

**UNIVERSITY OF  
CAMBRIDGE**

**Thermal issues in high current power  
semiconductor devices**

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# REPORT DOCUMENTATION PAGE

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# **OUTLINE**

**I. Introduction to High Power IGBTs**

**II. Issues in IGBT operation**

**III. IGBTs in series**

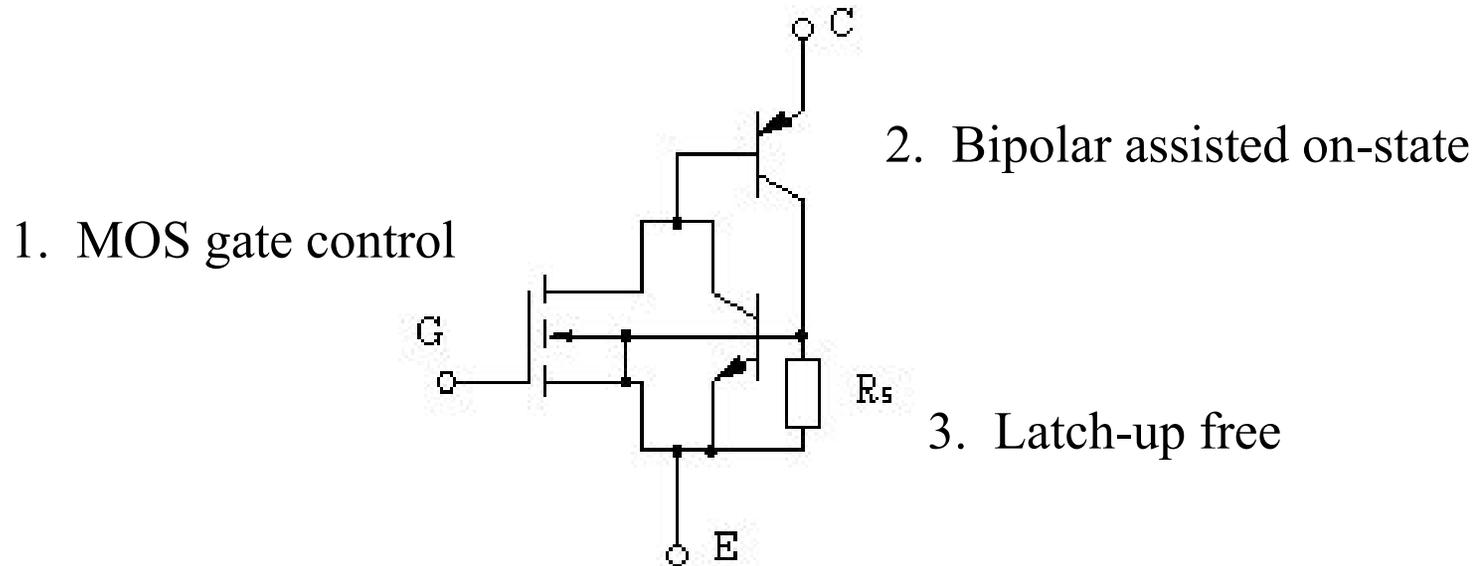
- **Future devices**

# **I Introduction to High Power IGBTs**

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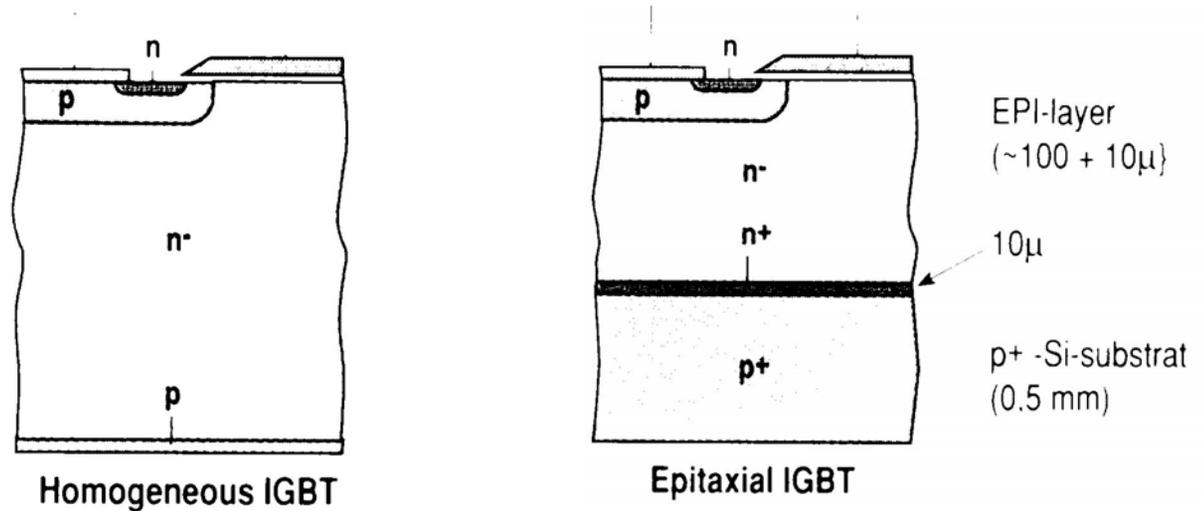
# The IGBT schematic

