ETH
Eidgenössische Technische Hochschule Zürich
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Electronics around the power switch:
Gate drives, sensors and control
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Power Electronic Systems Laboratory

Voltage, Current and Temperature Measurement Concepts Enabling Intelligent Gate Drives

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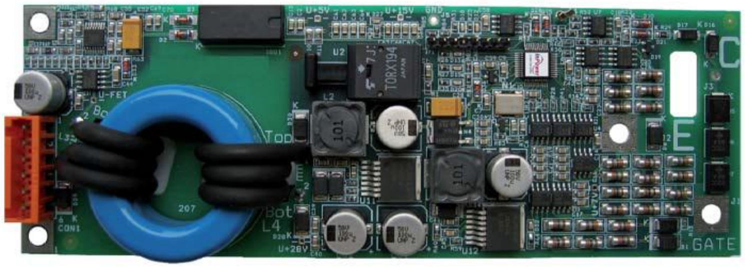
Motivation

Intelligent Gate Drive

- Digital control unit (FPGA, CPLD, DSP) with computing power close to the power semiconductor
  - Programmable output characteristics [Hemmer2009]
  - Advanced control (di_C/dt, du_{CE}/dt) [Kuhn2008]
  - Extended and adjustable protection functionality (short-circuit, over-current, overvoltage-limiting, health monitoring, ...)
  - Extensive communication possibilities (digital transmission bus with control unit)



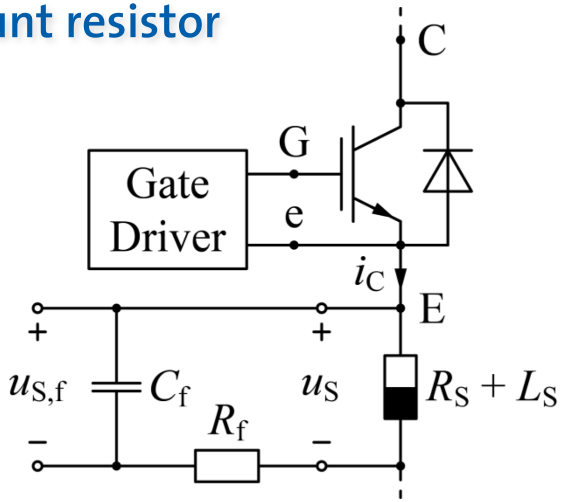
InPower digital gate driver

Need for measurements

- Integratable in gate driver, external circuits and IGBT; typ. without galvanic isolation
- Current measurement concepts
  - Collector current: i_C
  - Collector current slope: di_C/dt
- Voltage measurement concepts
  - Collector-Emitter voltage: u_{CE}
  - Collector-Emitter on-state voltage: $u_{CE,on}$
  - Collector-Emitter voltage slope: du_{CE}/dt
- Temperature measurement concepts
  - Junction temperature: T_j

Current measurement: i_C

Shunt resistor



Semikron Semitrans®
IGBT module with
integrated shunts

Infineon MIPAQ™ IGBT module
with integrated shunts
(in the output phases)

$$u_S(t) \approx R_S \cdot i_C(t) + L_S \cdot di_C(t)/dt$$

$$u_{S,f}(t) = R_S \cdot i_C(t) \quad \text{(for } R_f \cdot C_f = L_S / R_S\text{)}$$

(–)

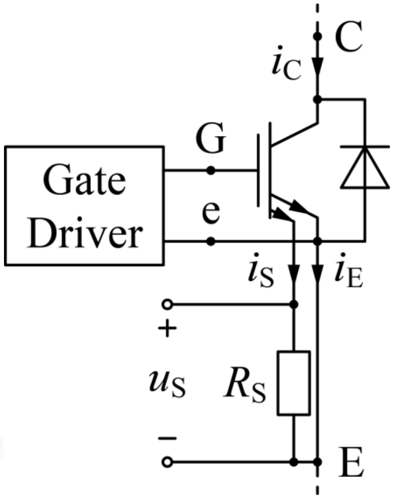
- Losses: $P_L \approx R_S \cdot i_C^2$
  - Low losses = low amplitude resolution
  - Temperature drift
- Parasitic (commutation) inductance L_S
  - Accurate compensation needed

(+)

- Simple, cheap, passive
  (low noise & low disturbance)
- Possibility of integration in IGBT module
  (Infineon MIPAQ™, Semikron Semitrans®)
  or busbar (well dissipated losses)
- DC & AC measurement $u_{S,f}(t) \sim i_C(t)$
  (high bandwidth due to compensation of L_S)

Current measurement: i_C

Current sense IGBT
(split-cells: n_S / n_{tot})



Mitsubishi Electric IGBT module with integrated current sense IGBT and corresponding terminals

$$u_S(t) = R_S \cdot i_S(t)$$
$$\approx R_S \cdot i_C(t) \cdot n_S / n_{tot}$$

(typ.: n_S / n_{tot} = 1/100 … 1/1000)

(+)

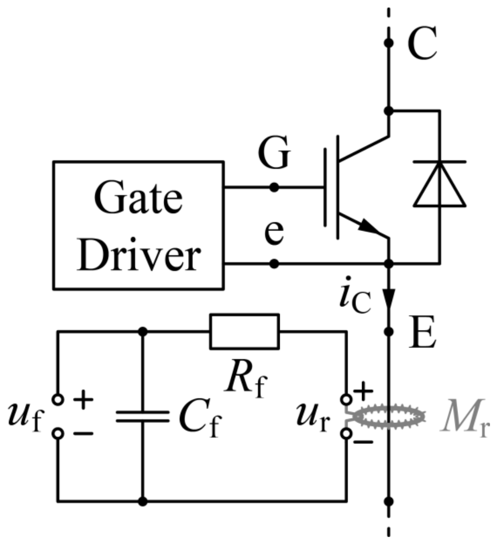
- Simple, passive
  (low noise & low disturbance)
- Integrated in IGBT module
  (Fuji Electric, Mitsubishi Electric)
- High bandwidth
- AC & DC measurement: $u_S(t) \sim i_C(t)$
- Low losses

