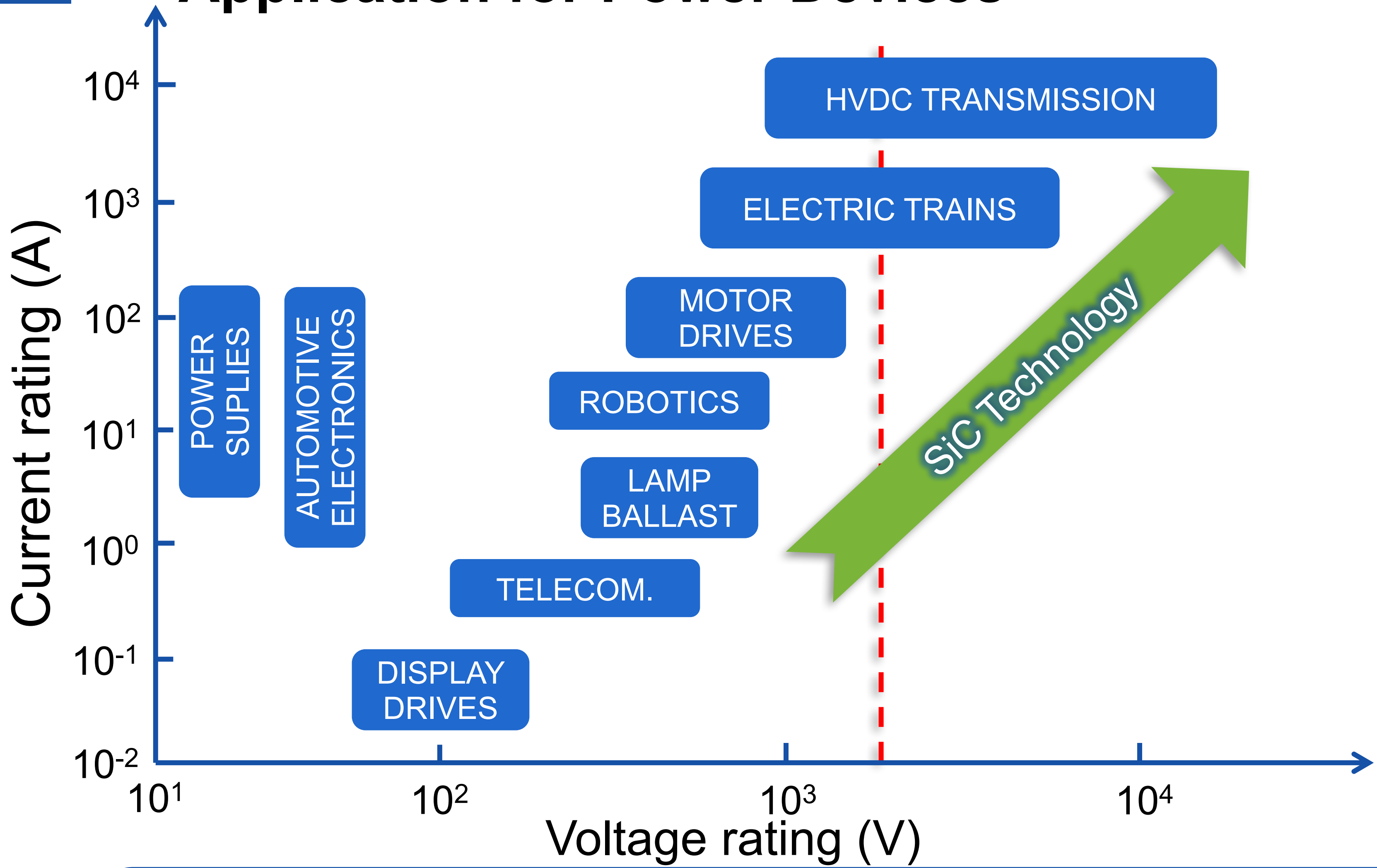




At least 50 % of the electricity used in the world is controlled by Power Devices.

B.J. Baliga, Advanced High Voltage Power Device Concepts, Springer

Application for Power Devices



SiC Device Roadmap

Going for more compactness for power converters

Going for more technological maturity

Years	Si 4.5 kV IGBT or BIGT	4H-SiC 1.2 - 1.7 kV MOSFET JFET/BJT	4H-SiC 3.3 kV MOSFET	4H-SiC 6.5 kV MOSFET IGBT	4H-SiC 10.0 kV MOSFET IGBT	4H-SiC 15.0 kV IGBT	4H-SiC 20 – 30 kV IGBT GTO	AlN/ Diamond 30 – 50 kV IGBT/GTO
2016	√√√	√√	√	x	x	x	x	x
2018	√√√	√√√	√√	√	x	x	x	x
2020	√√√	√√√	√√	√	√	x	x	x
2022	√√√	√√√	√√√	√√	√√	√	√	x
2024	√√√	√√√	√√√	√√√	√√√	√√√	√√	√

- x Fundamental potential exist but technological solution is not ready yet
- √ Engineering die samples available. Probably not qualified chip. Complete package solution may not be ready yet.
- √ √ Qualified chip ready. Complete package solution probably ready to be tested in the field.
- √ √ √ Fully mature and qualified chip is available along with qualified packaged power module to be tested in the field.

Source: Dr. Muhammad Nawaz, ABB, ESCDERC 2016 but modified

Price Scenario SiC

	1.2kV	1.7kV	3.3kV	4.5kV	6.5kV	10kV	15kV
Drift layer doping [cm^{-3}]	1×10^{16}	7×10^{15}	3×10^{15}	2×10^{15}	1.2×10^{15}	7×10^{14}	4×10^{14}
Drift layer thickness [µm]	10	15	30	40	60	95	145
R_{onsp} [mohm-cm^2]	1.7	2.5	7.8	14.5	34.0	89.1	237.8
Chip Area [mm^2]	3.7	4.5	8.0	11.0	17.3	29.5	50.9
Yield [%]	86.8	86	83	80.6	75.7	67	54
Packing factor	0.945	0.939	0.925	0.914	0.902	0.890	0.846
Price for 150 mm SiC + epilayer [$]	800	881	1126	1289	1615	2185	3000
Price per Amp ($/A) (50% Gross margin assumed)							
Price ($/A) for 20 A max.	0.046	0.061	0.131	0.203	0.399	0.960	2.744

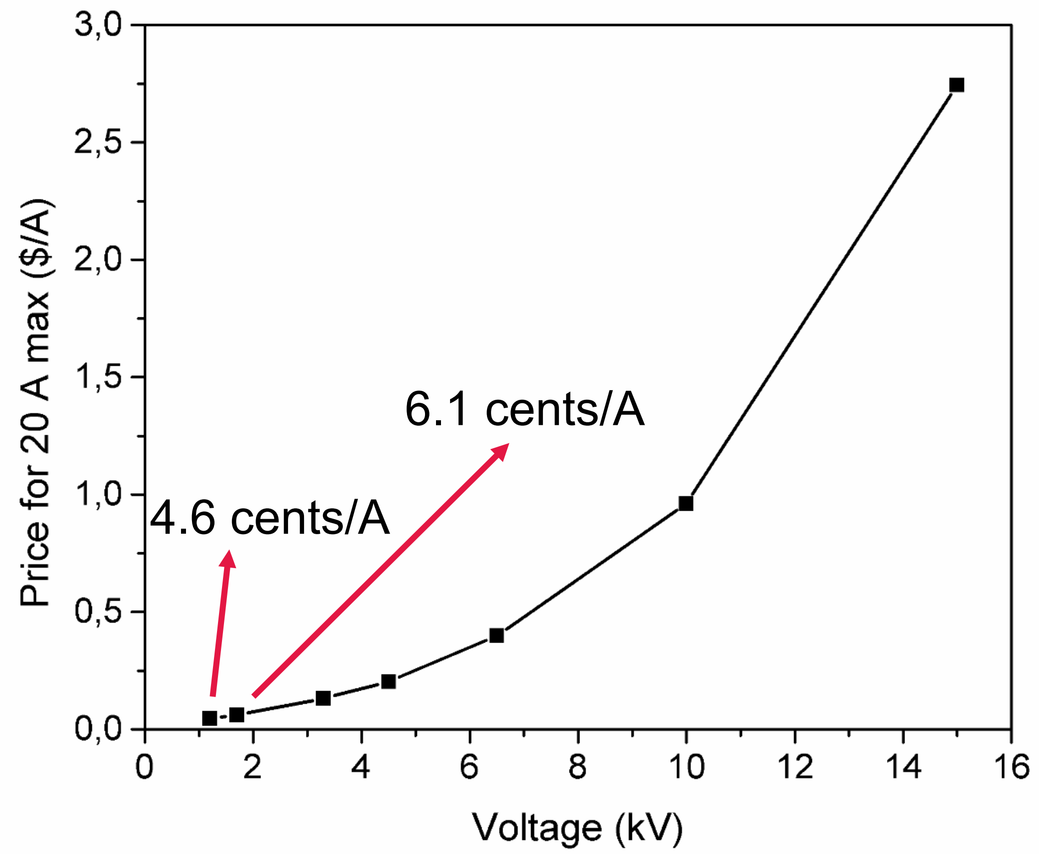
Source: Dr Anant Agarwal, US Department of Energy, ESCDERC 2016

Price Scenario SiC

The price for a 1.2 kV, is significantly below the PowerAmerica's target of 10 cents/A.

If the industry can approach these numbers in 3-5 years then the device demand will grow exponentially across multiple applications.

200mm SiC substrates, expected by 2020, will further reduce the cost of SiC MOSFETs.



Outline

1. Introduction

2. Device Review (JFET, MOSFET, BJT)

3. 6 kV-Class BJTs

4. 15 kV-Class BJTs

5. HT & harsh environments

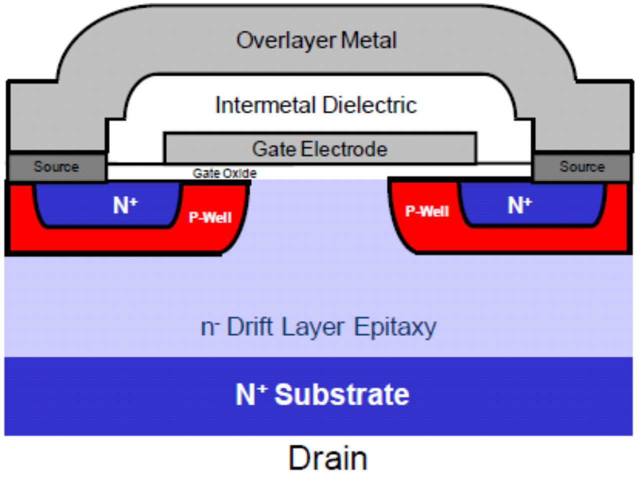
6. Summary

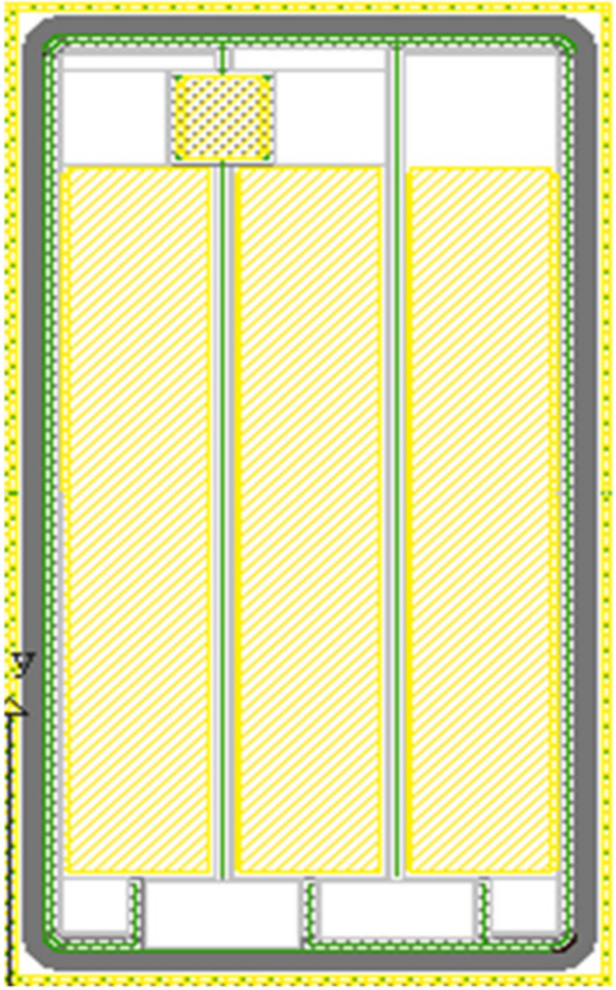
MOSFETs

Application: Solar inverters, switch mode power supplies, high voltage DC/DC converters, battery chargers, motor drive, pulsed power applications, renewable energy, lighting, telecom power supplies, induction heating, auxiliary power supplies, HVAC, LED lighting power supplies

1700 MOSFETs

Schematic DMOSFET Cross-section





JFETs

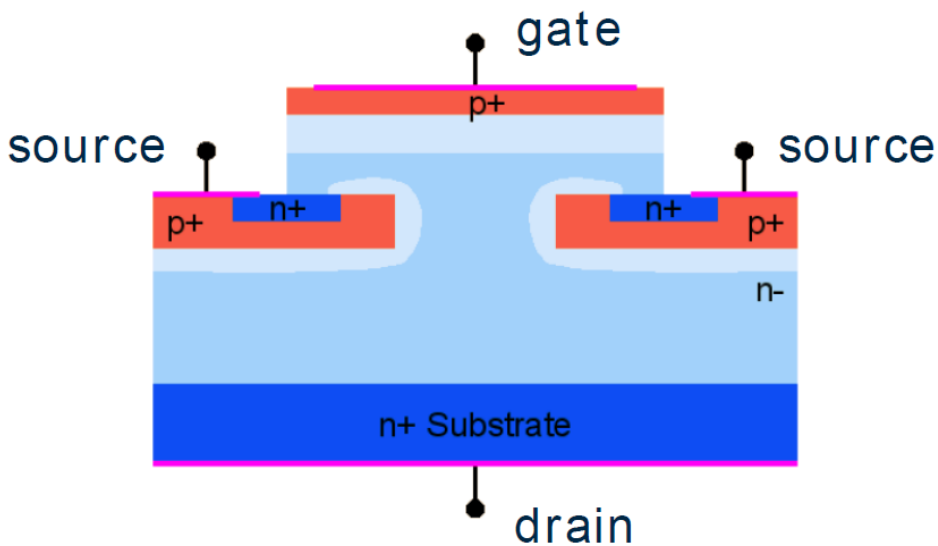
Applications: Solar inverters, high voltage DC/DC or AC/DC conversion, bidirectional inverter.

CoolSiC™ 1700 V JFETs

Home > Discretes & Standard Products > CoolSiC™ 1200V SiC JFET & Direct Drive Technology > **IJW120R100T1**

Overview

IJW120R100T1

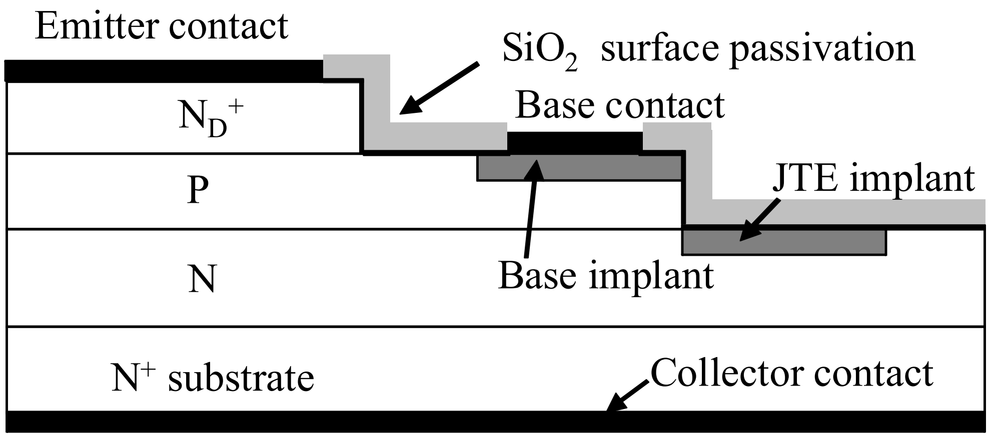


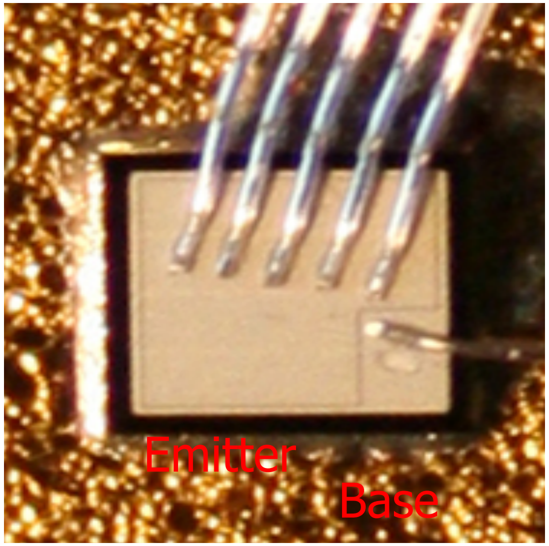
Recently, Infineon presented their 1200V CoolSiC™ with record low Ron of 45 $m\Omega \cdot cm^2$

BJTs

Application: Down hole oil drilling, geothermal instrumentation, hybrid electric vehicles (HEV), solar inverters, switched, mode power supply (SMPS), power factor correction (PFC), induction heating, uninterruptible power supply (UPS), motor drives.