## Main Features



Ratings up to 2000A and 4.5kV

# IGBT STRUCTURES

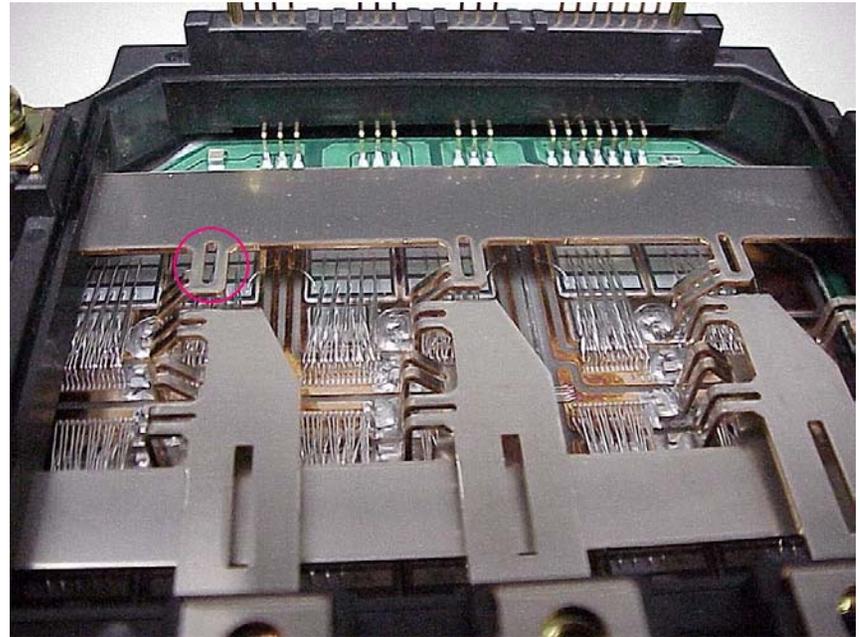


- Parasitic Thyristor is shorted out
- Wide-base pnp transistor
- Conventional MOS gate input

There are many variations including some Trench and Terraced Gates

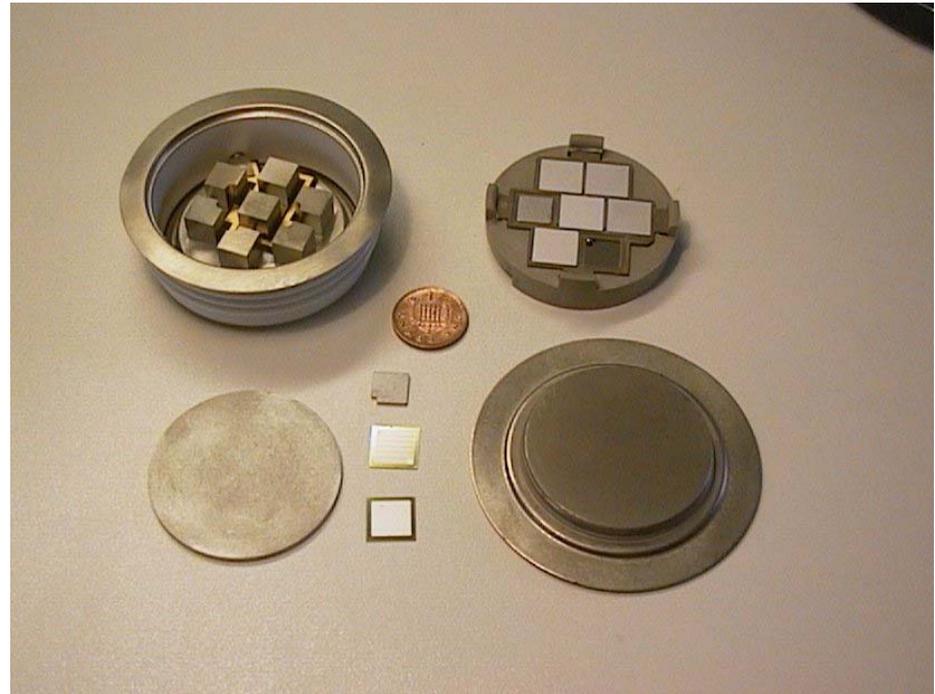
# MODULE IGBTs

- Permit simple inverter arrangement - Laminated busbars.
- Can be easily air cooled.
- Reliability is high.
- Are short circuit current rated.



# CAPSULE IGBTs

- Double sided cooling.
- Are easily water cooled.
- Reliable capsule package.
- Fail short circuit.



## **II Issues in IGBT operation**

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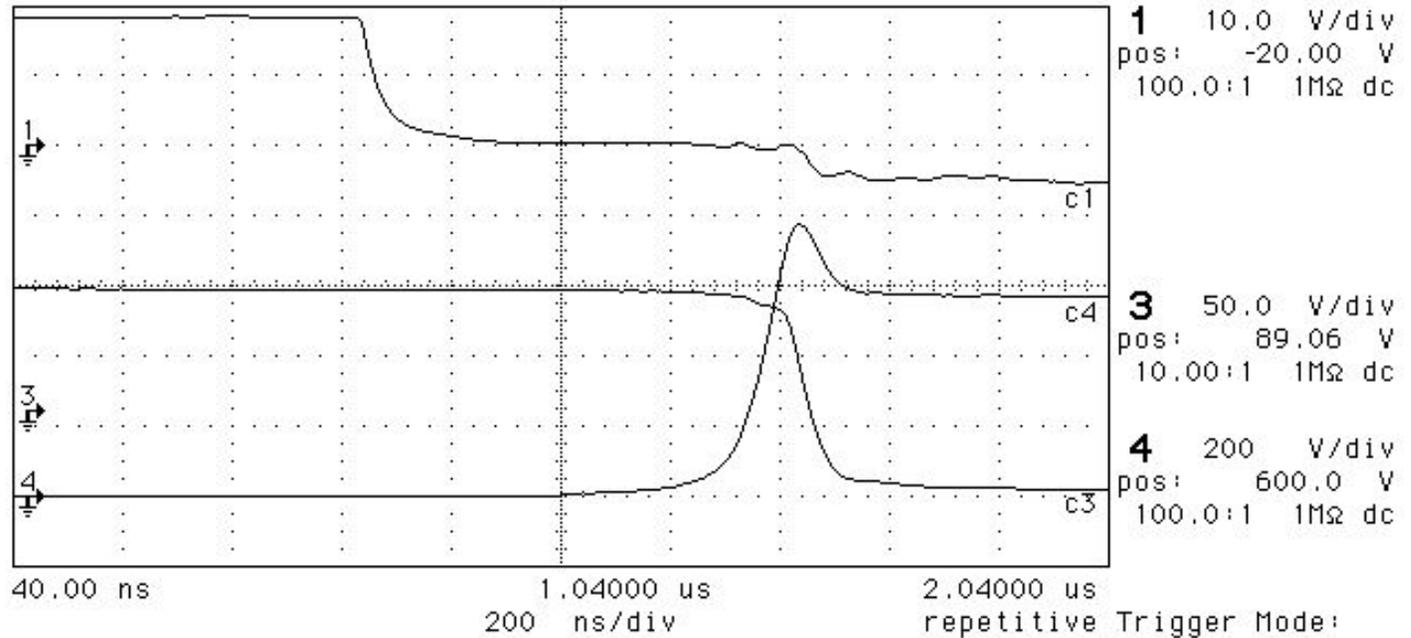
# SUMMARY OF ISSUES