(–)

- High accuracy = low resolution
  - Small R_S is needed for right scaling
- Cost, rarity
  - Only few types available
  - Often no alternatives

Current measurement: i_C

Rogowski coil (passive integration)

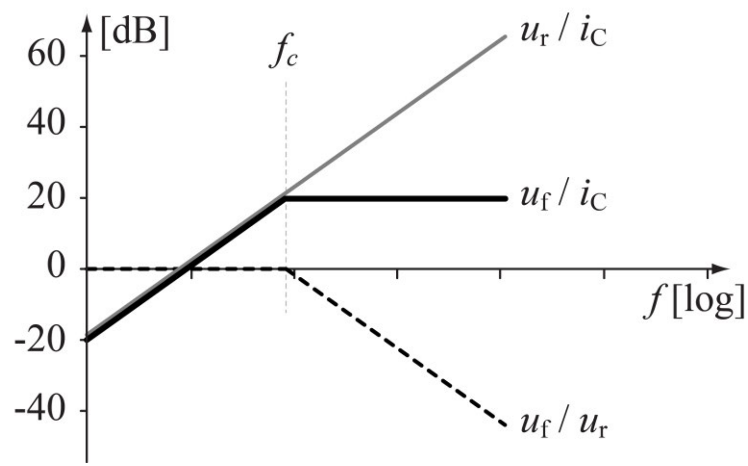


$u_r(t) = M_r \cdot di_C(t)/dt$

(-)

- No DC current measurement (high lower bandwidth f_c)
- Typ. too low amplitude resolution
- Signal integration needed

Amplitude characteristic of u_r / i_C | u_f / u_r | u_f / i_C

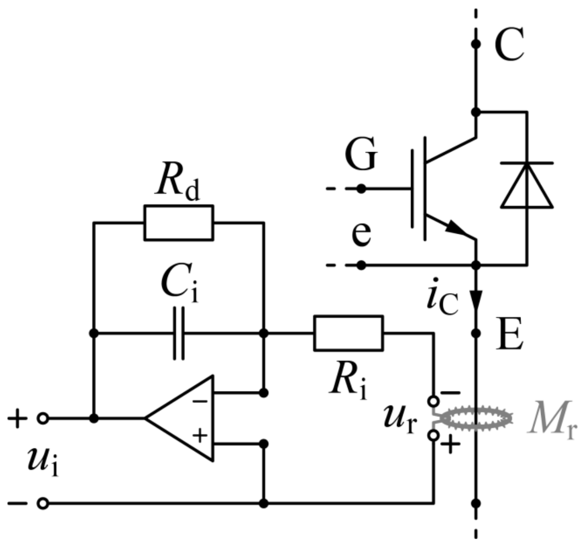


(+)

- Simple, cheap, passive (low noise & low disturbance)
- High upper bandwidth (typ. f_u > 50 MHz)
- Integration in PCB / IPEM possible
- High freq. AC measurement: $u_r(t) \sim i_C(t)$
- Low losses
- Isolated, no saturation effects
- No additional commutation inductance

Current measurement: i_C

Rogowski coil (activeintegration)

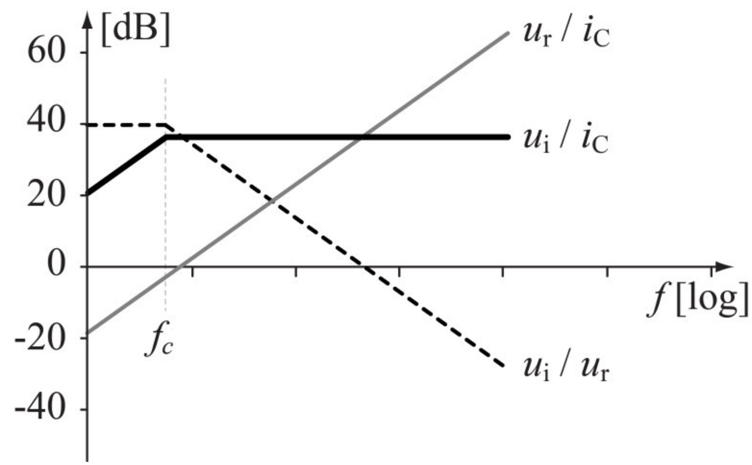


$u_i(t) \approx M_r / (R_i \cdot C_i) \cdot i_C(t)$ (for $f_{iC} > f_c$)

(-)

- Active (noise)
- Parasitic effects of operational amplifier
  - Bias current, offset voltage (R_d avoids DC-drift)
  - Limited gain-bandwidth-product
  - Limited lower bandwidth f_c, no DC

Amplitude characteristic of u_r / i_C | u_i / u_r | u_i / i_C

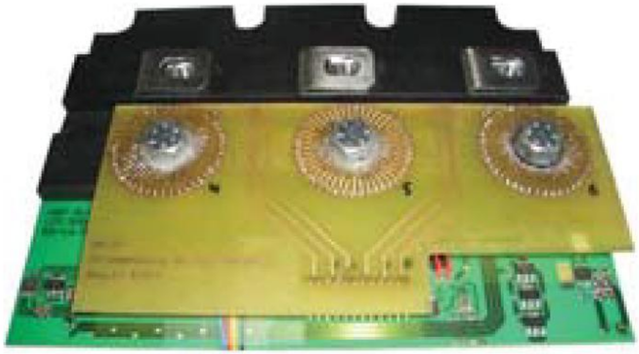


(+)