SiC power bipolar junction transistors by TranSiC

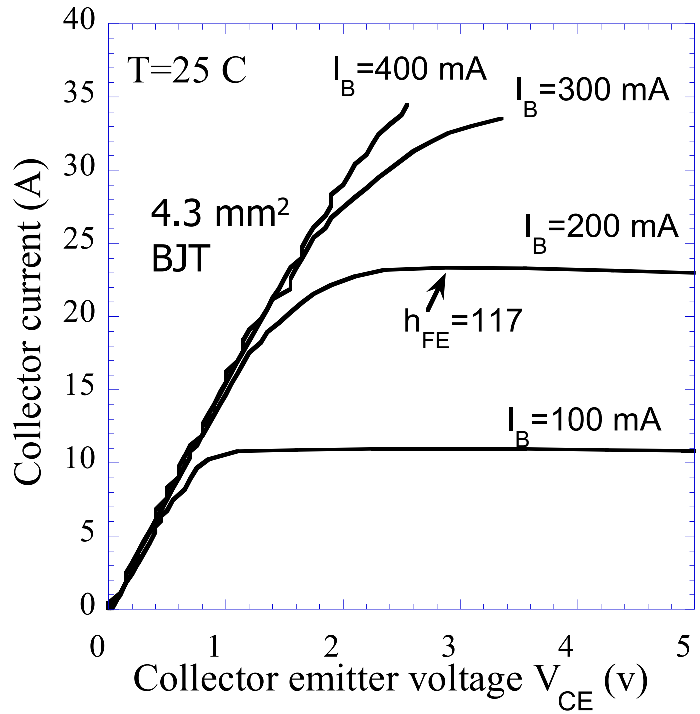




- Vertical epitaxial NPN structure
- Dry etching to form base-emitter and base-collector junctions
- Al implantation for low-resistive base contact and junction termination (JTE)
- Surface passivation by SiO_2, reduced surface recombination
- Large area BJT has many narrow emitter fingers
- Deposited isolation oxide, via holes and Al metal pads
- Active areas between 4.3mm^2 and 15 mm^2

TranSiC POWER TRANSISTORS IN SILICON CARBIDE

Recent Performance of SiC BJTs



FAIRCHILD SEMICONDUCTOR® The Right Technology for Your Success™

- Current gain at T=25 C : h_{FE}=117 at I_C=22 A
- V_{CESAT}=0.95 V at I_C=15 A (J_C=350 A/cm^2), ρ_{ON}=2.7 mΩcm^2
- Low leakage current at V_{CEO}=1200 V, Open-base breakdown ~ 1800 V

GeneSiC SEMICONDUCTOR

GA16JT17-247

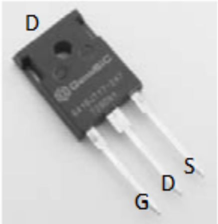
Normally – OFF Silicon Carbide Junction Transistor

V_{DS}	=	1700 V
$R_{DS(ON)}$	=	50 mΩ
$I_{D\ (Tc = 25°C)}$	=	45 A
$I_{D\ (Tc > 125°C)}$	=	20 A
$h_{FE\ (Tc = 25°C)}$	=	100

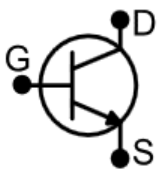
Features

- 175 °C Maximum Operating Temperature
- Gate Oxide Free SiC Switch
- Exceptional Safe Operating Area
- Excellent Gain Linearity
- Temperature Independent Switching Performance
- Low Output Capacitance
- Positive Temperature Coefficient of $R_{DS,ON}$
- Suitable for Connecting an Anti-parallel Diode

Package



TO-247



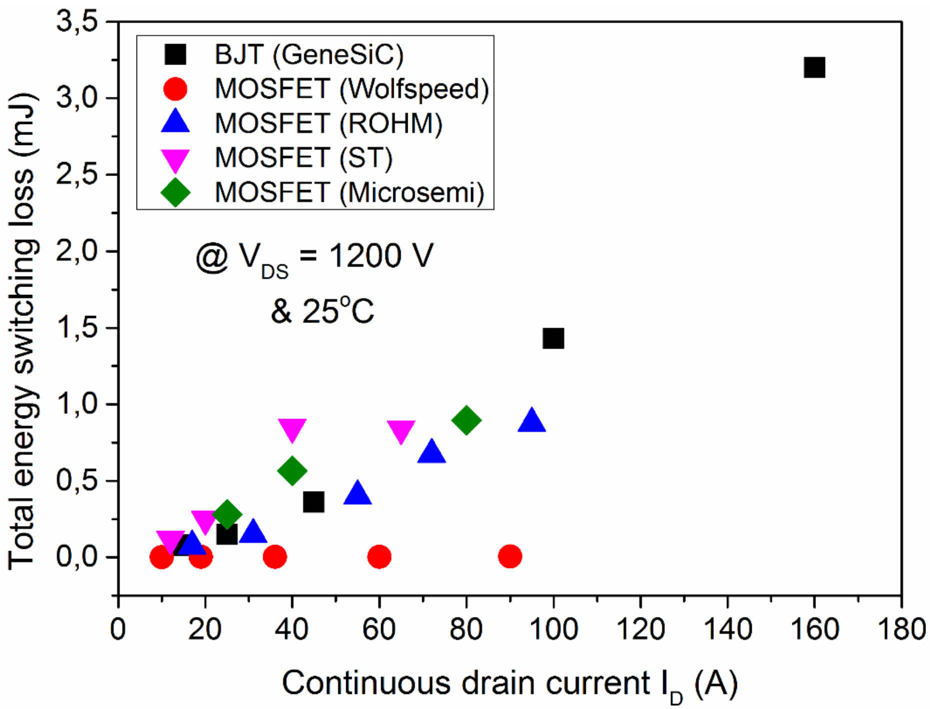
Advantages

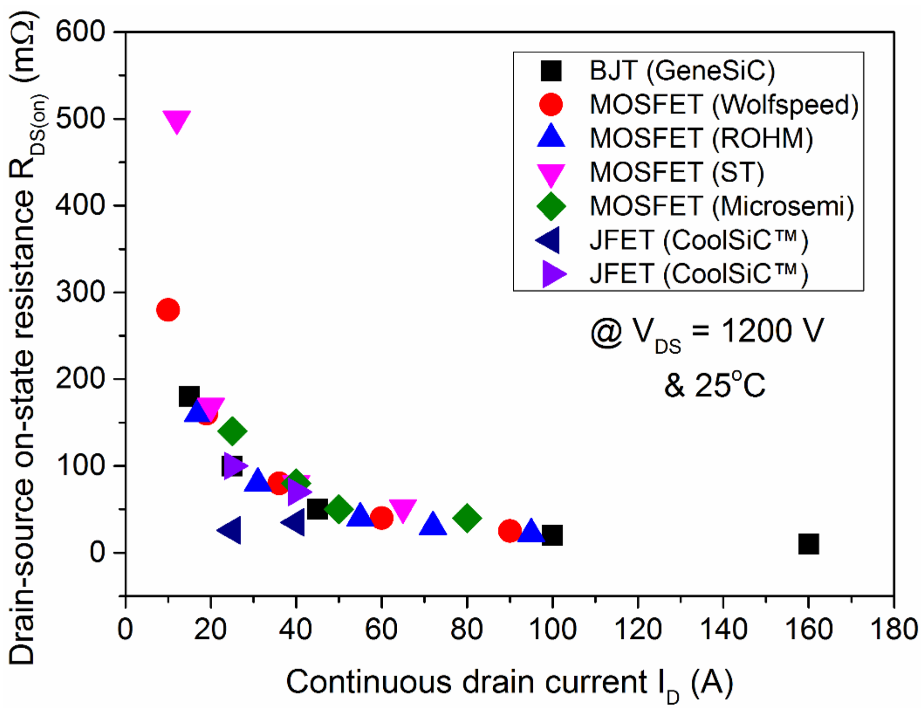
- Compatible with Si MOSFET/IGBT Gate Drive ICs
- > 20 µs Short-Circuit Withstand Capability
- Lowest-in-class Conduction Losses
- High Circuit Efficiency
- Minimal Input Signal Distortion
- High Amplifier Bandwidth

Applications

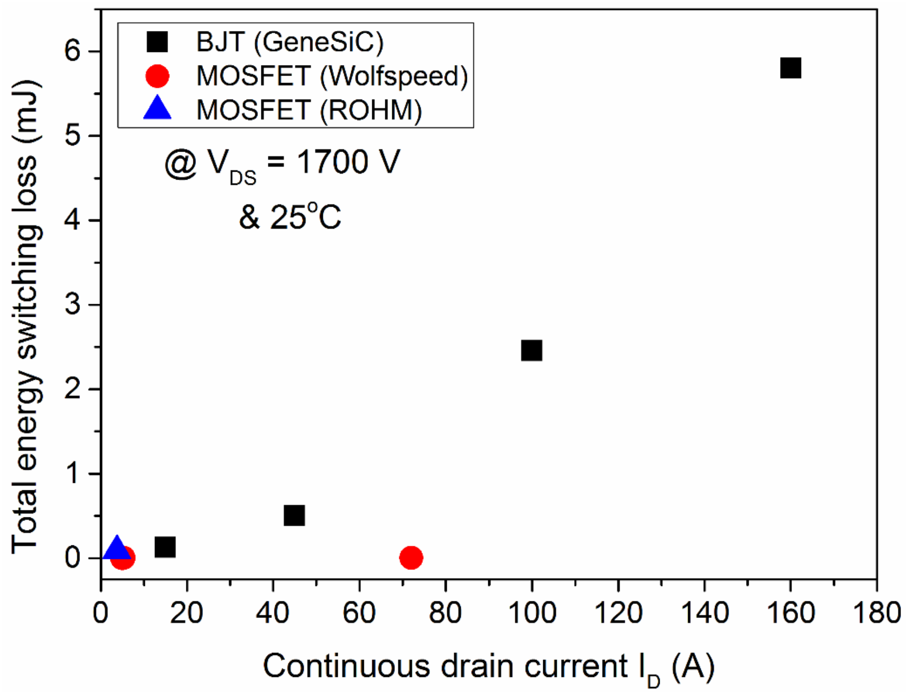
- Down Hole Oil Drilling, Geothermal Instrumentation
- Hybrid Electric Vehicles (HEV)
- Solar Inverters
- Switched-Mode Power Supply (SMPS)
- Power Factor Correction (PFC)
- Induction Heating
- Uninterruptible Power Supply (UPS)

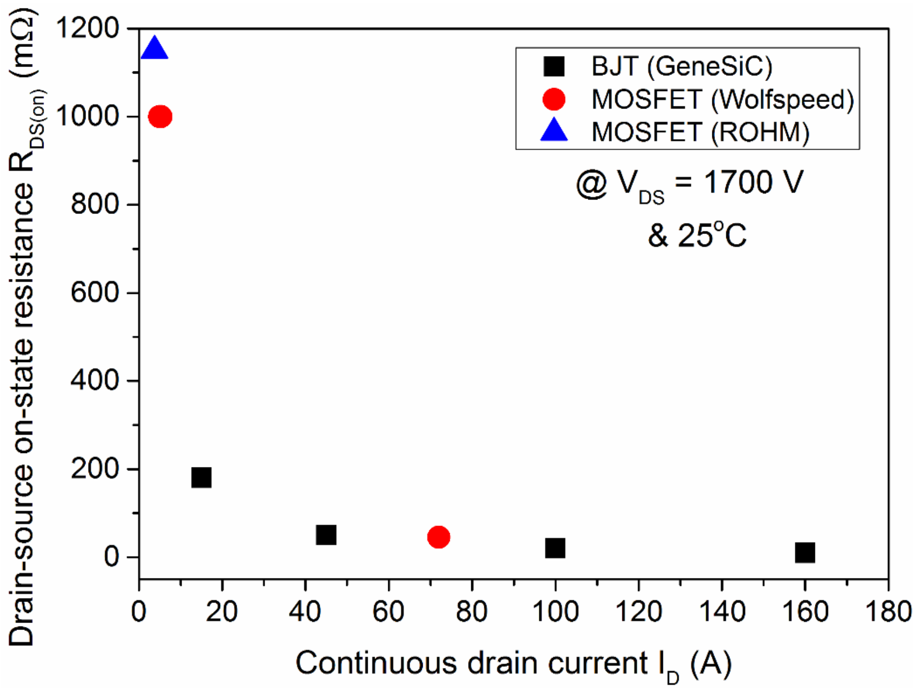
1200 V 4H-SiC Unipolar and Bipolar Devices





1700 V 4H-SiC Unipolar and Bipolar Devices





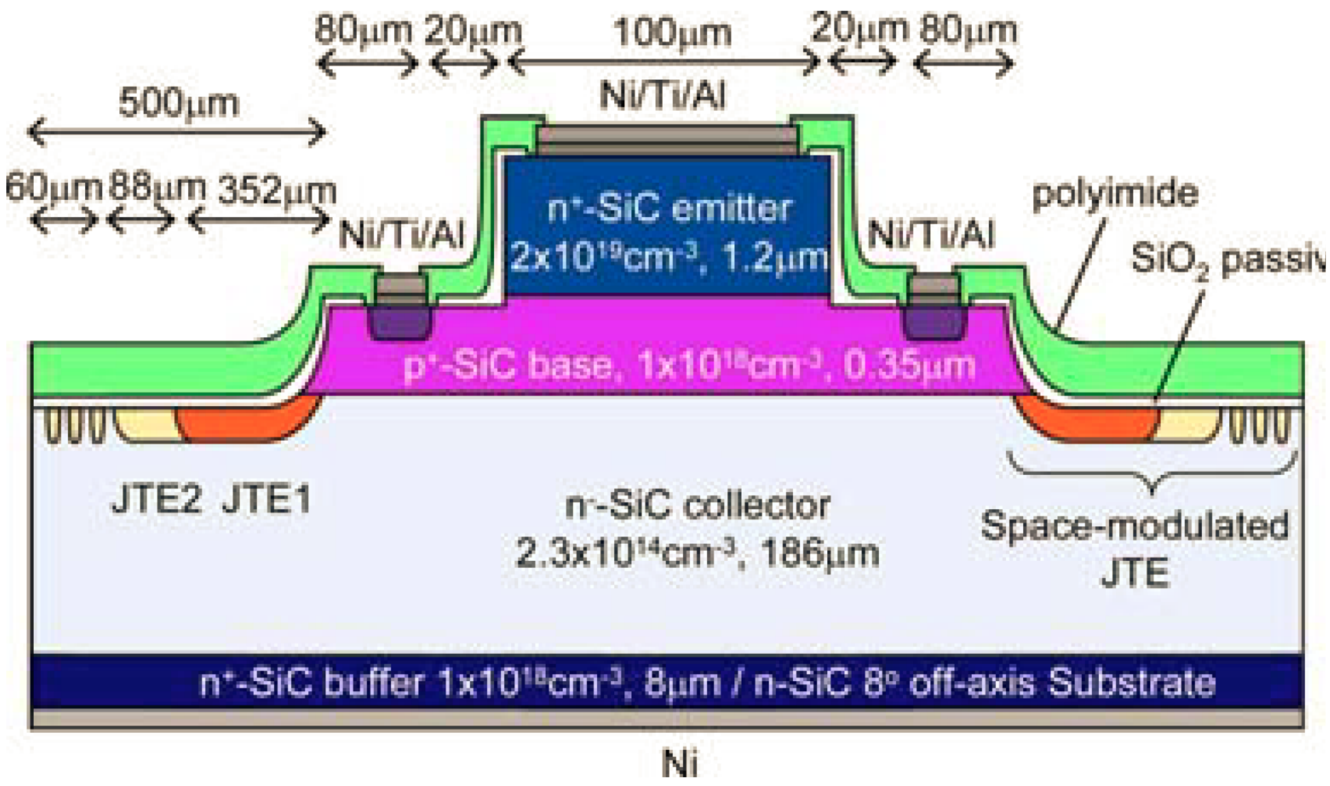
Ultra High Voltage Devices

The on-resistance for a 4H-SiC unipolar device above 15 kV, increases to the point where it is impractical from a yield standpoint and cost.