For devices made of paralleled chips we must consider

1. Steady State current sharing
2. Transient current sharing
3. Stability in operation - gate resistors

Chip manufacturing and selection cannot produce closely matched chips and the package often introduces asymmetry in the cooling

# TYPICAL IGBT SWITCHING WAVEFORMS



C1 Gate voltage (10V/div)

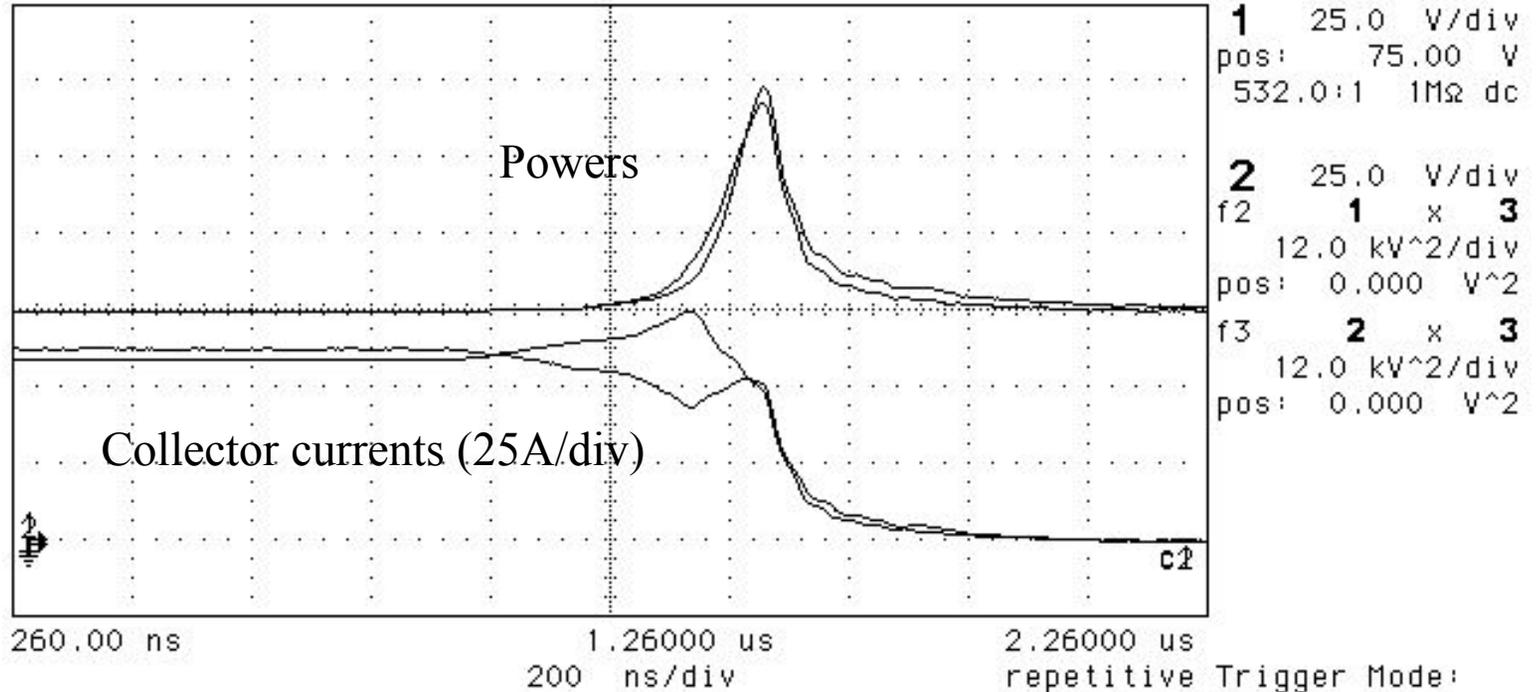
C3 Collector current (50A/div)

C4 Collector-emitter voltage (200V/div)