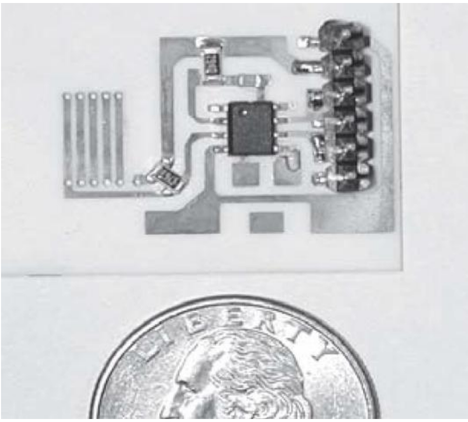
- Simple, cheap
- High upper bandwidth (typ. f_u > 50 MHz)
- Small lower bandwidth (typ. f_c < 50 Hz)
- Integration in PCB / IPEM possible
- Low to high freq. AC measurement: $u_i(t) \sim i_C(t)$
- Low losses
- Isolated, no saturation effects
- No additional commutation inductance

Integration of Rogowski coil to

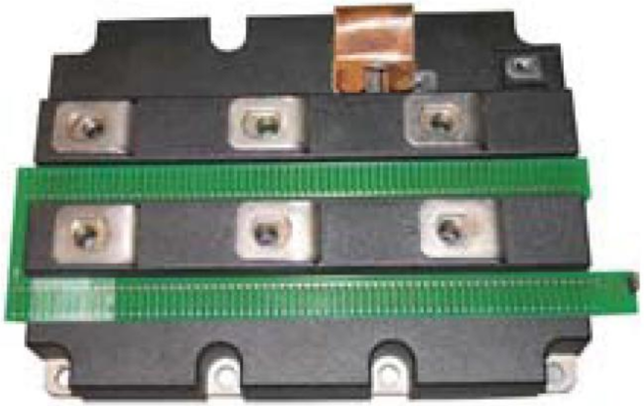
- IPEM
- PCB



[Bortis2008]
PCB integrated Rogowski coils
around single screwed terminals



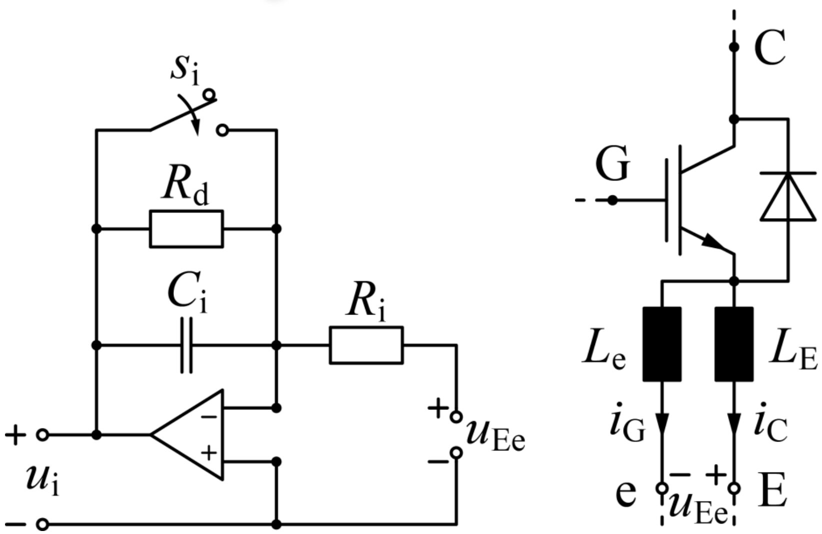
[Xiao2003]
Prototype of IPEM embedded
Rogowski coil sensor



[Bortis2008]
PCB integrated Rogowski coil
around multiple screwed terminals

Current measurement: i_C

IGBT bonding inductance



$$u_{Ee}(t) = -L_E \cdot di_C(t)/dt + L_e \cdot di_G(t)/dt$$

$$u_i(t) \approx (L_E \cdot i_C(t) - L_e \cdot i_G(t)) / (R_i \cdot C_i)$$

s_i is used to minimize the influence of i_G
(s_i closed during the gate current transients,
i.e. before the switching transients of i_C)

(-)

- Auxiliary (kelvin) emitter terminal needed
- Dependency on gate current
  - Resettable integrator circuit beneficial
- Parasitic effects of operational amplifier & switch
  - Bias current, offset voltage (R_d or s_i to avoid DC-drift)
  - Limited gain-bandwidth-product
  - Limited lower bandwidth f_c, no DC measurement
- Parasitic inductance L_E integrated in IGBT module
  - Depencency on tolerances of manufacturing process for accurate measurements without calibration

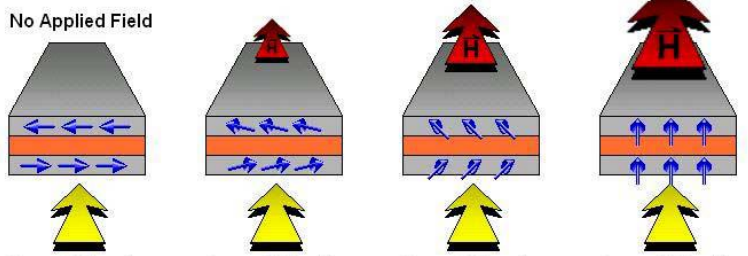
(+)

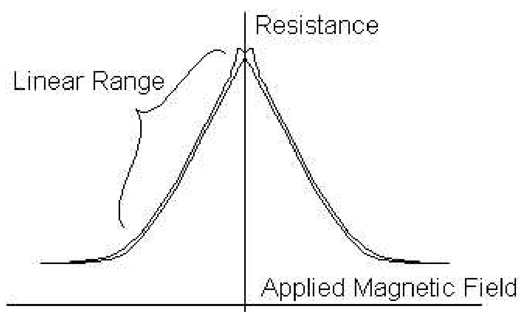
- Simple, cheap
- High upper bandwidth (typ. f_u > 50 MHz)
- Small lower bandwidth (typ. f_c < 50 Hz)
- Parasitic inductance L_E integrated in IGBT module
  - no sensing hardware needed
- Low to high freq. AC measurement: $u_i(t) \sim i_C(t)$
- Low losses
- No additional commutation inductance