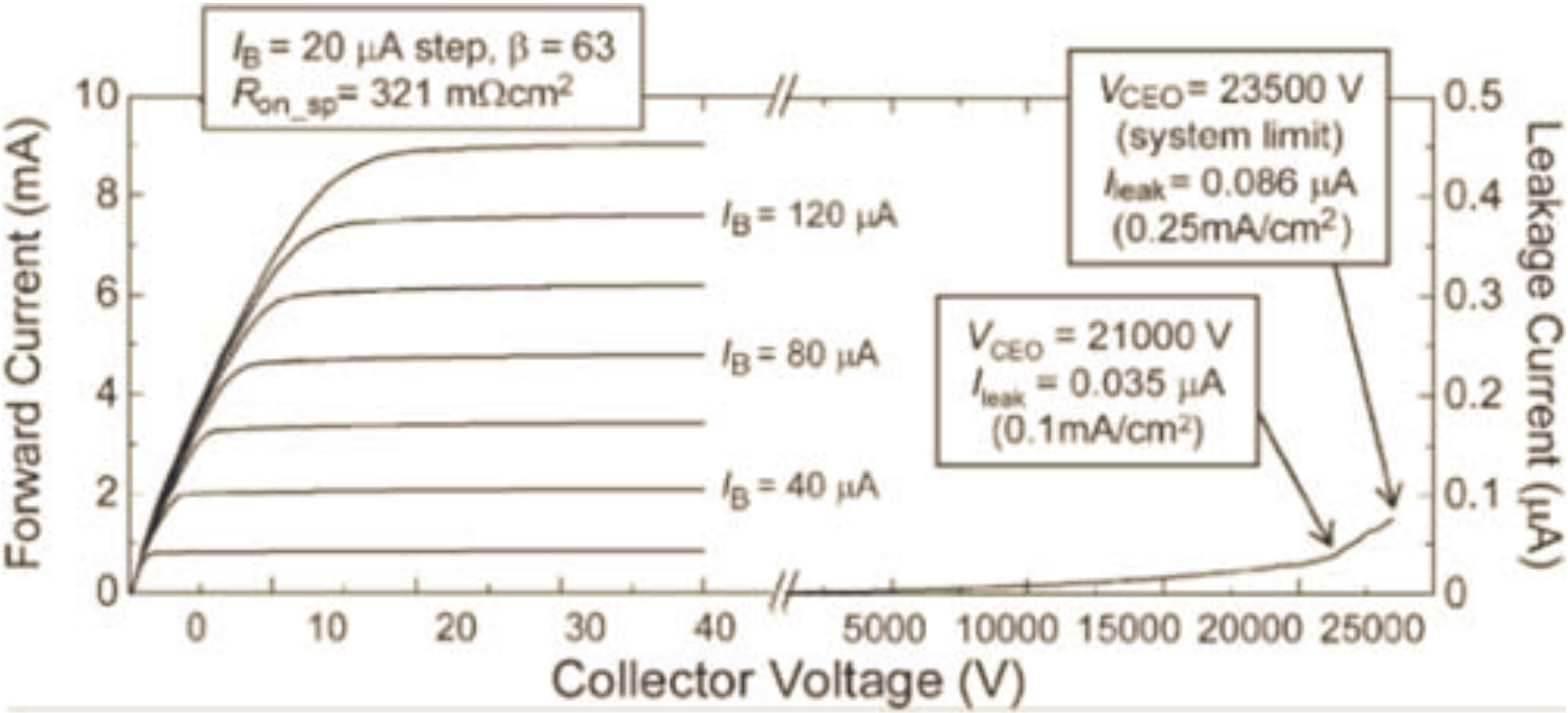
Bipolar devices are likely to be the first choice.

Source: Dr. John W. Palmour, CREE, IEDM 2014

21 kV BJT (T. Kimoto Kyoto University)