Note the significant gate 'plateau' period

# TRANSIENT CURRENT SHARING

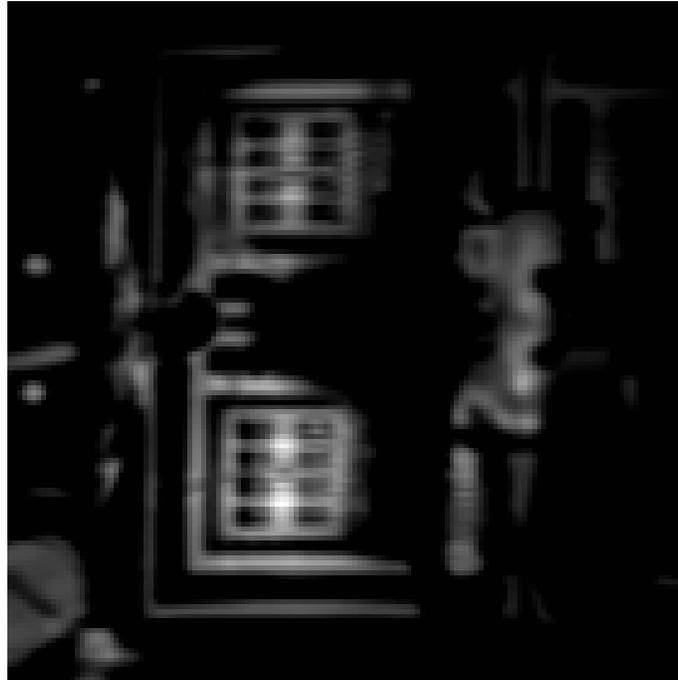
## Hard switched



- The divergence of the chip currents coincides with the gently rising collector-emitter voltage.
- No obvious problems.

# THERMAL IMAGE

Hard switched @ 4kHz

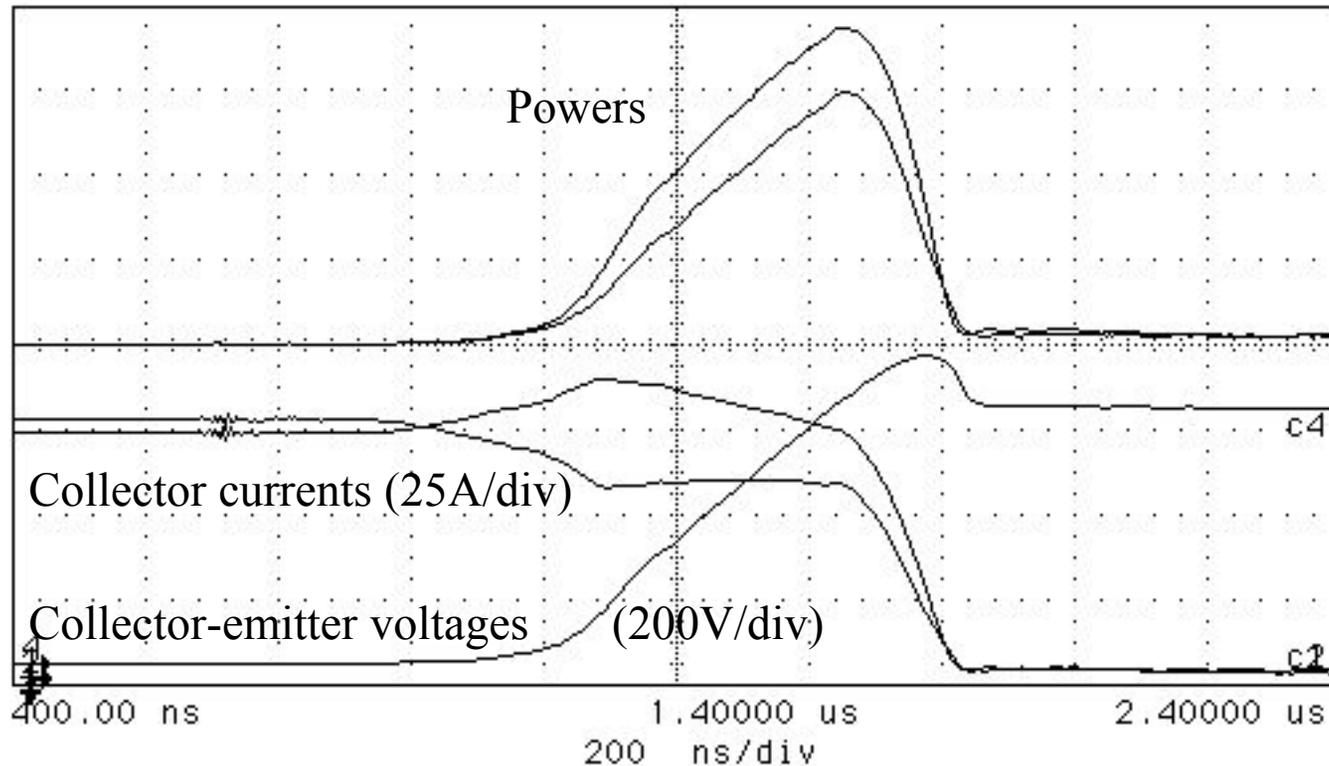


- Maximum temperature difference of about 3 °C

Positive feedback mechanism!