Current measurement: i_C

Giant Magnetoresistive (GMR) Sensor

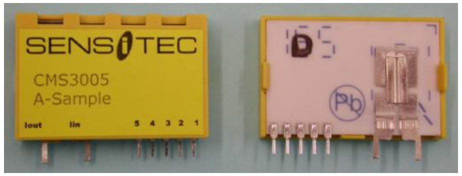
High resistance [Shah2004] Low resistance



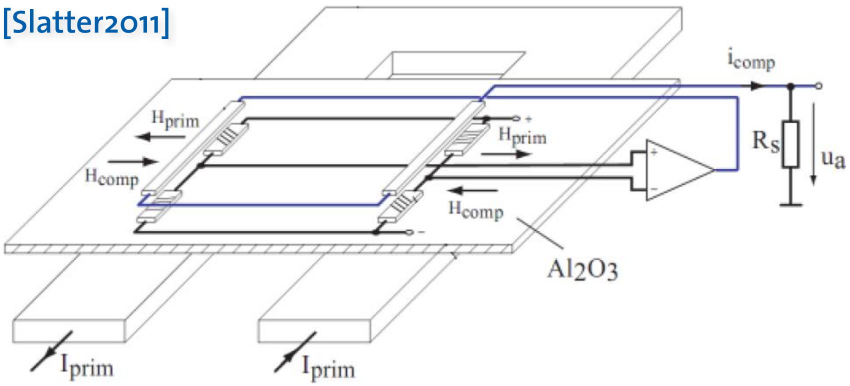


[Olson2003]

Prototype of Sensitec's GMR current sensor (CMS) $f_u \approx 4$ MHz



[Slatter2011]



(+)

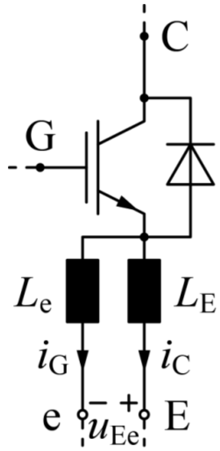
- DC to AC current measurement
- Possibility of integration to IPEM
- Low losses

(-)

- Additional commutation inductance
- Limited upper bandwidth (cf. Rogowski coil)
  - Sensitec CMS series: $f_u \approx 4$ MHz
- Active (noise)
- Evaluation & compensation circuit needed

Current derivative measurement: di_C/dt

Bonding inductance



$$u_{Ee}(t) = -L_E \cdot di_C(t)/dt + L_e \cdot di_G(t)/dt$$

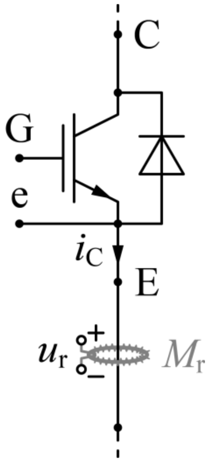
(+)

- Simple, cheap, no sensing hardware needed
- Accurate (direct signal measurement)

(-)

- Auxiliary (kelvin) emitter terminal needed
- Dependency on manufacturing process

Rogowski coil



$$u_r(t) = M_r \cdot di_C(t)/dt$$

(+)

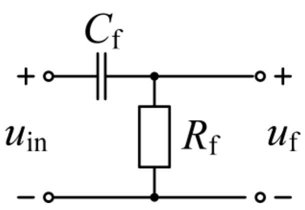
- Simple, cheap
- Accurate (direct signal measurement)

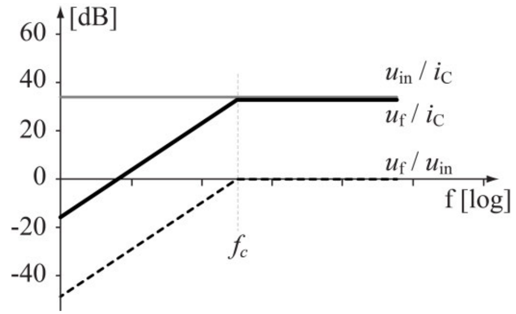
(-)

- Rogowski coil needed
- Dependency on stray field

Current derivative measurement: di_C/dt

Passive derivation of current signal u_{in}





$u_f(t) = a \cdot du_{in}(t)/dt = b \cdot di_C(t)/dt$ (for $f_{in} < f_c$)

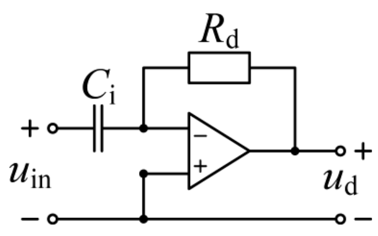
(+)

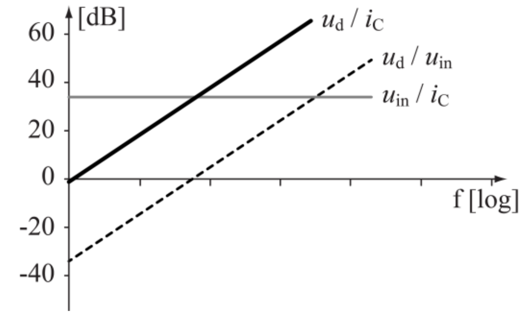
- Simple, cheap
- Passive (low noise)

(-)

- Indirect measurement (derivation)
- Low amplitude resolution
- High amplitude = low bandwidth

Active derivation of current signal u_{in}





$u_d(t) = a \cdot du_{in}(t)/dt = b \cdot di_C(t)/dt$

(+)

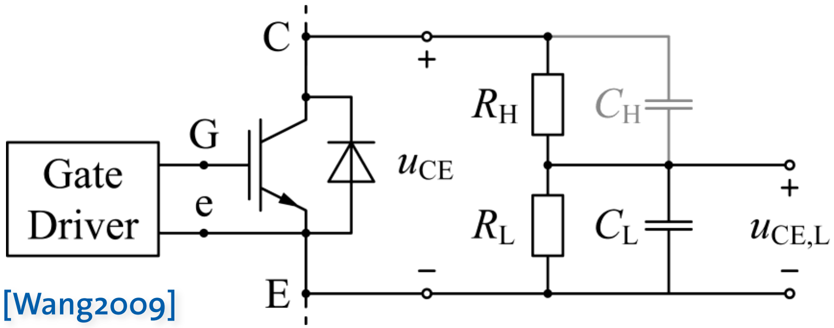
- Simple, cheap
- High amplitude

(-)