MIYAKE et al. IEEE ELECTRON DEVICE LETTERS, VOL. 33, NO. 11, NOVEMBER, 2012, p.1598



Active area small – 0.0035 mm^2

MIYAKE et al. IEEE ELECTRON DEVICE LETTERS, VOL. 33, NO. 11, NOVEMBER, 2012, p.1598

Outline

1. Introduction

2. Device Review (JFET, MOSFET, BJT)

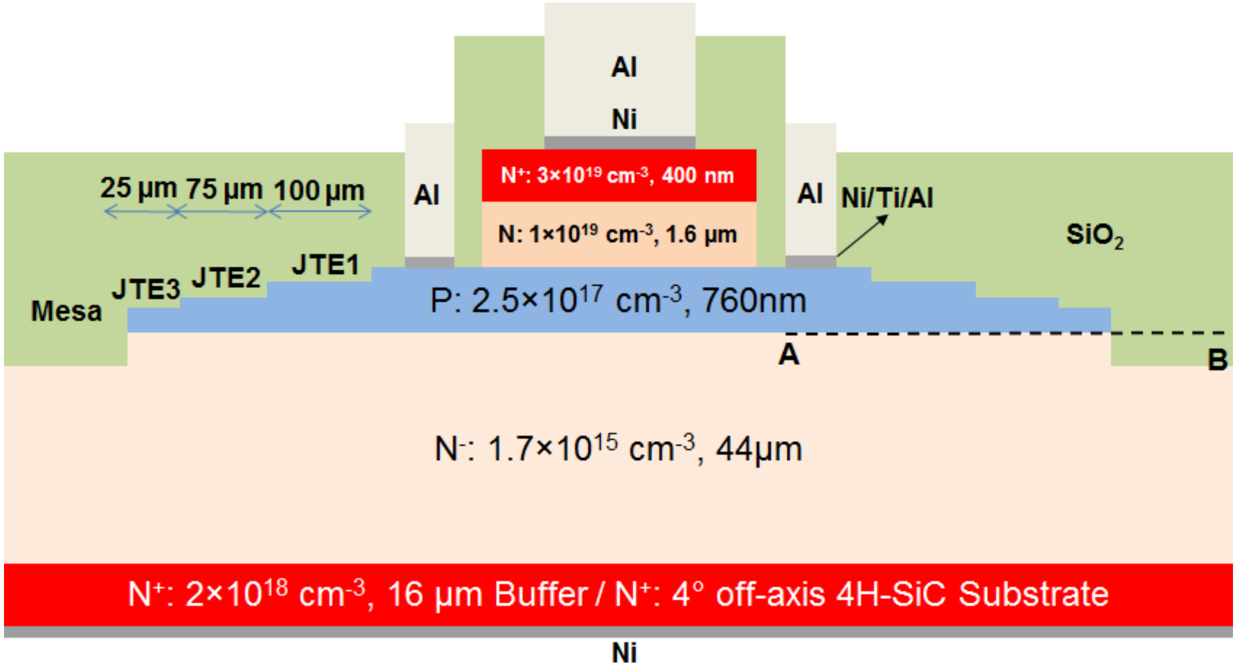
3. 6 kV-Class BJTs

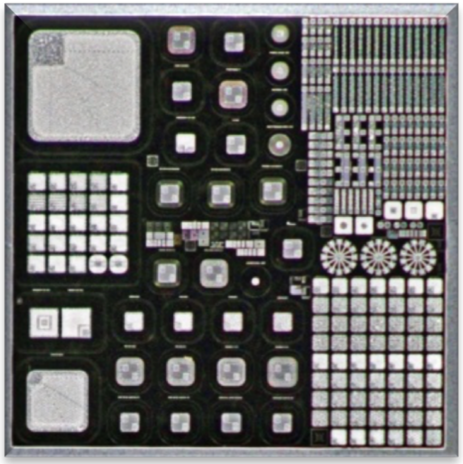
4. 15 kV-Class BJTs

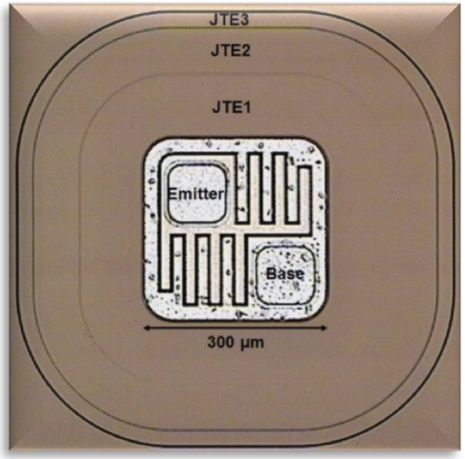
5. HT & harsh environments

6. Summary

6 kV-Class 4H-SiC BJTs

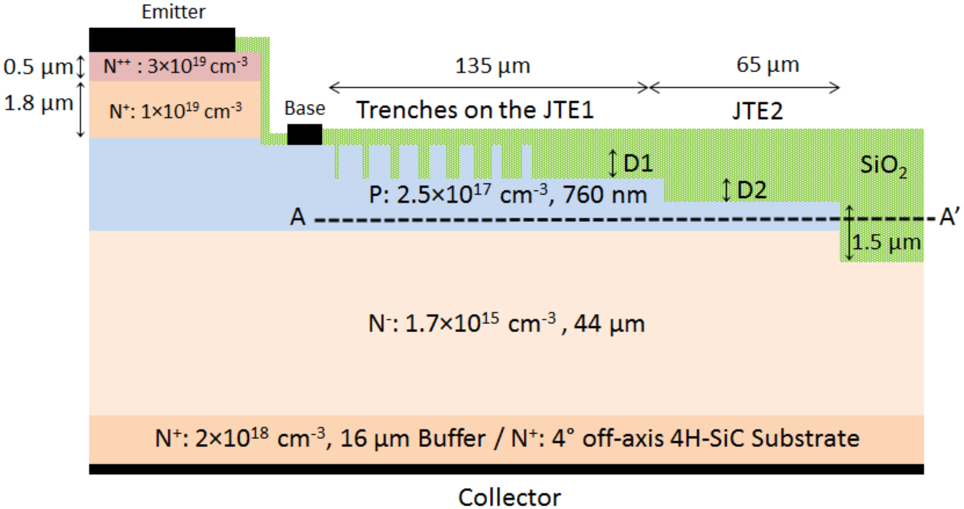


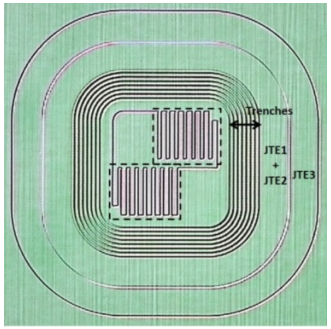


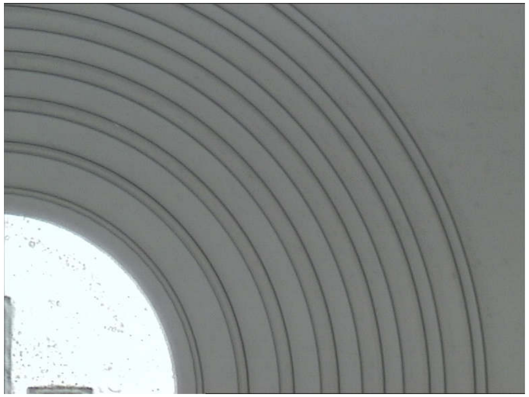


in *Proc. 27th ISPSD*, May 2015, pp. 249-252

Trench JTE Design

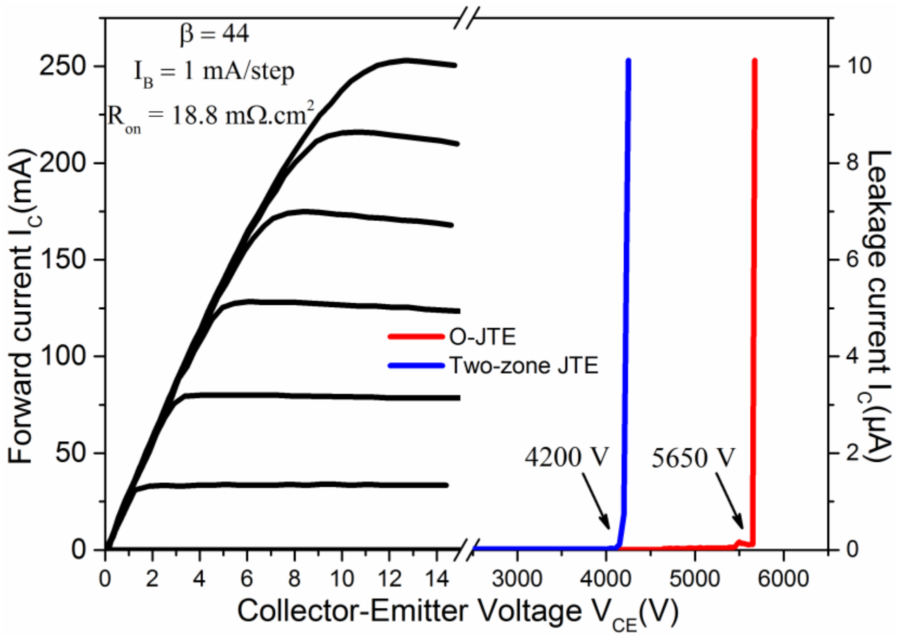


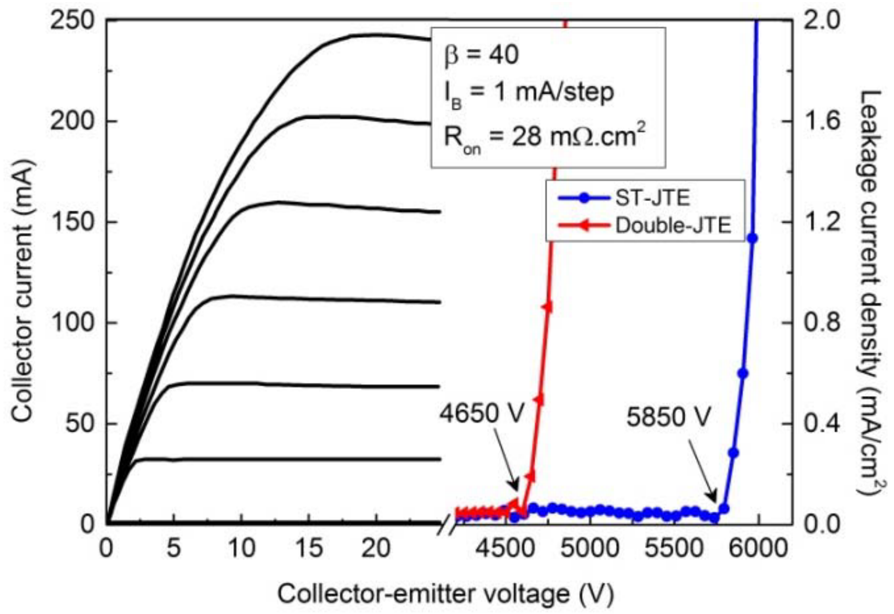




IEEE ELECTRON DEVICE LETTERS, VOL. 36, NO. 2, Feb. 2015

I-V Characteristics





Termination efficiency 92 %

Termination efficiency 93 %

in *Proc. 27th ISPSD*, May 2015, pp. 249-252

IEEE ELECTRON DEVICE LETTERS, VOL. 36, NO. 2, Feb. 2015

Outline

1. Introduction

2. Device Review (JFET, MOSFET, BJT)

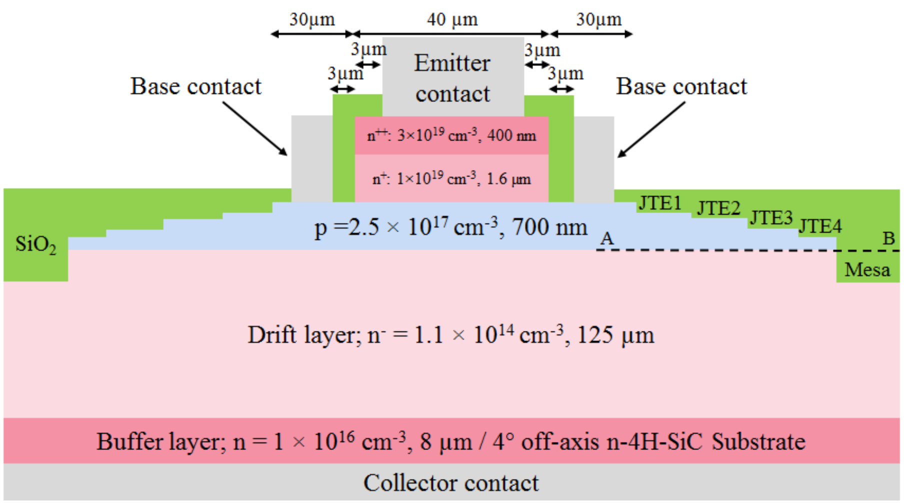
3. 6 kV-Class BJTs

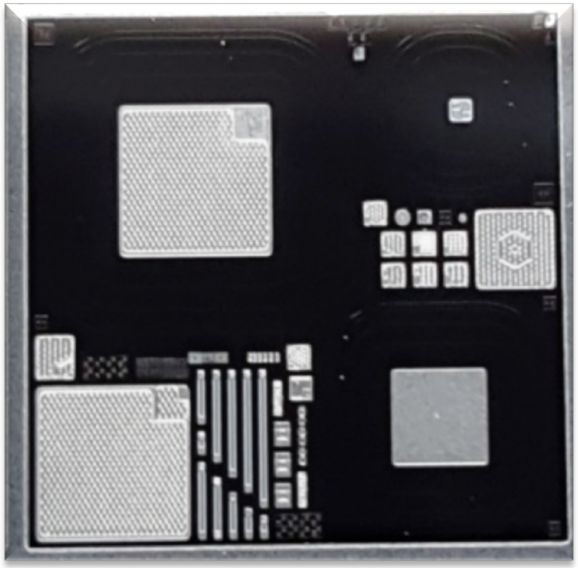
4. 15 kV-Class BJTs

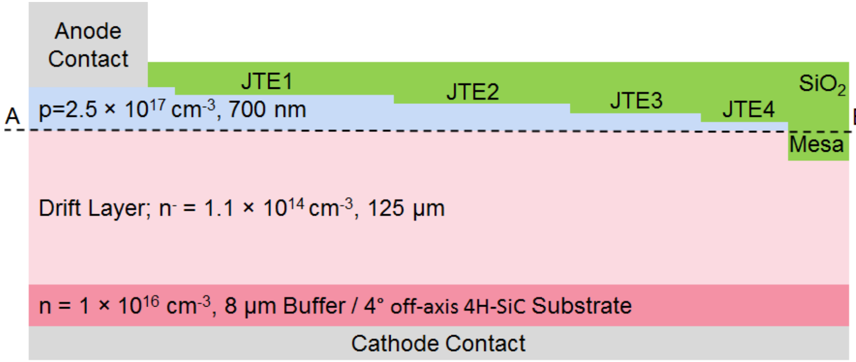
5. HT & harsh environments

6. Summary

15 kV-Class BJTs and PiN Diodes

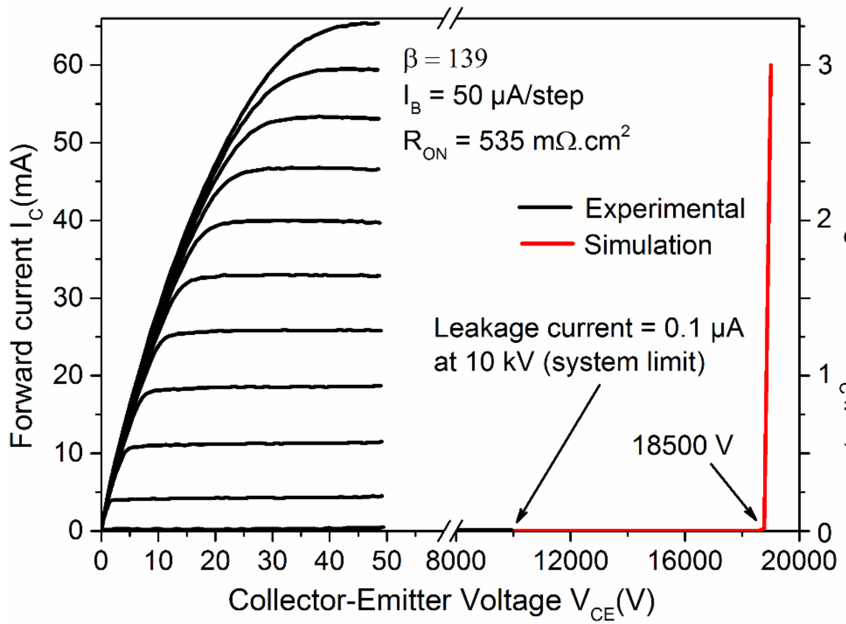


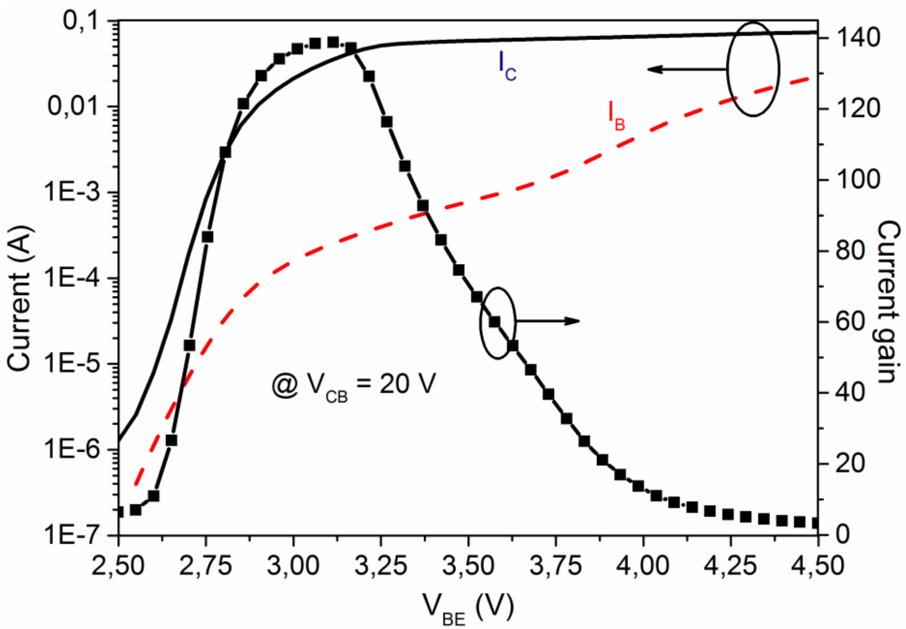




15 kV-class PiN diodes will be presenteded in Tu1.04

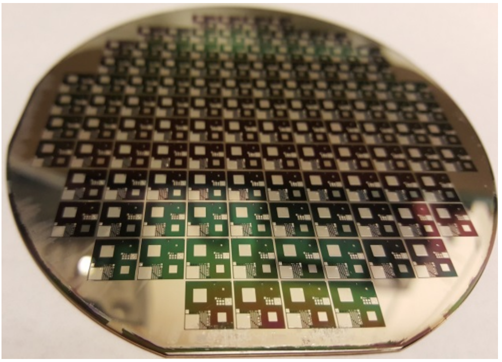
I-V Characteristics of the BJTs

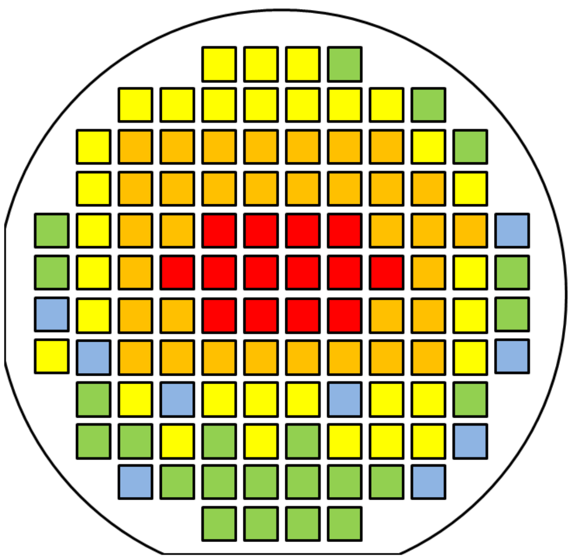




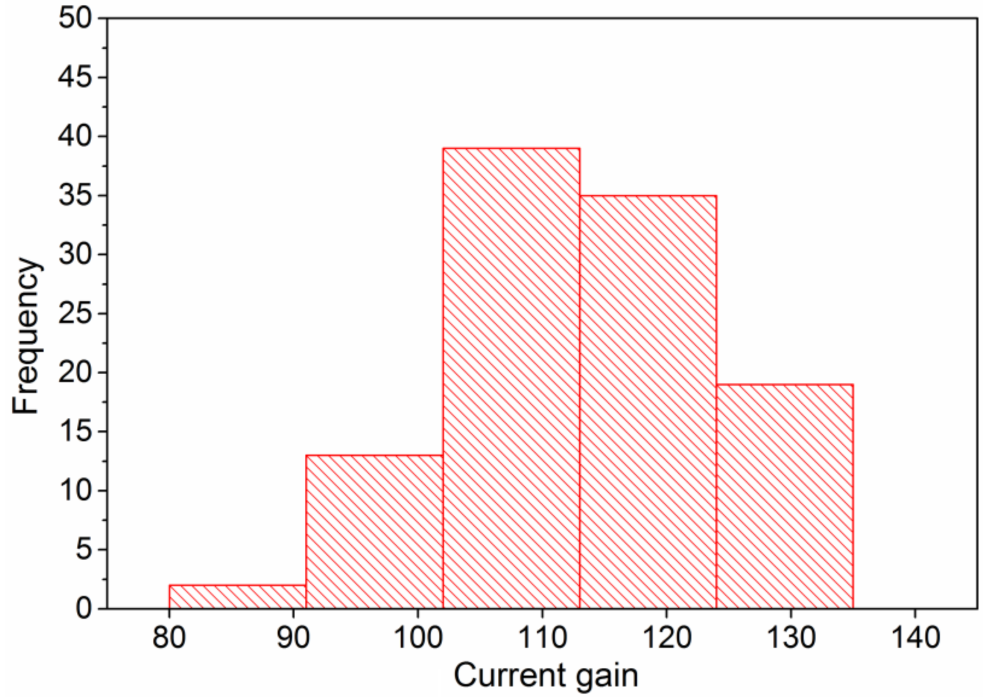
A current gain record of 139 for 15 kV-class BJTs

Current Gain Wafer map





(blue)	85-94
(green)	95-104
(yellow)	105-114
(orange)	115-124
(red)	>125



$\beta \geq 100$ (91 % of the dies)

Outline

1. Introduction

2. Device Review (JFET, MOSFET, BJT)

3. 6 kV-Class BJTs

4. 15 kV-Class BJTs

5. HT & harsh environments

6. Summary

Applications for HT & harsh environments

Application	Type	Temperature	Radiation
Oil and gas drilling	P, S	600 °C	No
Industrial motor drives	P	300 °C	No
Automotive	P, S	300-600 °C	No
Aviation	P, S	300-600 °C	(Yes)
Space exploration	S	600 °C	Yes
Nuclear energy	(P) S	300-600 °C	Yes

P = Power switching applications
S = Sensor signal processing





A new high temperature SiC electronics project

WOV – Working on Venus

WOV – Working On Venus Research plan

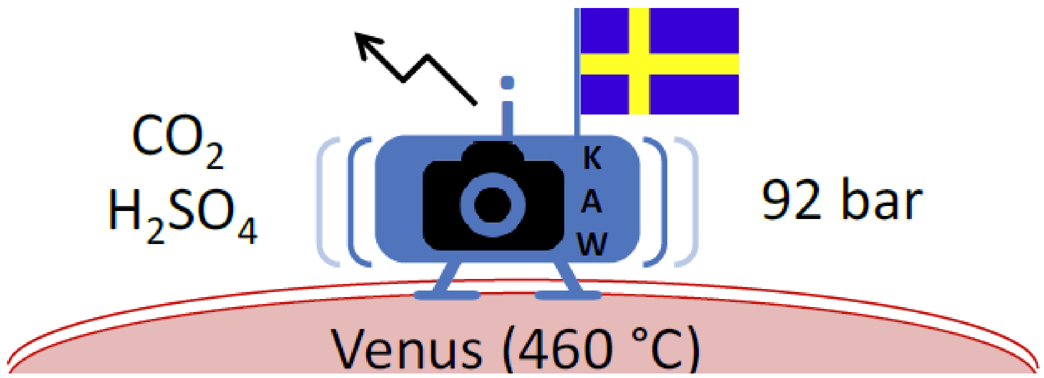
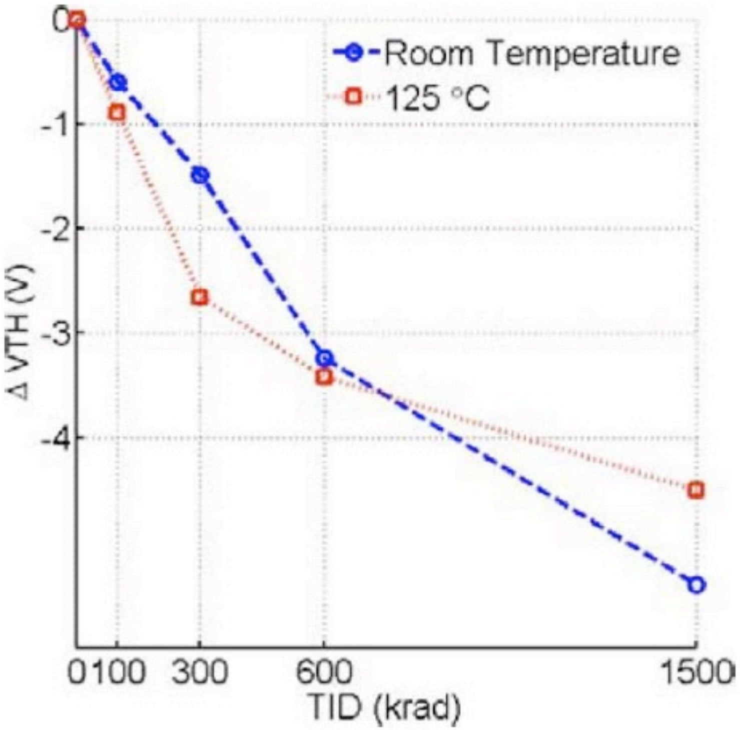


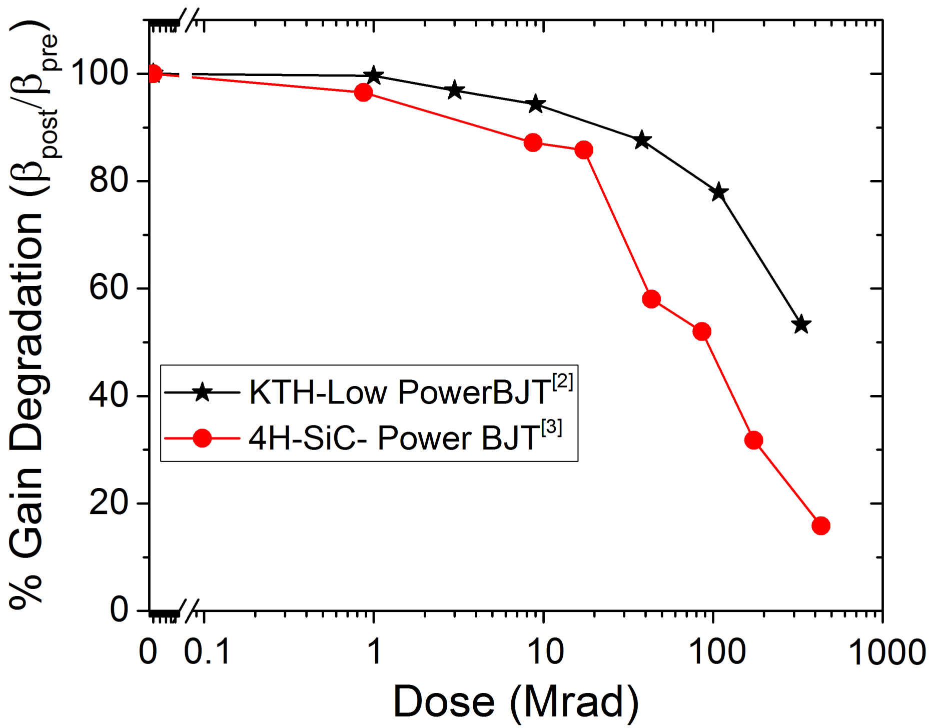
Figure 1 Artist's impression of Venus Lander functionality: Seismology, environmental sensing, imaging, and transmitter.