# TRANSIENT CURRENT SHARING

## Active $dv/dt$ Snubber



The form of the divergence varies with the circuit conditions

# THERMAL IMAGE

## Active $dv/dt$ Snubber @ 4kHz

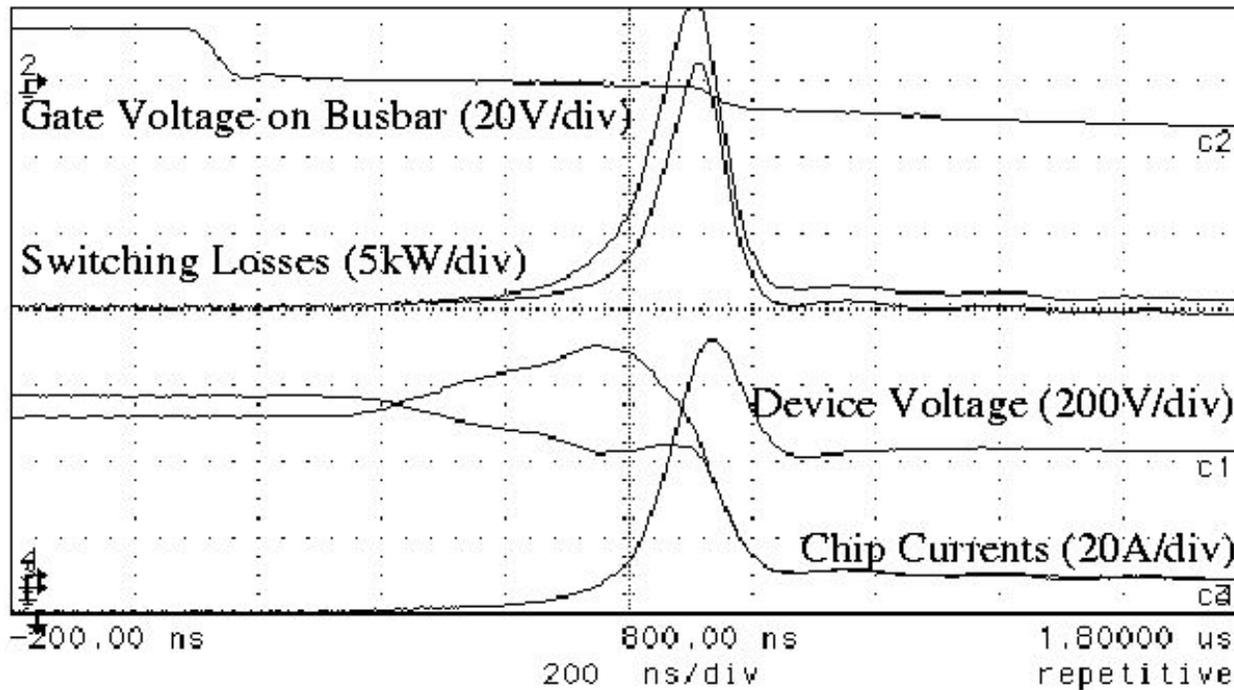


- Maximum temperature difference of about 10°C

# TRANSIENT CURRENT SHARING

## Matched Pair, Hot (100°C and 50°C)

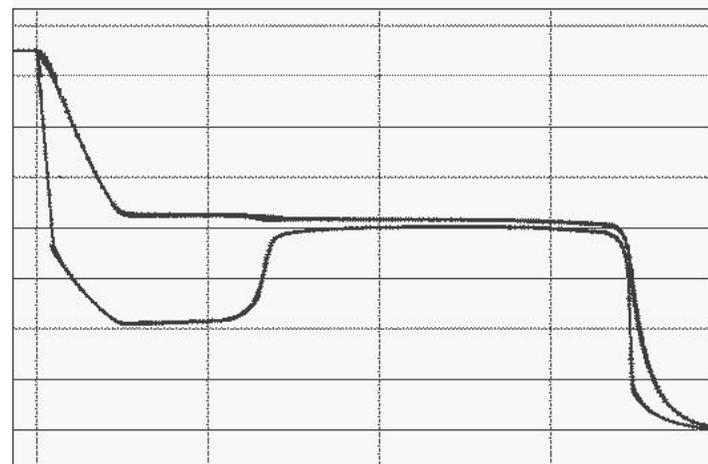
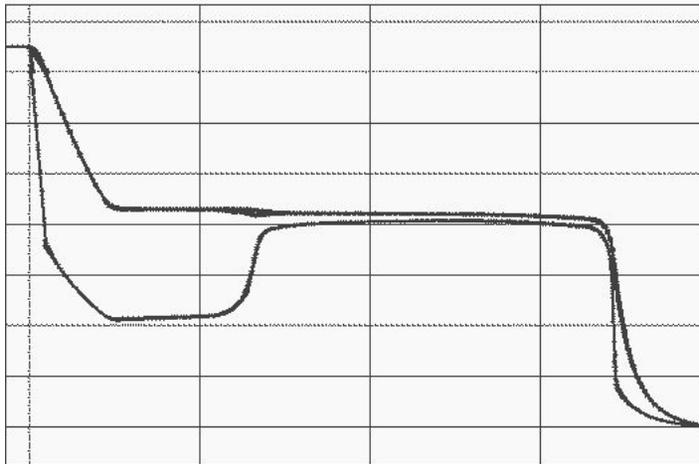
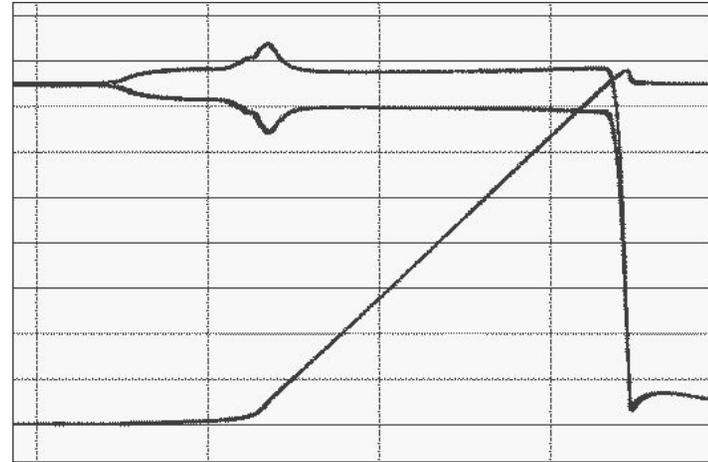
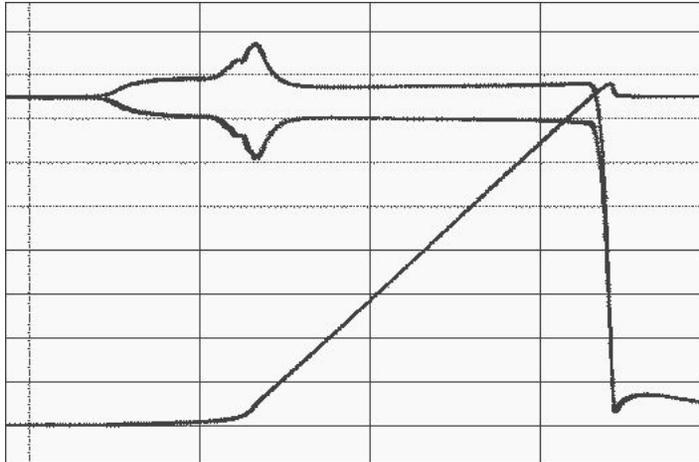
hp stopped



- Ideal behaviour is lost when the chips are at different temperatures.