- Indirect measurement (derivation)
- Active (noise)
- High amplitude = high noise

Voltage measurement: u_{CE}

Compensated passive voltage divider



[Wang2009]

$$u_{CE,L}(t) = R_L / (R_H + R_L) \cdot u_{CE}(t)$$

(for $C_L = C_H \cdot R_H / R_L$)

(+)

- Simple, cheap
- Passive (low noise)
- High bandwidth, adjustable gain

(-)

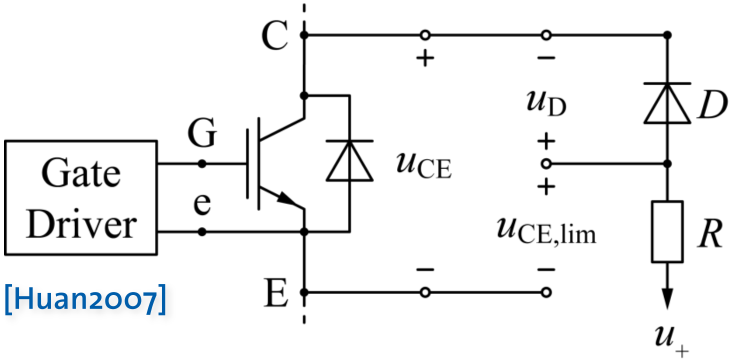
- Additional IGBT output capacitance
- Blocking voltage of R_H is about $u_{CE,max}$

Typ. no additional capacitor C_H needed as the parasitic capacitances of R_H and the PCB layout are high enough for compensation with C_L

- Minimal possible output capacitance
- High impedance

Voltage measurement: $u_{CE,on}$

Decoupling diode *D*



[Huan2007]

$$u_{CE,lim}(t) = u_{CE}(t) + u_{D,f} \quad (\text{for } u_{CE} < u_+ - u_{D,f})$$

$$u_{CE,lim}(t) = u_+ \quad (\text{for } u_{CE} >= u_+ - u_{D,f})$$

- Voltages of u_{CE} above $u_+ - u_{D,f}$ are clipped by diode *D* that is then in blocking state
- Compensation of $u_{D,f}$ is needed if the exact value of $u_{CE,on}$ is needed

(-)

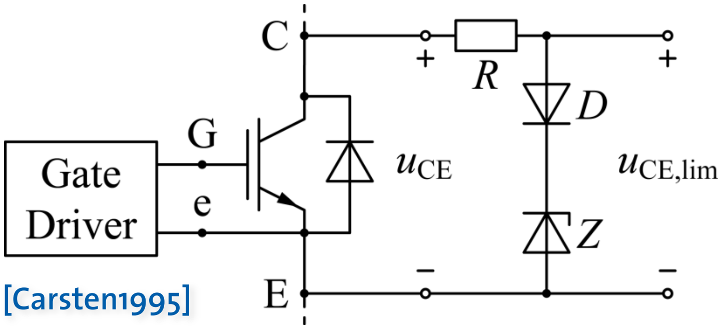
- Offset u_D in measured voltage $u_{CE,lim}$
- Dependency of u_D on
  - Temperature T_D
  - Current i_D
- High blocking voltage of diode *D* needed (about $u_{CE,max}$)

(+)

- Simple, cheap
- Passive (low noise)
- High bandwidth

Voltage measurement: $u_{CE,on}$

Limiting Z-diode



[Carsten1995]

$u_{CE,lim}(t) = u_{CE}(t)$ (for $u_{CE} < u_Z + u_{D,f}$)

$u_{CE,lim}(t) = u_Z + u_{D,f}$ (for $u_{CE} >= u_Z + u_{D,f}$)

- Voltages of u_{CE} above $u_Z + u_{D,f}$ are clipped by Z-diode *Z* and diode *D*

(-)

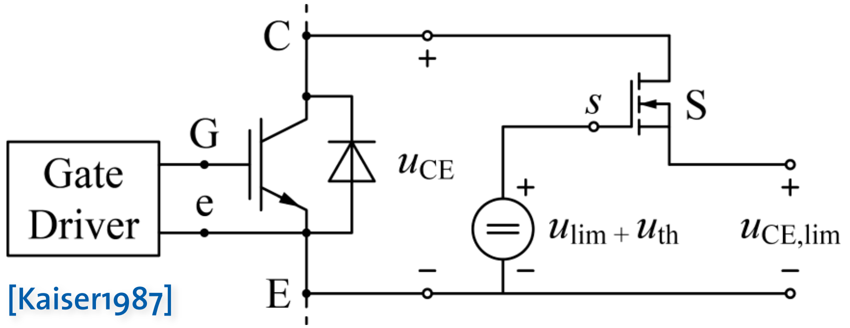
- Low bandwidth (*Z* and *D* conducting before v_{CE} drops below $v_Z + v_{D,f}$)
  - Charge recovery of diodes
  - Low-pass of *R* and diode's capacitances
- High voltage rating for *R* (about $u_{CE,max}$)

(+)

- Simple, cheap
- Passive (low noise)
- No offset voltage in $u_{CE,lim}$
- Low blocking voltages of *D* & *Z* needed

Voltage measurement: $u_{CE,on}$

Parallel switch S



[Kaiser1987]

$u_{CE,lim}(t) = \min(u_{CE}(t), u_{lim})$

When $s = 1$ then: $u_{CE,lim} = u_{CE,on}$

(+)