$ 3,3M Project funding 2014 – 2018

Knut och Alice Wallenbergs Stiftelse

Radiation stability of SiC BJT vs. MOSFET





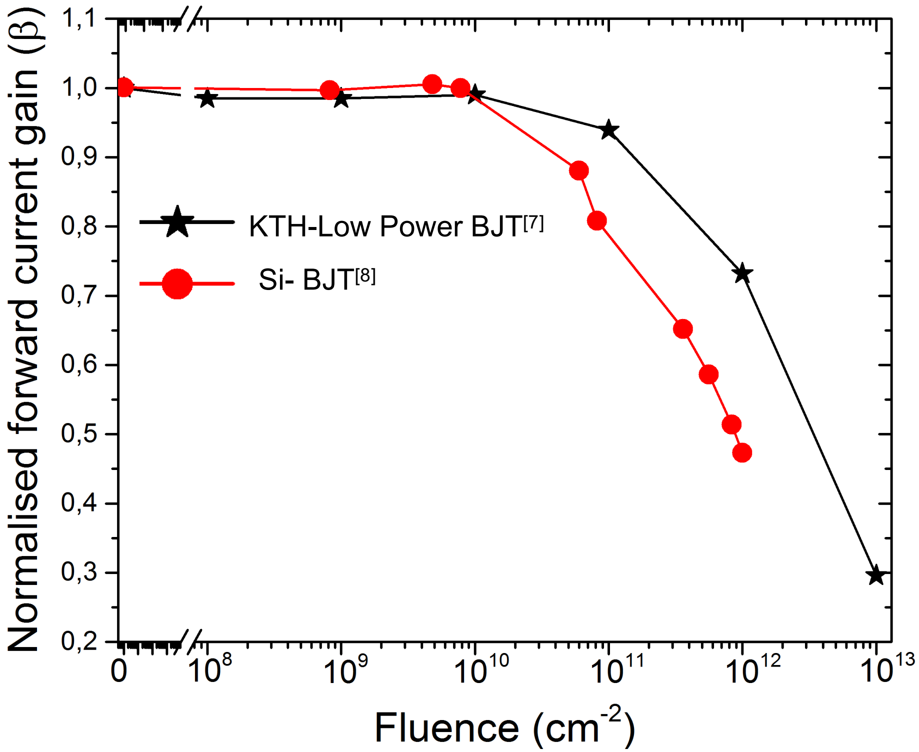
Commercially available 24 A (CMF10120D) SiC power MOSFETs fabricated by CREE, shows a large negative threshold voltage shift and becomes inoperative after a dose of only 300 krad. A. Akturk, et.al, IEEE Trans. Nucl. Sci., 59 (2012).

Forward current gain degradation up to 38 Mrad was found negligible, but for the dose of 332 Mrad, a degradation of 52% is seen.

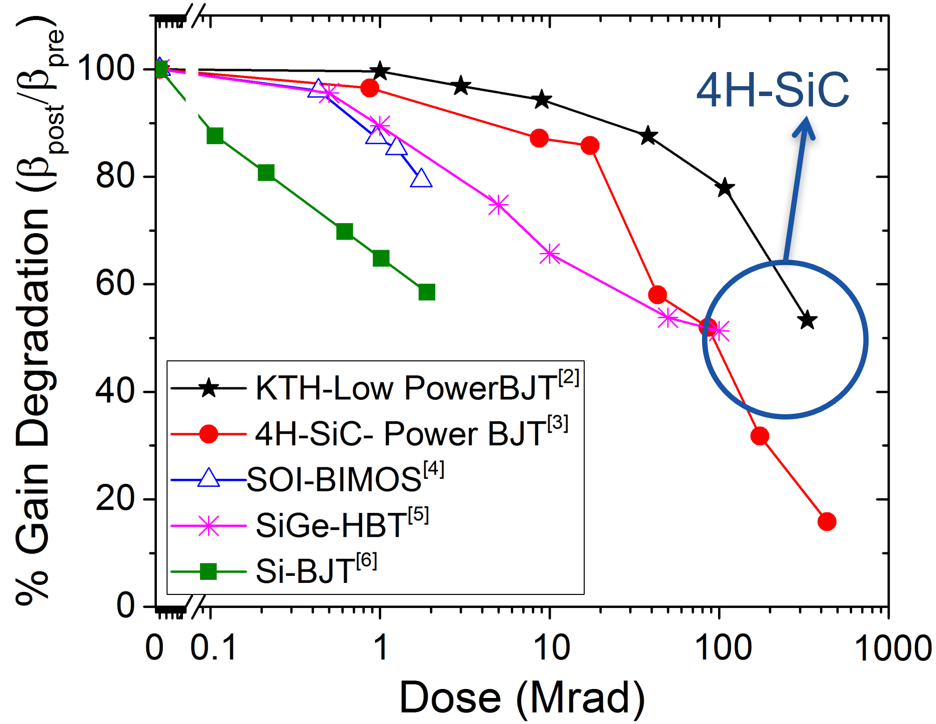
To be published in IEEE TED

Comparison of various bipolar technology

Protons irradiation



Gamma irradiation



- 4H-SiC technology show more tolerance to gamma radiation in comparison to other technologies.
- 4H-SiC devices irradiated with 3 MeV protons show about one order of magnitude higher tolerance in comparison to the Si technology

Outline

1. Introduction

2. Device Review (JFET, MOSFET, BJT)

3. 6 kV-Class BJTs

4. 15 kV-Class BJTs

5. HT & harsh environments

6. Summary

Summary

- Replacing Si with SiC switch devices gives great savings with respect to energy density, efficiency, and physical systems volume
- At 1200-1700V SiC MOSFETs, JFETs and BJT performs about equally good
- In a few years the cost issues with SiC looks very competitive < 5 cents/Amp
- Above 15 kV, BJTs/IGBTs are likely to be the first choice
- For high temperature and radhard environments BJTs have a clear advantage

Acknowledgments

The KTH research team

The Swedish Energy Agency

The Swedish Research Council

VINNOVA – research and innovation for sustainable growth

Swedish Foundation for Strategic Research

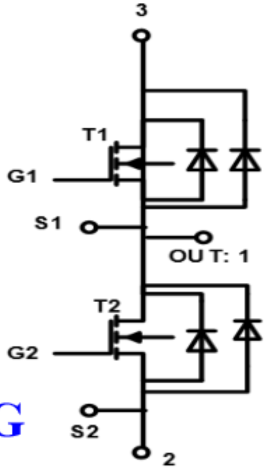
KAW Foundation

STandUP for Energy

Commercial SiC-MOSFET (Si-IGBT) Power Module

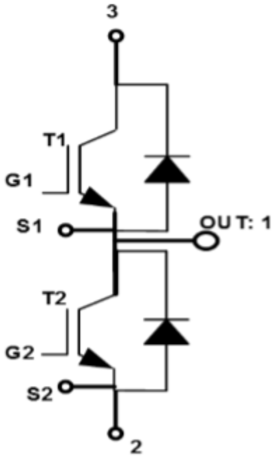
SiC-MOSFETs

APTMC170AM07CD3AG



Si-IGBTs

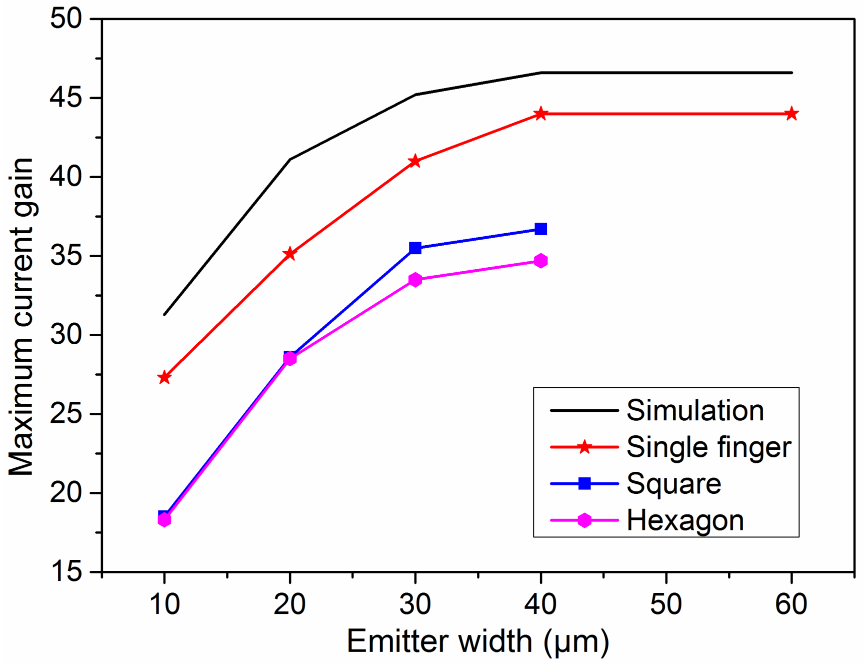
APTGT300A170D3G

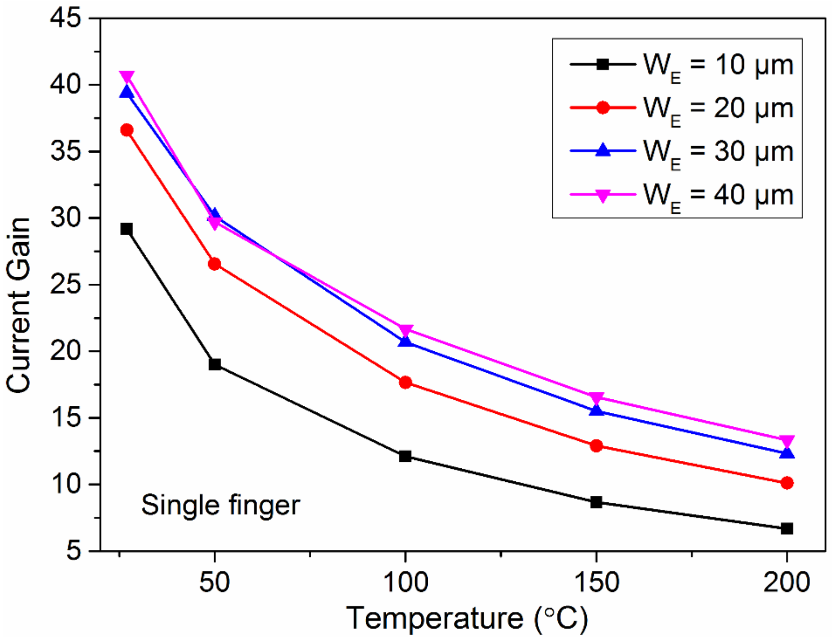


V_{CES} = 1700 V, I_{CE} = 300 A @ 25 ^oC
V_{CE-ON} = 2.0 V @ 300 A, 25 ^oC, V_{GE} =15 V
V_{GE-TH} = 2.3 V @ 15.0 mA, 25 ^oC
R_{th-JC} = 0.075 ^oC/Watt
T_J = 150 ^oC, P_{D-max} = 2080 Watt
R_{ON}= 6.5 mΩ (13.3 mΩ) @ 25 ^oC (150 ^oC)

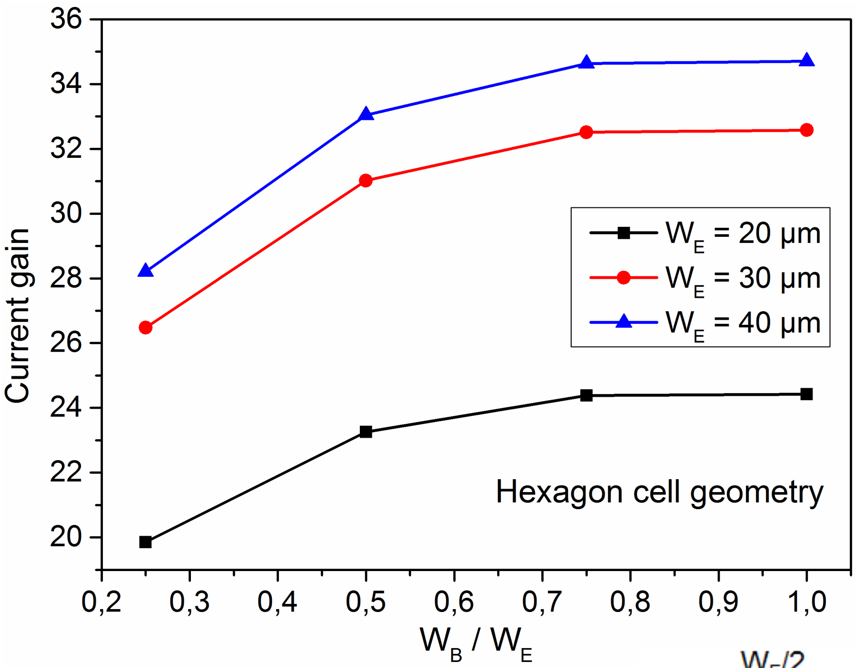
V_{CES} = 1700 V, I_{CE} = 300 A @ 80 ^oC
V_{CE-ON} = 2.0 V @ 300 A, 25 ^oC, V_{GE} =15 V
V_{GE-TH} = 5.8 V @ 12.0 mA, 25 ^oC
R_{th-JC} = 0.085 ^oC/Watt (IGBT)
R_{th-JC} = 0.13 ^oC/Watt (Diode)
T_J = 150 ^oC, P_{D-max} = 1470 Watt