And a positive feedback mechanism appears in the transient losses!

# TRANSIENT CURRENT SHARING - Silvaco



1% Gate oxide difference

2.7% P-base doping difference

Ideally matched devices cannot be made!

# **III IGBTs in series and the 2-Step method**

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# THE SERIES CONFIGURATION

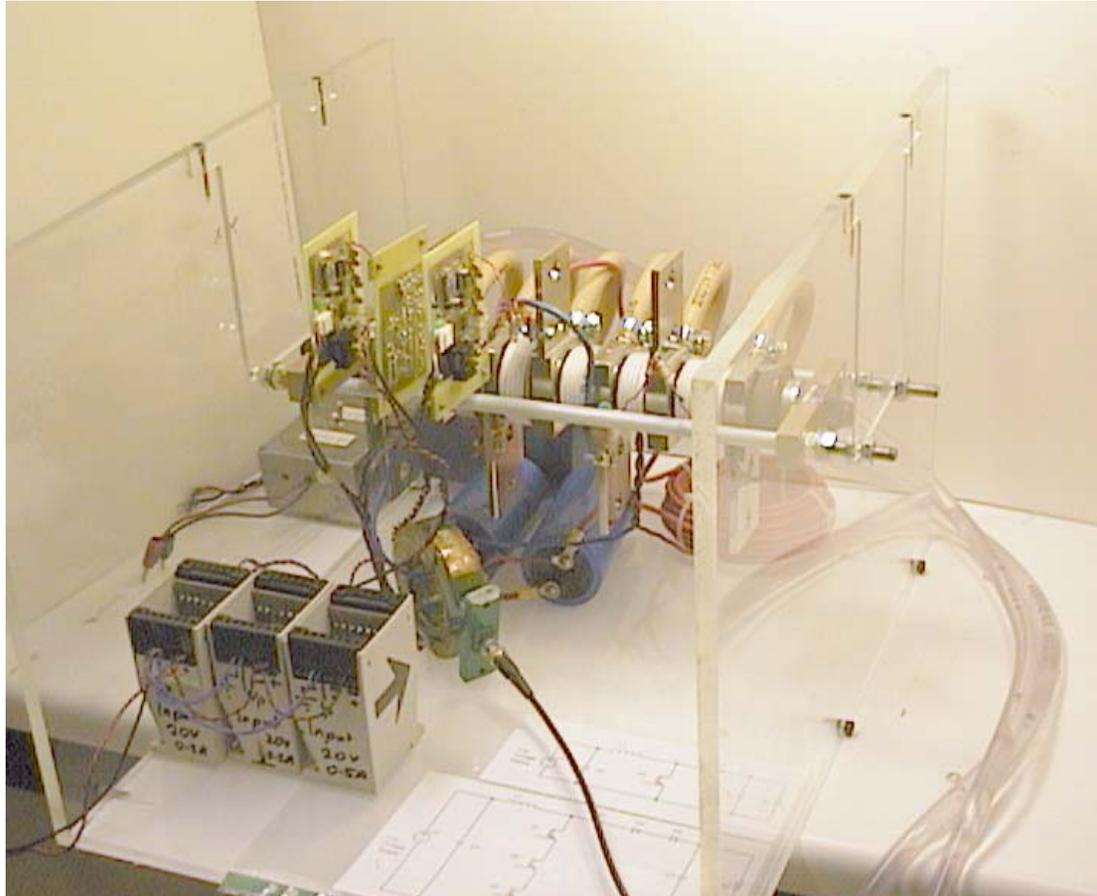
Necessity for seriesing:

1. To achieve high voltage ratings
2. To utilise low voltage devices - cheaper?
3. Redundancy

- Many new applications are appearing due to deregulation and distributed generation with new energy sources.

For example: ABB's 'HVDC Lite'

# HIGH VOLTAGE SERIES IGBT RIG



Three capsule IGBTs and three Diodes in series with water cooling

# Specification of the Westcode Capsule IGBT

- 400A, 1700V 'development' devices
- 47mm diameter, hermetic, cold weld
- Each capsule has 5 IGBT chips, 2 anti-parallel diodes
- On state volts of 5V
- Internal diode rating 400A,  $V_f = 2V$ ,  $t_r = 550ns$
- Thermal resistance IGBT 55K/kW, diode 84K/kW