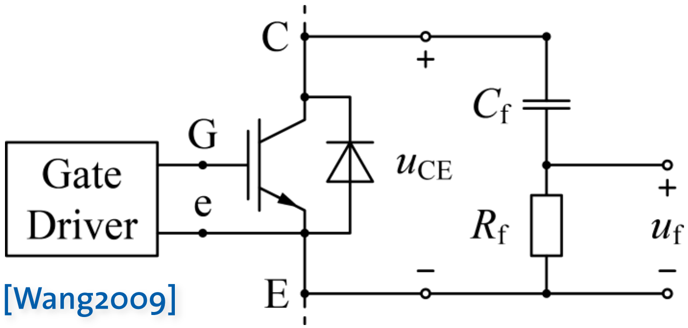
- Direct connection when switch is closed ($s = 1$) (low noise)
- No offset voltage in $u_{CE,lim}$

(-)

- Switch S needs same blocking voltage as IGBT (about $u_{CE,max}$)
- Separate switching signal s needed
  - Derived passively by u_{CE} [Kaiser1987]
  - Provided by digital control unit
- Limited bandwidth due to delayed switching of S

Voltage derivative measurement: du_{CE}/dt

Passive derivation of voltage signal u_{CE}



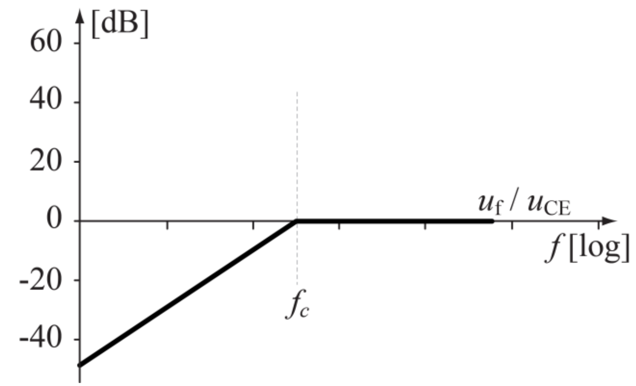
[Wang2009]

$$u_f(t) \approx R_f \cdot C_f \cdot du_{CE}(t)/dt$$

(for $u_f << u_{CE}$ and f < fc:

(i) $du_{Cf}/dt \approx du_{CE}/dt$
(ii) $i_{Cf} = C_f \cdot du_{Cf}/dt$
(iii) $u_f = R_f \cdot i_{Cf}$)

Amplitude characteristic



(+)

- Simple, cheap
- Passive (low noise)
- Low gain needed (allows high bandwidth)

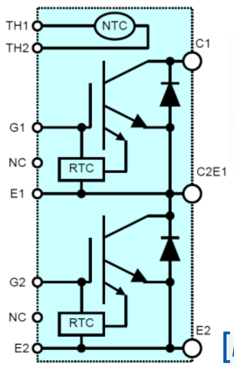
(-)

- Additional IGBT output capacitance
- Voltage rating of C_f is $u_{CE,max}$
- Good linearity of C_f required

Temperature measurement: T_j

NTC thermistor: $R_t = f(T)$

- On-chip integration
  - Distance to IGBT cell
- Typ. resolution: R_t / $T \approx$ 10kΩ / 200 °C

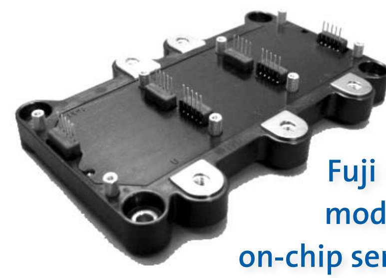


[Motto2005]

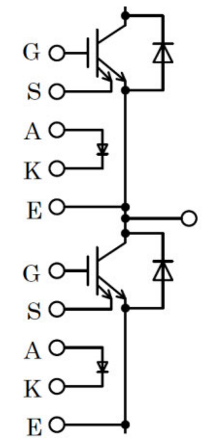
Powerex IGBT module with integrated NTC thermistor [Motto2005]

Sensing pn-diode: $v_f = f(T, i_f)$

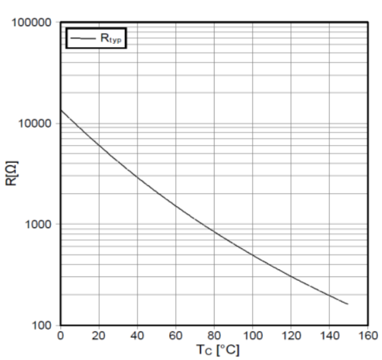
- On-chip integration
  - Arranged directly next to IGBT cell
- Typ. resolution v_f / $T \approx$ 1.7 mV / °C



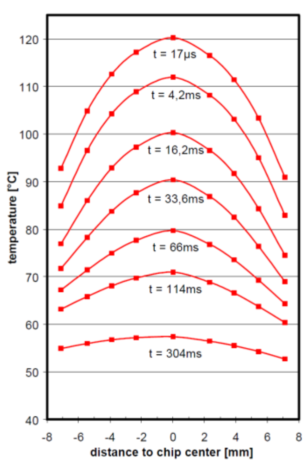
Fuji Electric IGBT module with int. on-chip sensing diodes



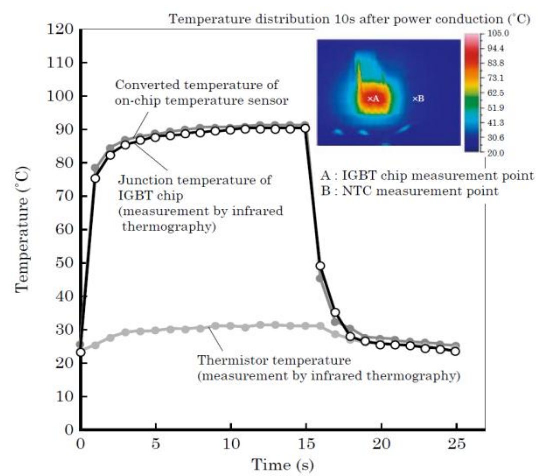
Fuji Electric [Ichikawa2009]