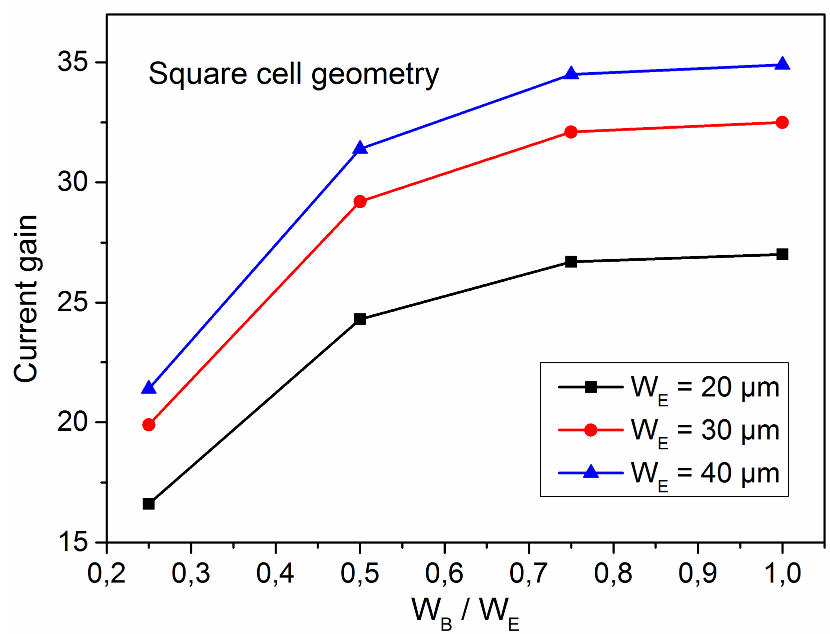
Emitter Size Effect

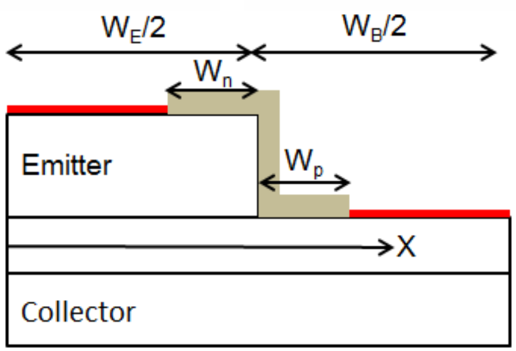




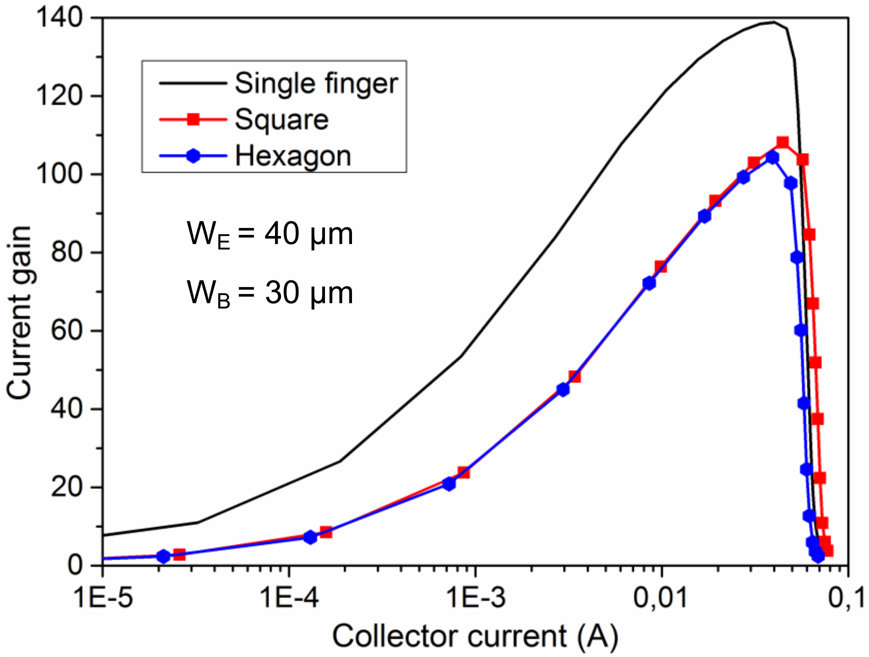
Base Size Effect

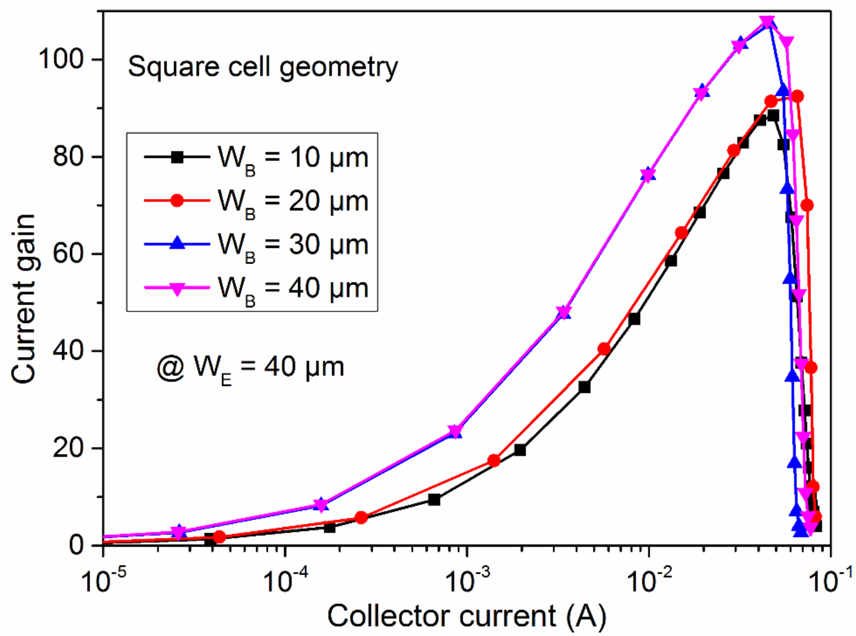




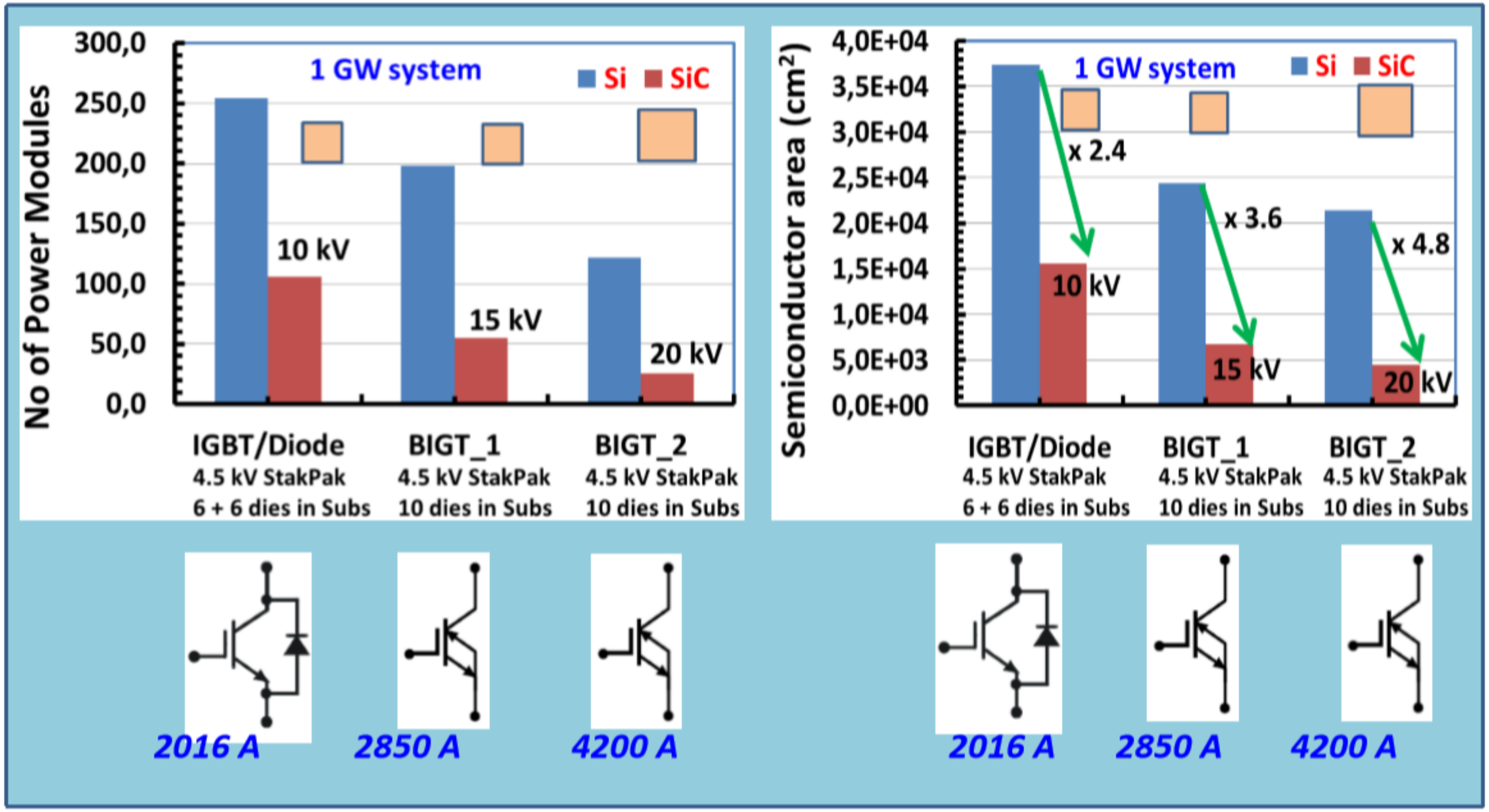


Current Gain vs Geometry



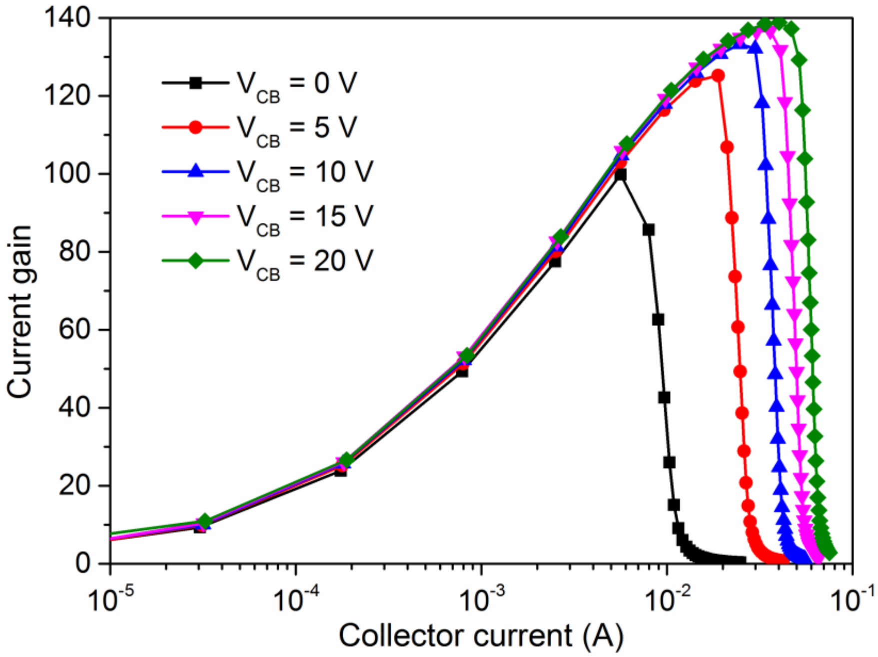


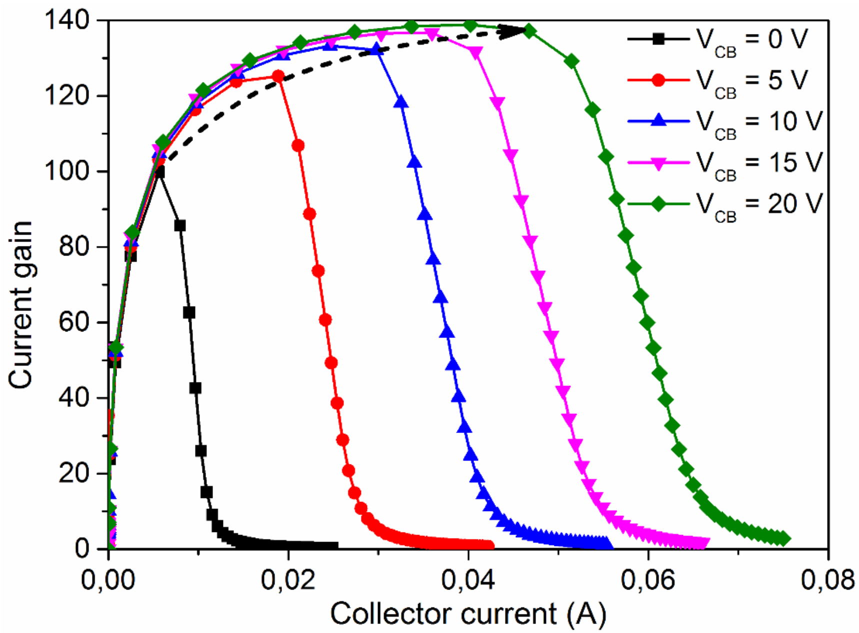
Compactness: Si Vs SiC



Source: Dr. Muhammad Nawaz, ABB

Current Gain vs Applied Voltage

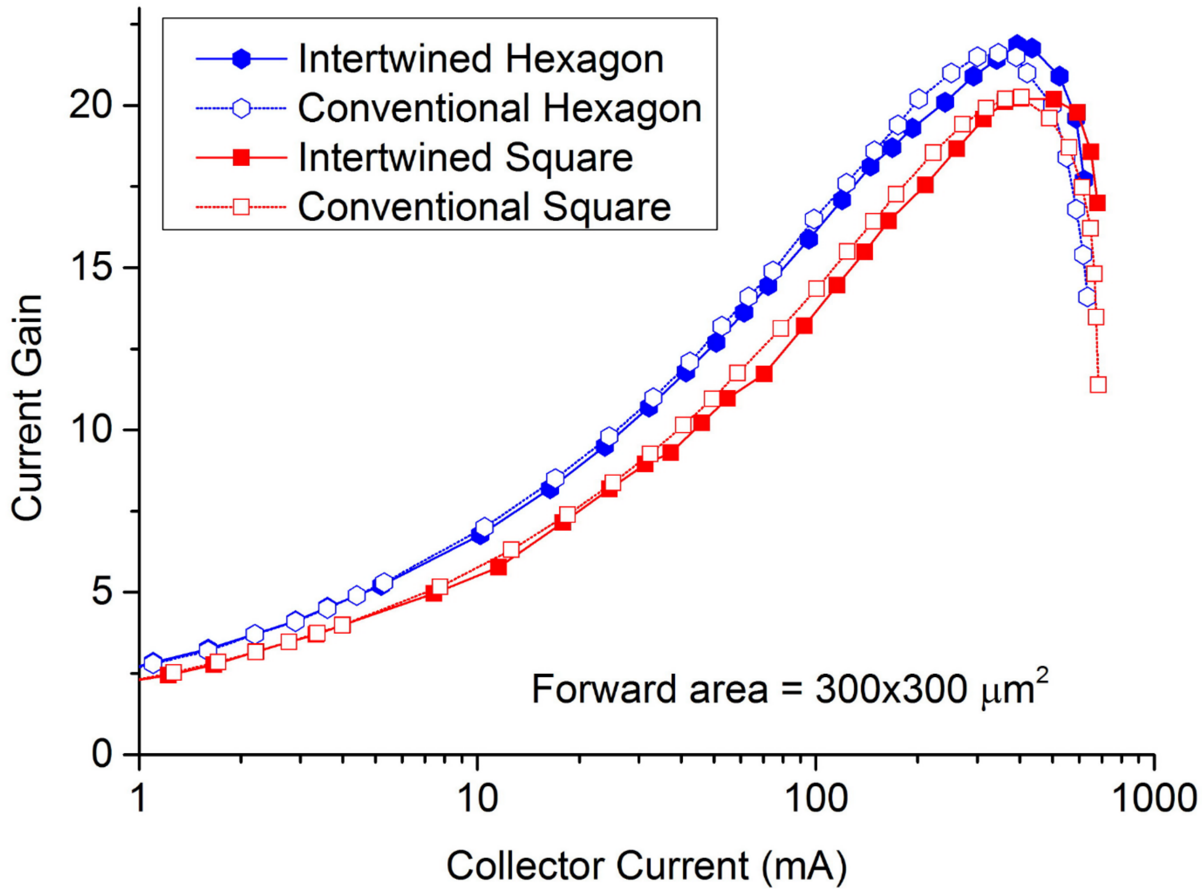




Decreasing effective base

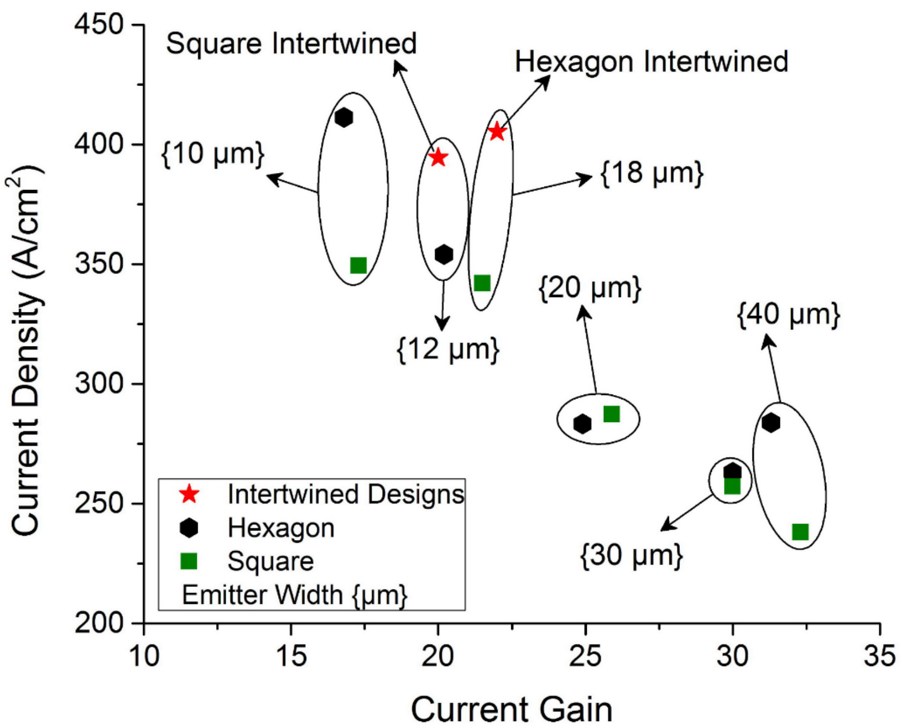
Base width modulation (Early effect)