# ISSUES IN SERIES CONNECTION

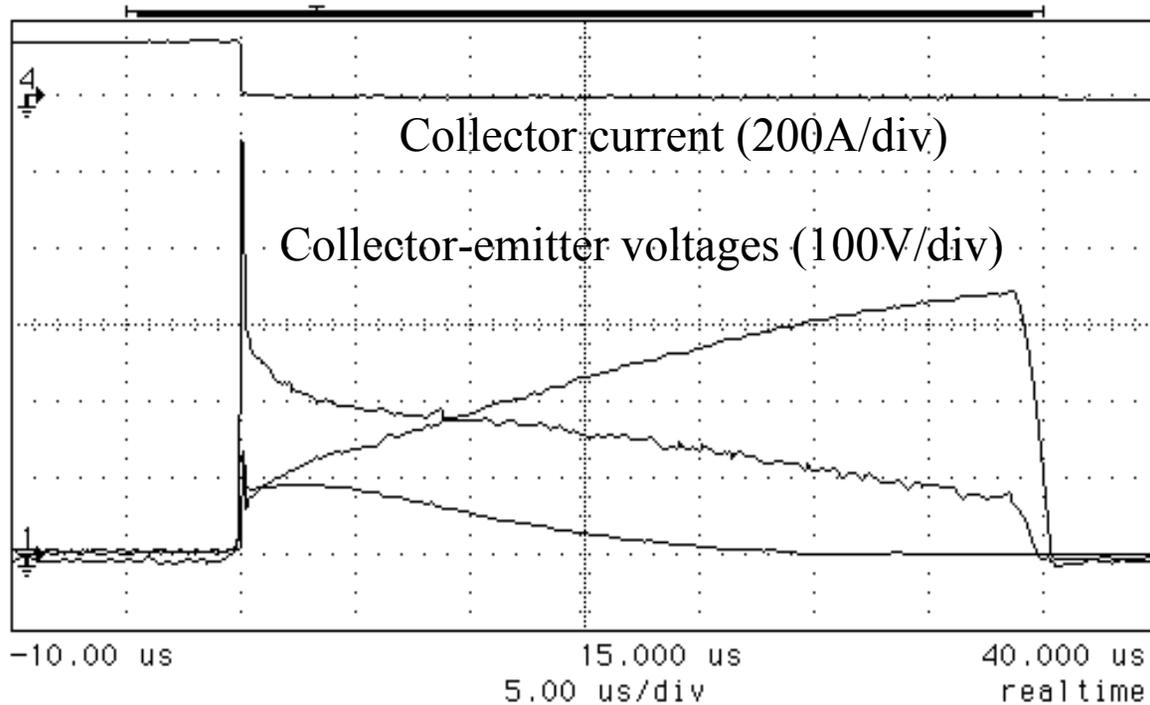
The voltage sharing problem can be divided up:

- transient behaviour
- steady state behaviour
- losses.

Driven by:

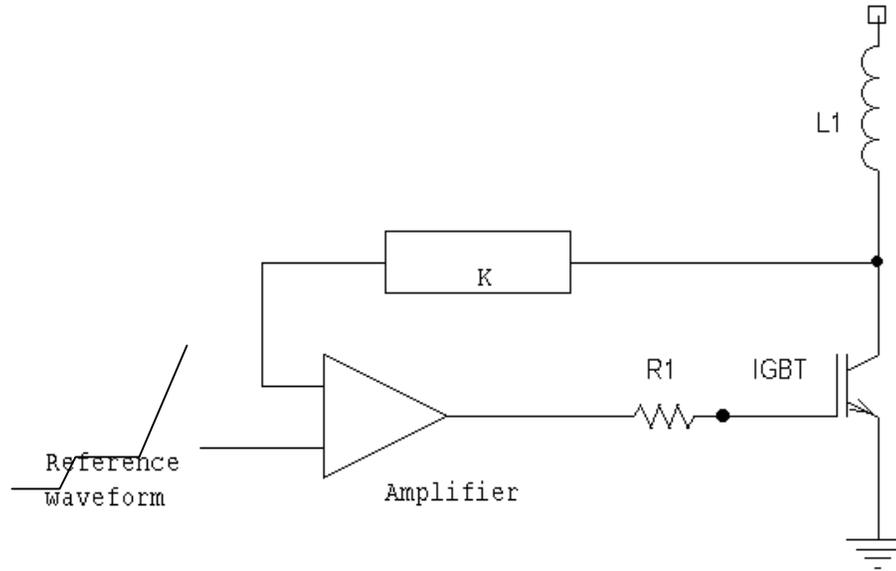
- differences between similar devices
- long term maintainability
- total cost over whole life.

## HARD SWITCHED - 3 devices in series



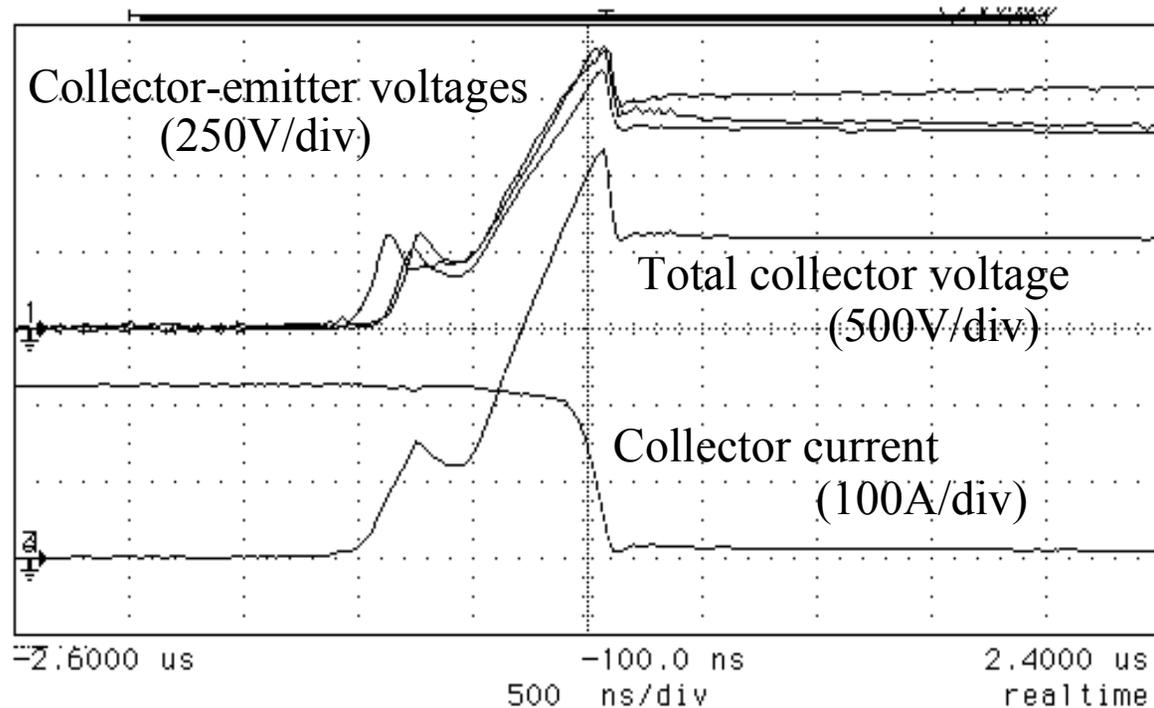
- The poor transient sharing is followed by poor sharing in the off state.