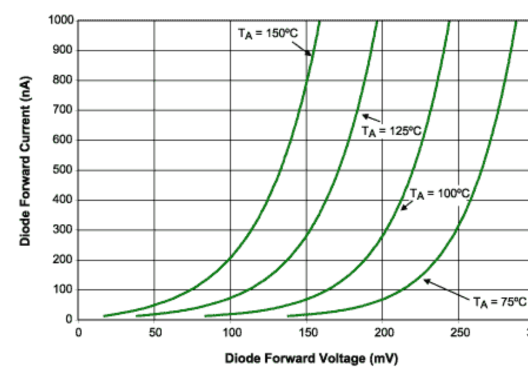
Infineon Datasheet



[Schmidt2009]



[Ichikawa2009]

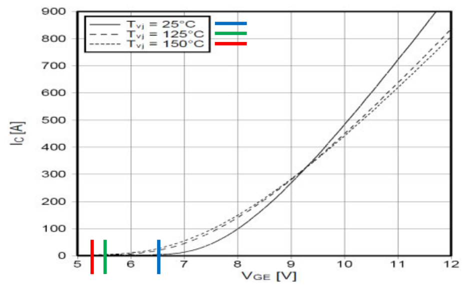


[Maxim AN3500,2005]

Temperature measurement: T_j

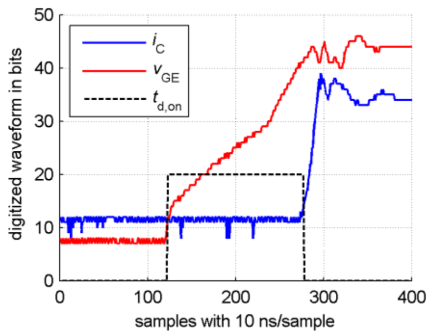
Gate driving characteristic:

- T_j = f($v_{GE,th}$) - resolution: typ. 1 V /100 °C (depending on IGBT)

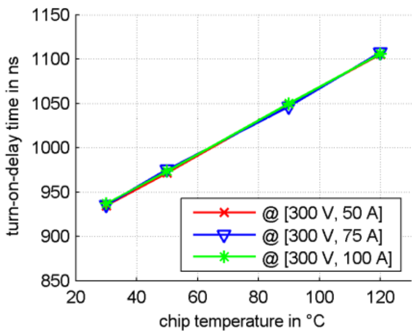


Infineon datasheet

- f($t_{d,on}$, $t_{d,off}$) - resolution: typ. < 2ns / °C (depending on IGBT & gate current)



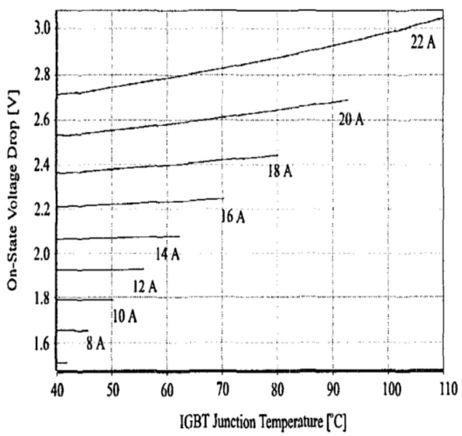
[Kuhn2009]



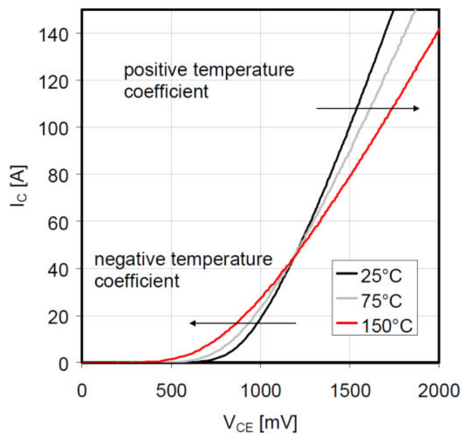
[Kuhn2009]

IGBT output characteristic: T_j = f(i_C, $v_{CE,on}$)

- Need for and dependency on i_C & $v_{CE,on}$ measurements



[Kim1998]



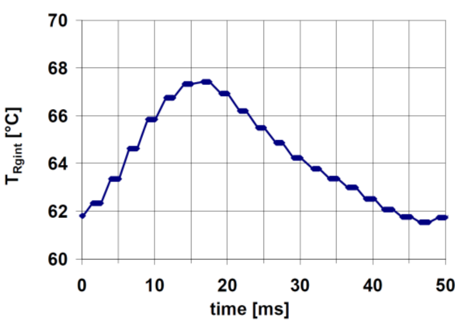
[Schmidt2009]

- Evaluation by DSP / FPGA in interpolated 3D-table
- Not usable around the crossover-point between positive and negative temperature coefficient, that is typ.
  - above nominal current for PT IGBTs
  - well below nominal current for NPT IGBTs

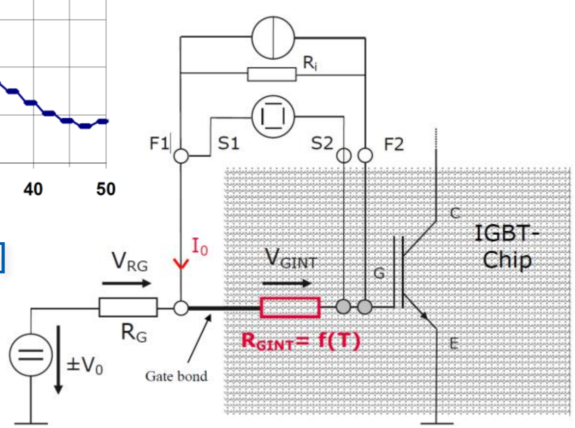
Temperature measurement: T_j

Internal gate resistor: $T_j = f(R_{G,int})$

- Integrated in IGBT module
  - No additional sensor needed
  - Very small distance to IGBT junction
  - Connection to int. gate terminal needed
- Low temperature dependency of $R_{G,int}$
  - Positive temp. coefficient
  - Precise acquisition system needed