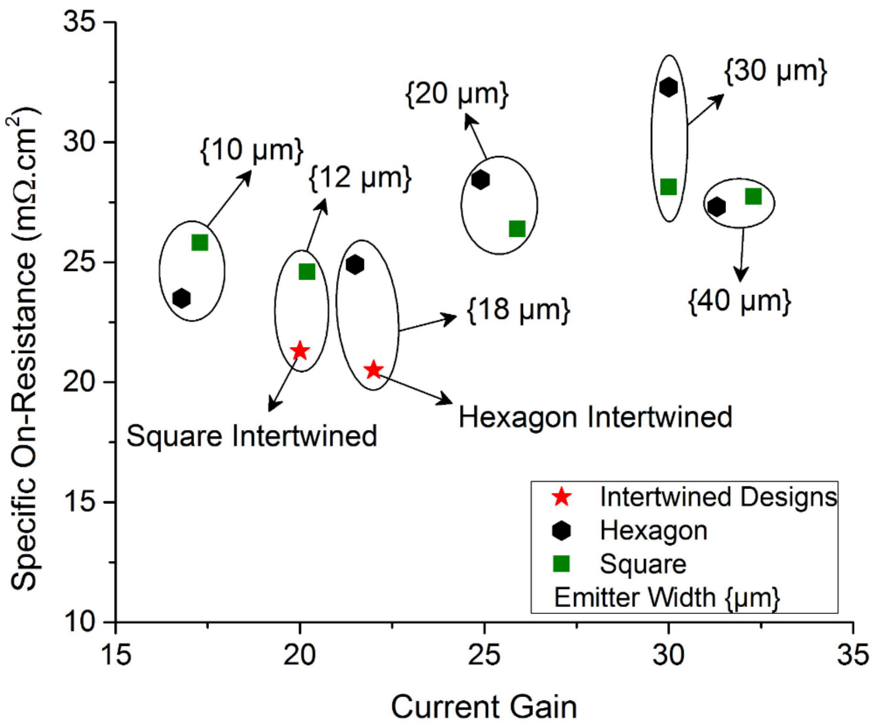
Current gain improvement



To be published in IEEE TED

On-resistance and current density improvement

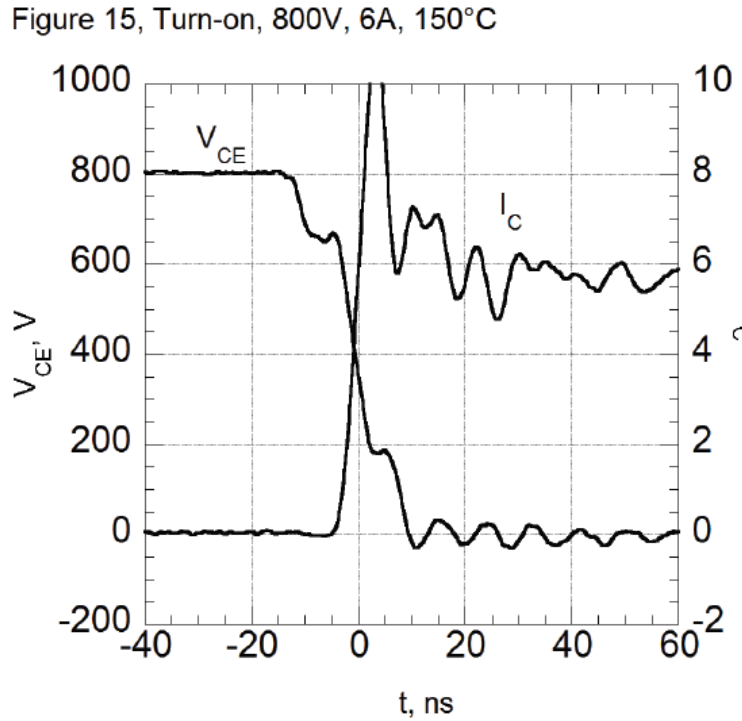


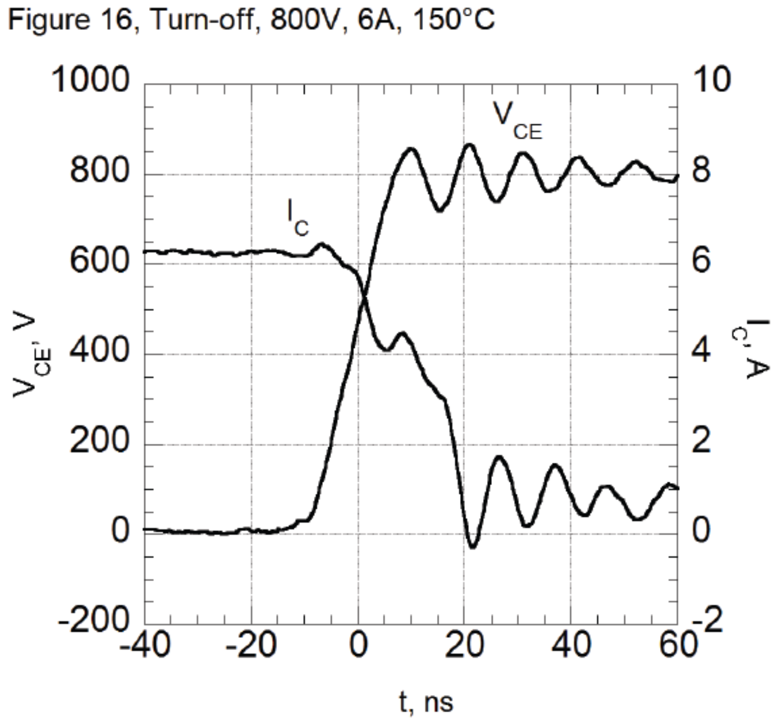


To be published in IEEE TED

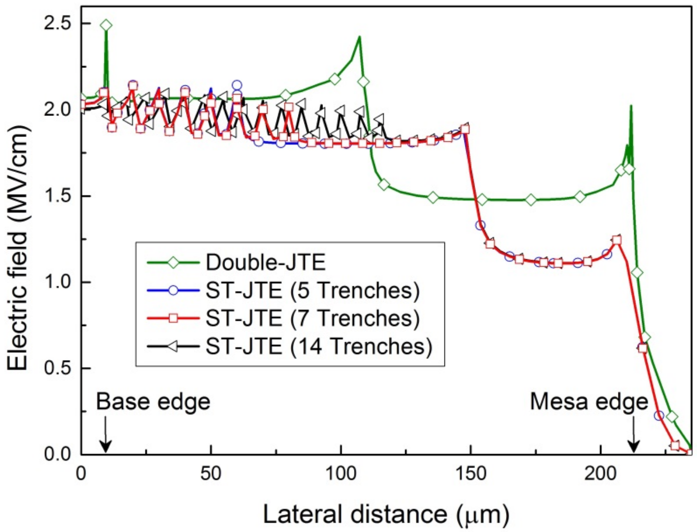
1) A. Akturk, et.al, IEEE Trans. Nucl. Sci., 59 (2012) 3258-3264.
2) S S. Suvanam, et al., submitted to IEEE Trans. Nucl. Sci., (2016)
3) M. Nawaz, et al., 2009 Device Research Conference, University Park, PA, (2009) 279-280.
4) L. Ratti et al., IEEE Trans. Nucl. Sci., 52 (2005) 1040-1047.
5) J. Metcalfe et al., Nucl. Instr. Meth. Phys. Res. A, 579 (2007) 833–838.
6) S. L. Kosier et al., IEEE Trans. Nucl. Sci., 40 (1993) 1276-1285.
7) S. S. Suvanam, et al., IEEE Trans. Nucl. Sci., 61 (2014)1772-1776.
8) X. J. Li et al., Chin. Phys. B, 19 (2010) 066103.

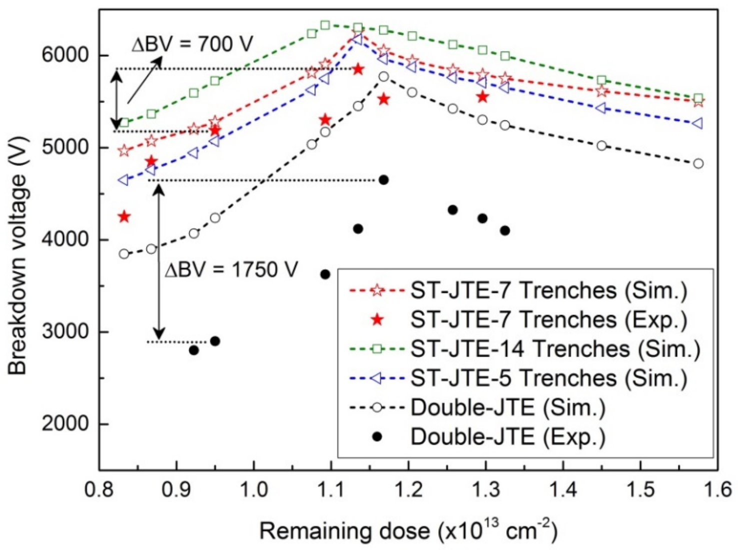
Switching waveforms at 150 C



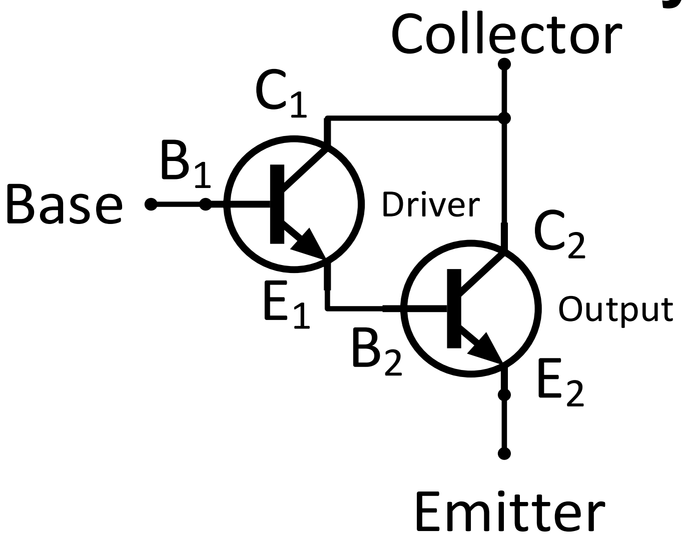


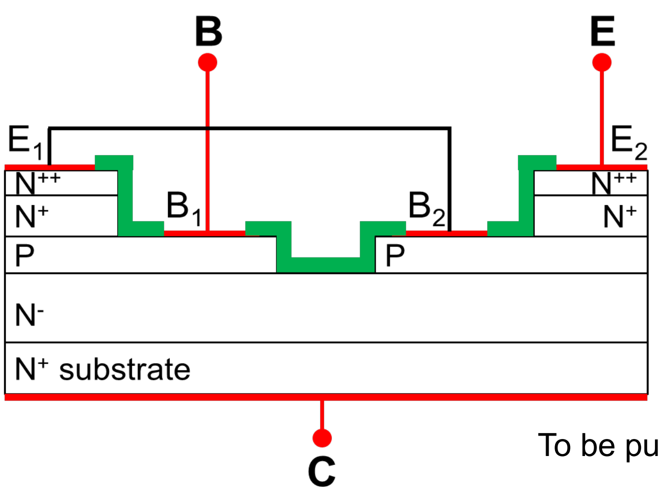
- Turn-on to I_C=6 A (140 A/cm^2), V_{CE} fall-time of 15 ns
- Turn-off to 800 V with V_{CE} rise-time of 12 ns, and negligible tail current
- Fast switching using 22 nF external base cap for dynamically increased I_B

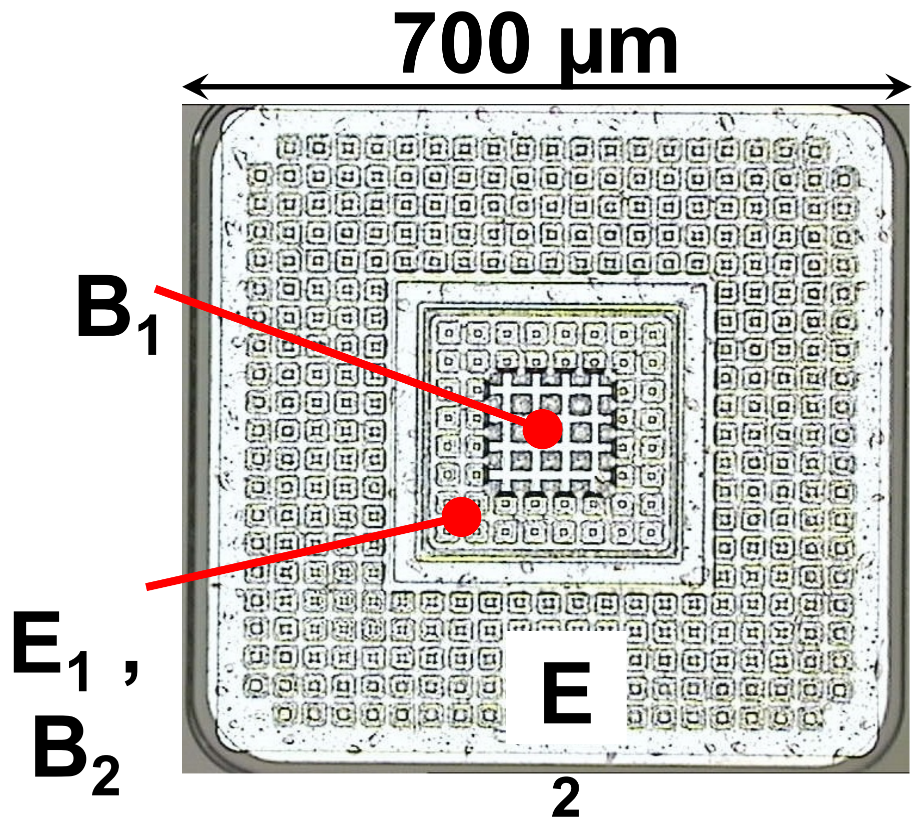

Electric field (MV/cm)
Lateral distance (μm)
Double-JTE
ST-JTE (5 Trenches)
ST-JTE (7 Trenches)
ST-JTE (14 Trenches)
Base edge
Mesa edge


Breakdown voltage (V)
Remaining dose (x10^13 cm^-2)
ΔBV = 700 V
ΔBV = 1750 V
ST-JTE-7 Trenches (Sim.)
ST-JTE-7 Trenches (Exp.)
ST-JTE-14 Trenches (Sim.)
ST-JTE-5 Trenches (Sim.)
Double-JTE (Sim.)
Double-JTE (Exp.)