# ACTIVE VOLTAGE CONTROL PRINCIPLES



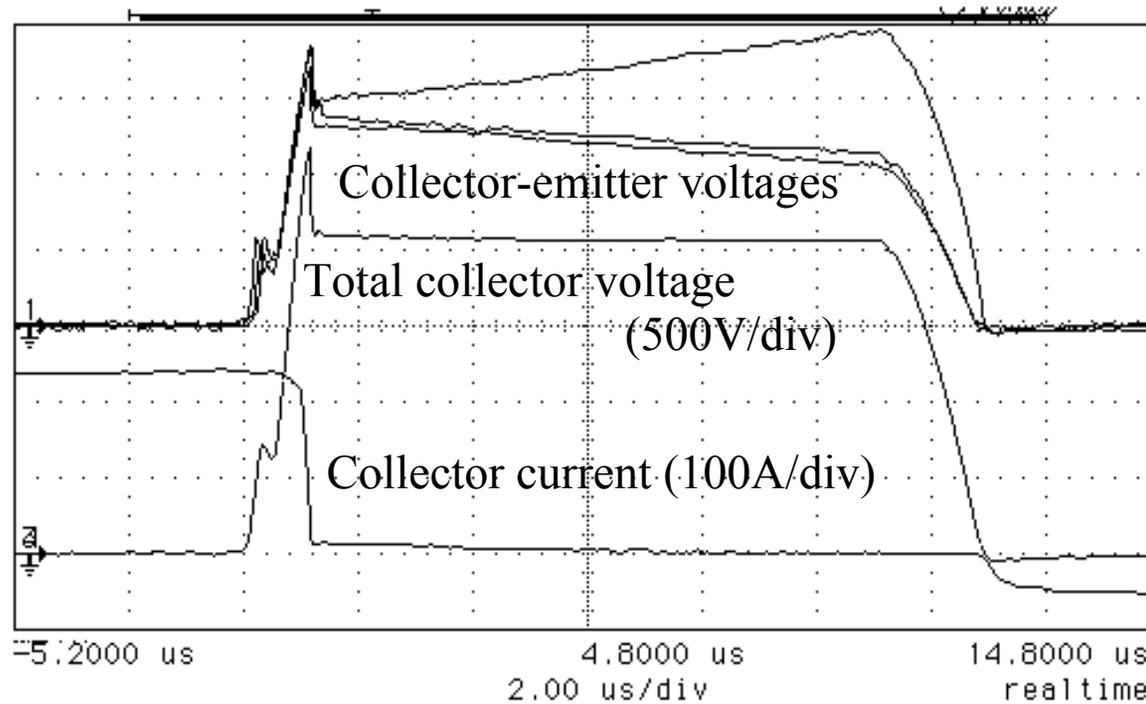
- Utilises the IGBT's gate control capability
- Closed Loop Voltage Control
- Collector voltage follows reference waveform

## ACTIVE VOLTAGE CONTROL - 3 devices in series



- Small preconditioning step followed by turn-off ramp.
- Poor transient sharing in step 1 followed by excellent sharing in the ramp.

# ACTIVE VOLTAGE CONTROL - 3 devices in series



- Sharing in the off state is much improved also.

Off-state characteristics are temperature dependent

# **IV Future Devices**

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# TECHNOLOGY DRIVERS

- High Ratings: 6.5 kV, 1000A IGBTs
  - Very high switching losses per unit volume
- High Temperatures: SiC , 300 °C
  - Materials issues within the package
- Integrated Systems: Power chips and logic/microprocessors in one plastic package
  - Large Power ‘Bricks’

# CONCLUSIONS

- The thermal arrangement must be symmetrical to ensure balanced operation.
- Plastic and Capsule devices are reliable under typical conditions, but asymmetries cause problems when switching at a high frequency.
- Feedback control offers exciting opportunities.
- New Si and SiC devices demand better packages.
- New package topologies are needed to remove some of the stability problems and make power bricks more practical.

## V SELECTED PUBLICATIONS

- "Non-invasive measurement of chip currents in IGBT modules". *P.R. Palmer*, B.H. Stark and J.C. Joyce, IEEE PESC' 97 Vol. 1, pp.166-171, St Louis, June 1997
- "Current redistribution in multichip IGBT modules under various gate drive conditions", *P.R. Palmer* and J.C. Joyce, PEVD'98, IEE Conference Publication No. 456, pp. 246-251, London, Sept. 1998
- "Some causes of current redistribution in IGBTs during turn off", J.C. Joyce and *P.R. Palmer*, IEEE/IEEJ International Symposium on Power Semiconductor Devices and ICs, pp. 273-, Toronto, May 1999
- "The use of capsule IGBTs in the series connection", *P.R. Palmer*, H.S.Rajamani, N.Dutton, PEVD'00, IEE Conference Publication No. 475, pp. 250-255, London, Sept. 2000
- "A formalised method for effecting multiple modes in single MOS gated power devices", *P.R. Palmer* and B.H. Stark, IEE Proceedings on Circuits, Devices and Systems, Vol. 146, No. 4, pp. 203-209, August 1999

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