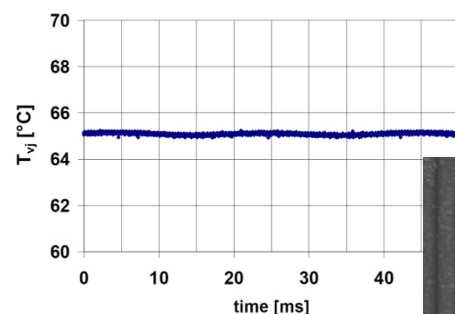


[Brekel2009]

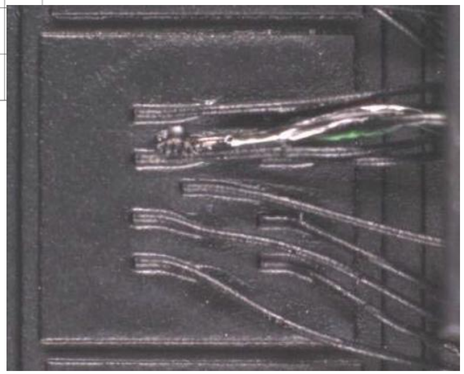


Thermocouple (e.g. Pt100)

- Glued on the IGBT chip
  - Glue with low thermal impedance needed
  - Location close to IGBT chip center
- Large time constant of thermocouple (≈ 200 ms)
  - Switching transients of T_j can not be measured
- High accuracy for $T_{j,avg}$ measurement
- Opening of IGBT module needed



[Brekel2009]



Literature

[Bortis2008] D. Bortis, J. Biela and J. W. Kolar, “Active gate control for current balancing of parallel-connected IGBT modules in solid-state modulators,” IEEE Transactions on Plasma Science, vol. 36, no. 5, pp. 2632—2637, Oct. 2008.

[Brekel2009] W. Brekel, Th. Duetemeyer, G. Puk and O. Schilling, “Time resolved in situ Tvj measurements of 6.5kV IGBTs during inverter operation,” Proc. of the Power Conversion Intelligent Motion Conf. (PCIM Europe), pp. 808—813, 2009.

[Carsten1995] B. Carsten, “A “clipping pre-amplifier” for accurate scope measurement of high voltage switching transistor and diode conduction voltages,” Proc. of the 31st Int. Power Conversion Electronics Conf. and Exhibit, pp. 335—342, 1995.

[Huan2007] F. Huang and F. Flett, “IGBT fault protection based on di/dt feedback control,” Proc. of the Annual IEEE Power Electronics Specialists Conf. (PESC), pp. 1478—1484, 2007.

[Ichikawa2009] H. Ichikawa, T. Ichimura and S. Soyano, “IGBT modules for hybrid vehicle motor driving,” Fuji electric review, vol. 55, no. 2, pp. 46—50, 2009.

[Kaiser1987] K. Kaiser, “Untersuchung der Verluste von Pulswechselrichterstrukturen mit Spannungszwischenkreis und Phasenstromregelung,” Diss. Vienna Univ. of Tech., pp. 41—45, 1987.

[Kim1998] Y.-S. Kim and S.-K. Sul, “On-line estimation of IGBT junction temperature using on-state voltage drop,” Proc. of the 33rd IEEE Industry Applications Society Annual Meeting (IAS), pp. 853—859, 1998.

[Kuhn2009] H. Kuhn and A. Mertens, “On-line junction temperature measurement of IGBTs based on temperature sensitive electrical parameters,” Proc. of the 13th European Conf. on Power Electronics and applications (EPE), 2009.

[Motto2005] E. R. Motto and J. F. Donlon, “New compact IGBT modules with integrated current and temperature sensors,” Powerex technical library, 2005.

[Musumeci2002] S. Musumeci, R. Pagano, A. Raciti, G. Belverde and A. Melito, “A new gate circuit performing fault protections of IGBTs during short circuit transients,” Proc. of the 37th IEEE Industry Applications Society Annual Meeting (IAS), pp. 2614—2621, 2002.

[Olson2003] E. R. Olson and R. D. Lorenz, “Integrating giant magnetoresistive current and thermal sensors in power electronic modules,” Proc. of the 18th Annual IEEE Applied Power Electronics Conf. and Exposition (APEC), pp. 773—777, 2003.

[Schmidt2009] R. Schmidt and U. Scheuermann, “Using the chip as a temperature sensor – the influence of steep lateral temperature gradients on the Vce(T)-measurement,” Proc. of the 13th European Conf. on Power Electronics and applications (EPE), 2009.

[Shah2004] H. N. Shah, Y. Xiao, T. P. Chow, R. J. Gutmann, E. R. Olson, S.-H. Park, W.-K. Lee, J. J. Connors, T. M. Jahns and R. D. Lorenz, “Power electronics modules for inverter applications using flip-chip on flex-circuit technology,” Proc. of the 39th IEEE Industry Applications Society Annual Meeting (IAS), pp. 1526—1533, 2004.

[Slatter2011] R. Slatter, J. Schmitt and G. von Manteuffel, “Highly dynamic current sensors based on magnetoresistive (MR) technology,” Proc. of the Power Conversion Intelligent Motion Conf. (PCIM Europe), pp. 616—620, 2011.

[Wang2009] Y. Wang, P. R. Palmer, A. T. Bryant, S. J. Finney, M. S. Abu-Khaizaran and G. Li, “An analysis of high-power IGBT switching under cascade active voltage control,” IEEE Transactions on Industry Applications, vol. 45, no. 2, pp. 861—870, Mar. / Apr. 2009.

[Xiao2003] C. Xiao, L. Zhao, T. Asada, W. G. Odendaal and J. D. van Wyk, “An overview of integratable current sensor technologies,” Proc. of the 38th IEEE Industry Applications Society Annual Meeting (IAS), pp. 1251—1258, 2003.