Darlington pairs with square-cell intertwined layout design

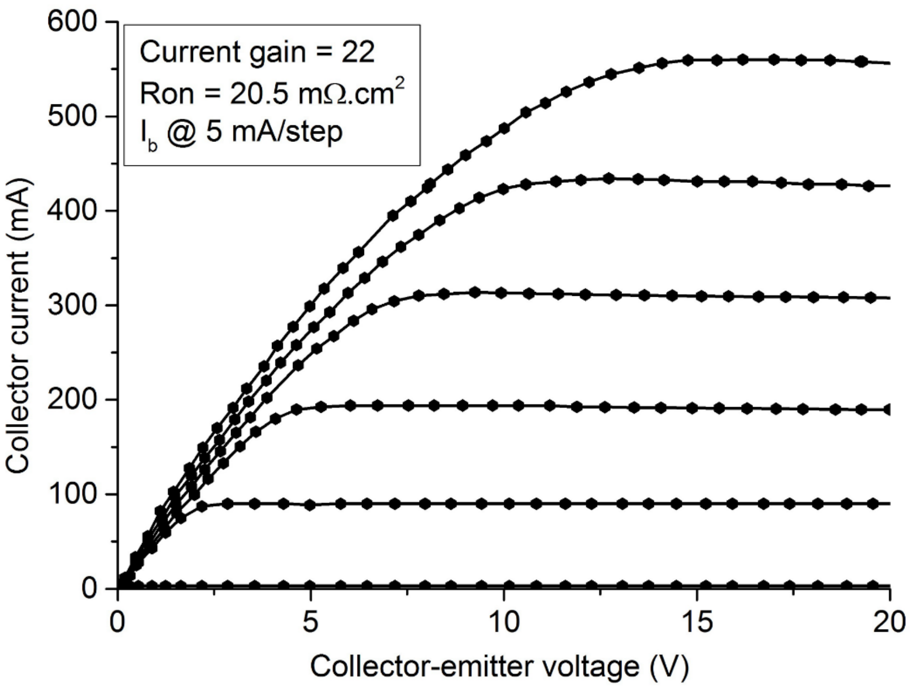


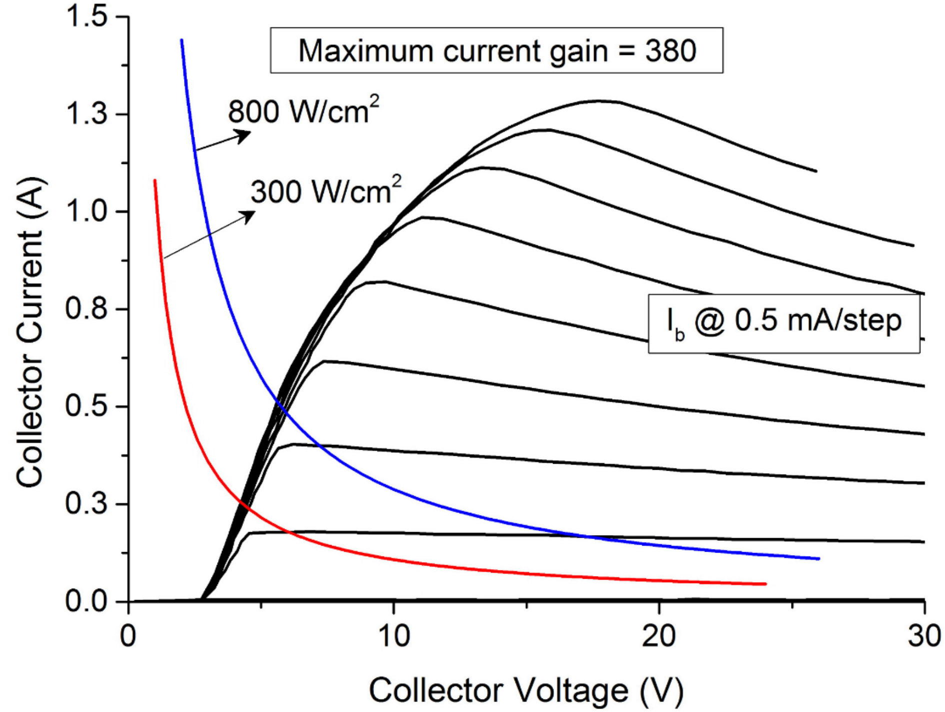




To be published in IEEE TED

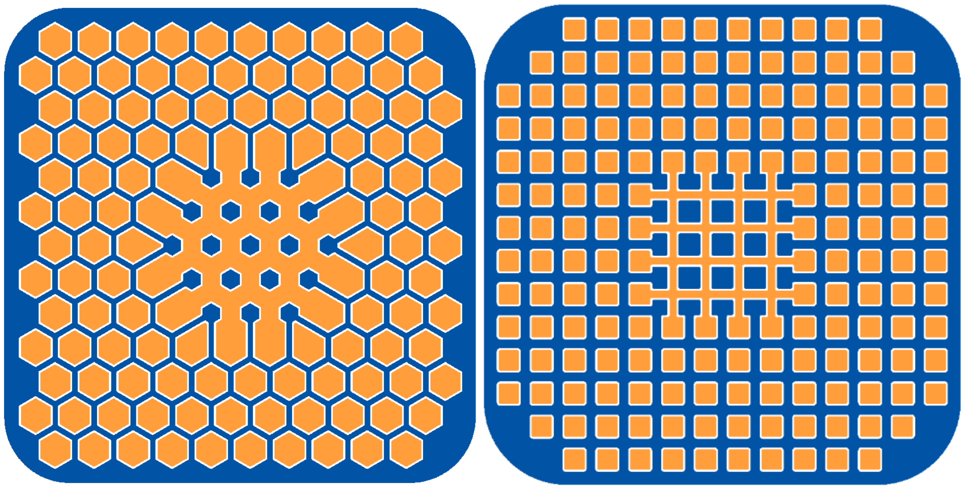
I-V Characteristics



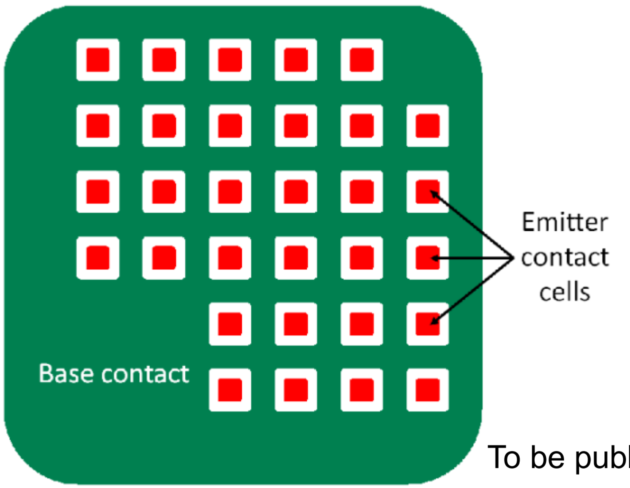


To be published in IEEE TED

Intertwined Design

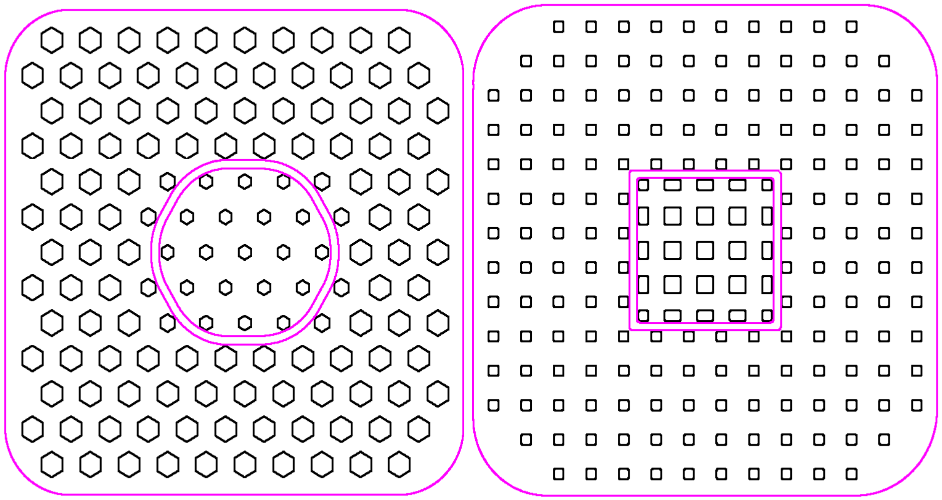


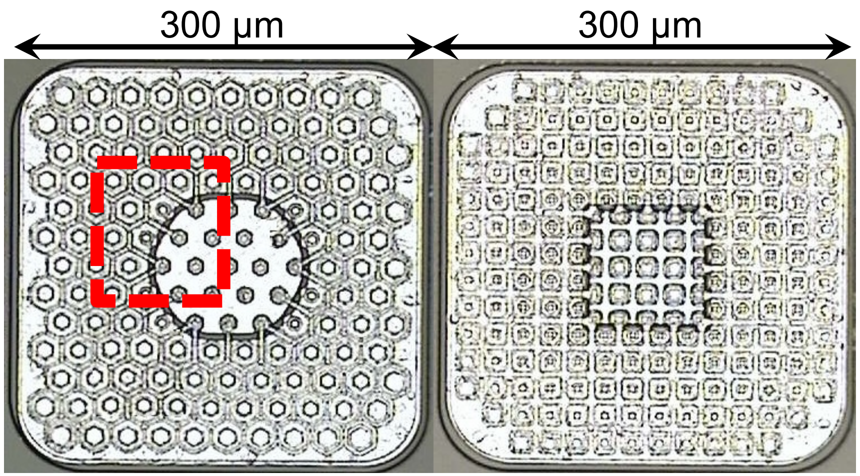
The hexagon and square emitter contacts (orange) and base contacts (blue) which are inverted in the center of BJTs to form the intertwined design.

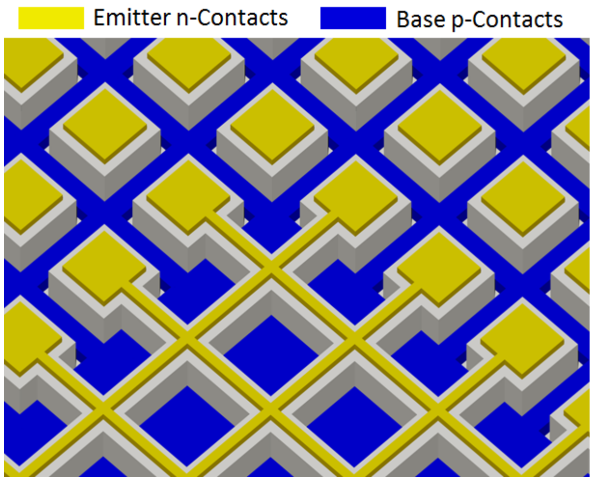


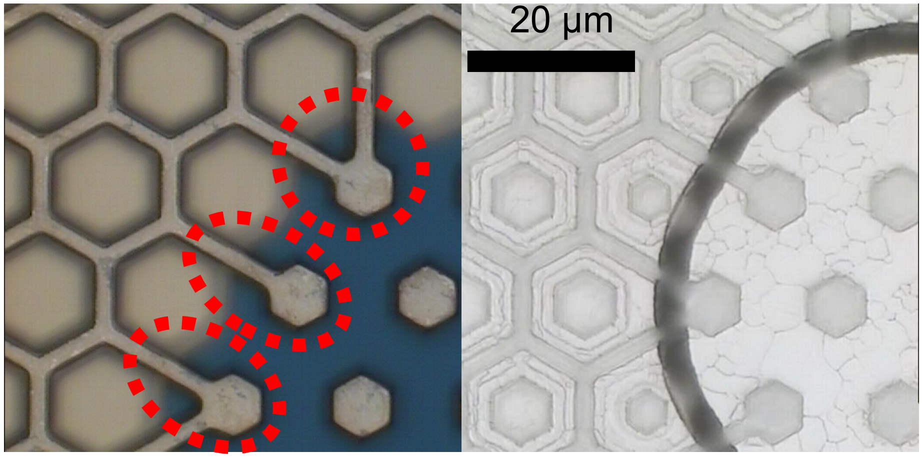
To be published in IEEE TED

The oxide openings (black) and top metal contacts (magenta).





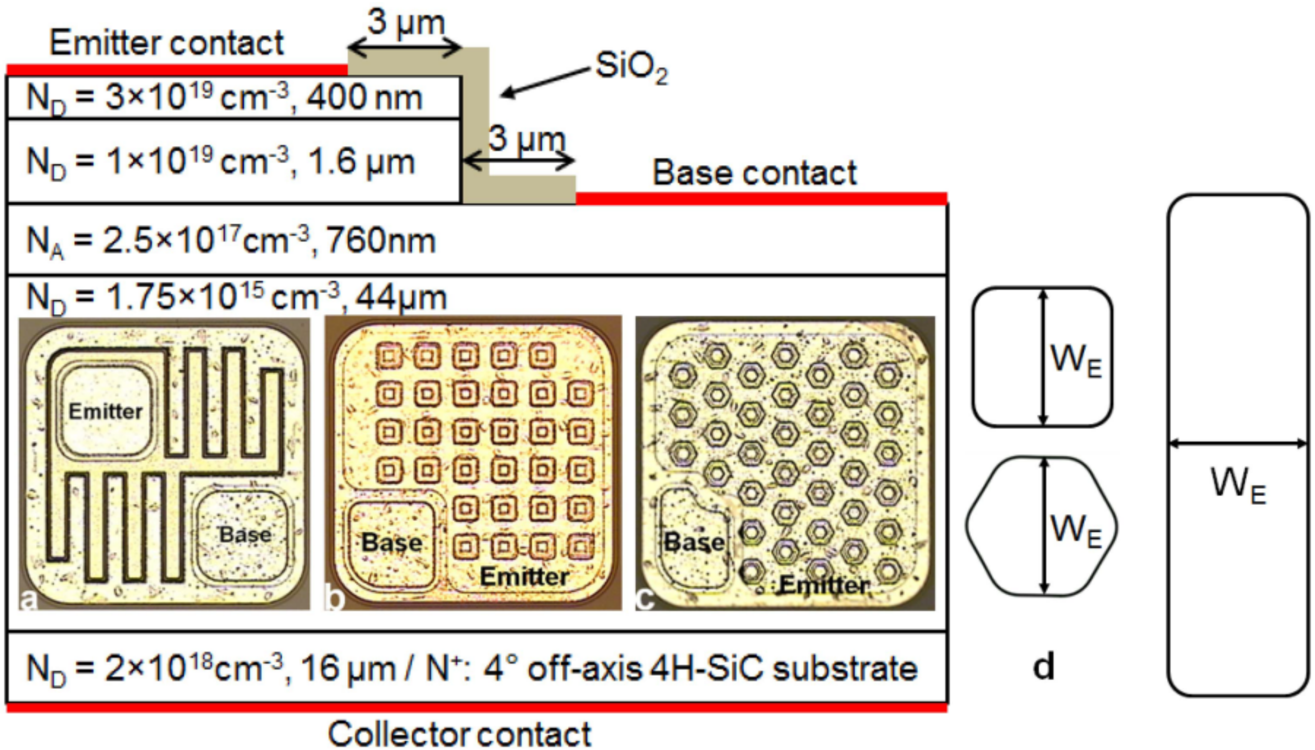




About 15% higher current density and lower On-resistance

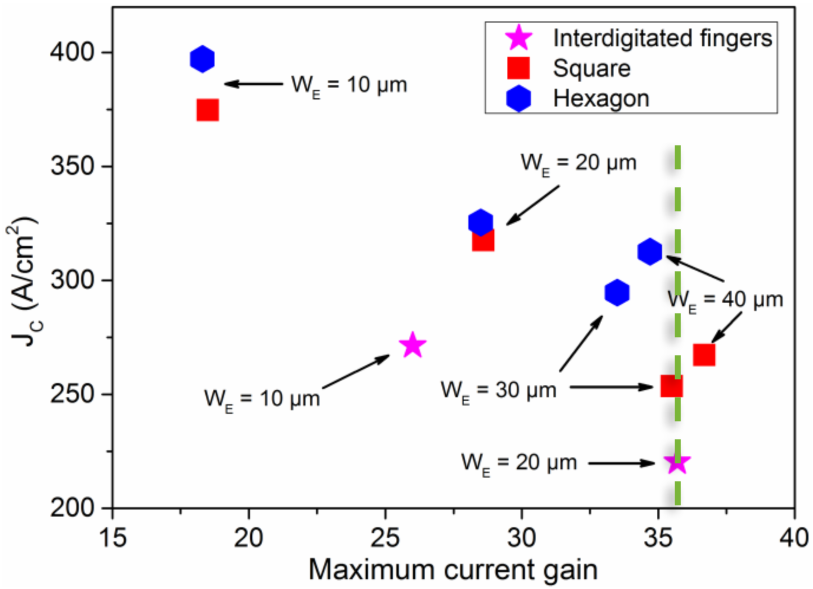
To be published in IEEE TED

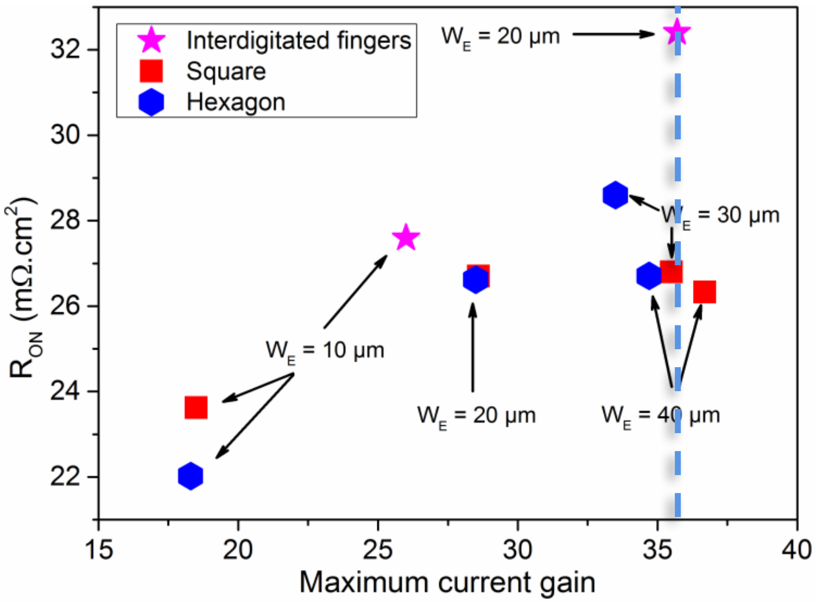
Emitter Cell Geometry



At the first time, new cell geometries (square and hexagon) were investigated for BJTs, which opens a new design space for improved performance.

Optimal Emitter Cell Geometry





42 % higher J_C and 21% lower R_{ON} for the new cell geometries due to a better utilization of the base area.

IEEE ELECTRON DEVICE LETTERS, VOL. 36, NO. 10, Oct. 2015

High Switching Speeds Enable Greater Power Density

Low Frequency Silicon vs. High Frequency Silicon Carbide

Comparisons

	80kHz	200kHz	Delta
PCB Area	23.9 in^2 154.1 cm^2	14.8 in^2 95.5 cm^2	-38%
Volume	47.8 in^3 782.8 cm^3	29.6 in^3 485.1 cm^3	-38%
Weight	18.4 oz. 521.6 gm	10.4 oz 294.8 gm	-44%
Density	10.5 W/ in^3 0.64 W/ cm^3	16.9 W/ in^3 1.03 W/cm^3	+61%