Compact Modelling of GaN-HEMTs

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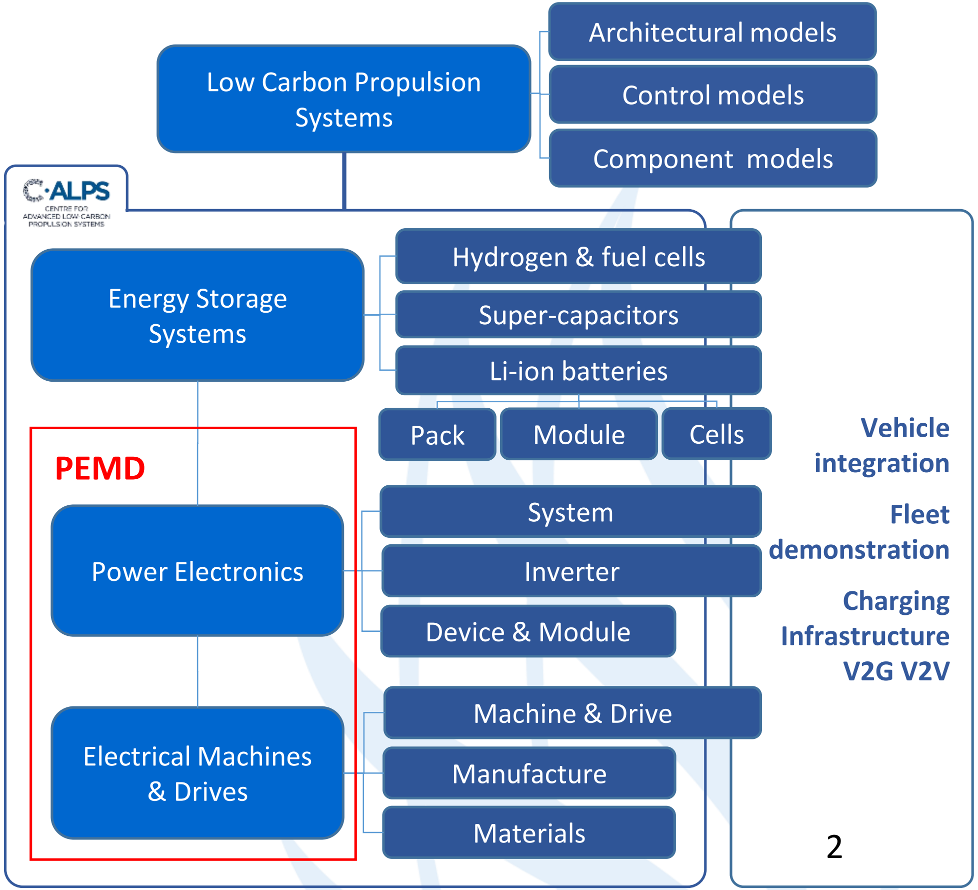
Centre for Clean Growth and Future Mobility
Coventry University e-Mobility Research Group

Research Centre
E-Mobility and Clean Growth

Coventry University

- E-mobility research cluster
- Established in 2018 now formed of 18 academics.
- Based in FEV / C-ALPS building on Coventry Technology Park



Power Electronics, Machines and Drives Group

Research Centre
E-Mobility and Clean Growth
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Research Areas

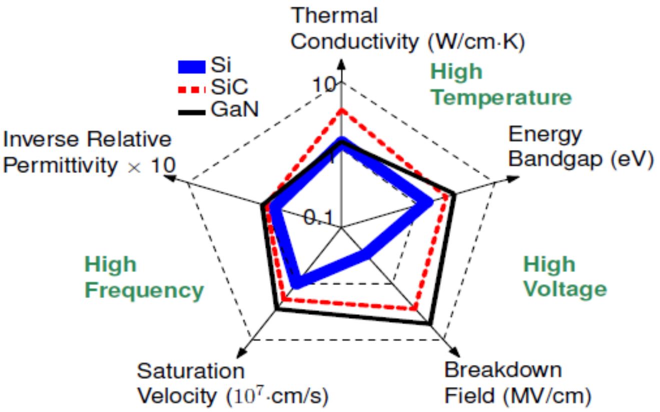
- Technology & Devices: Si, SiC and GaN
- Power electronics converters & Drives: high efficiency and high power density
- Power Systems, Vehicle Charging & Smart Grid Infrastructure: Hardware in the loop, digital twin
- eMachines: test under different scenarios

- 500A/10kV semiconductor device analyser

- 3m x 3m EMC chamber with conducted and radiated emission up to 10GHz for pre-compliance measurement and research
- DUT DC/AC operation, DC power range up to 1kV/200A

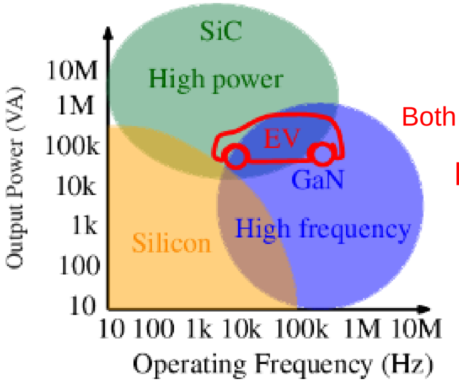
Content

Introduction

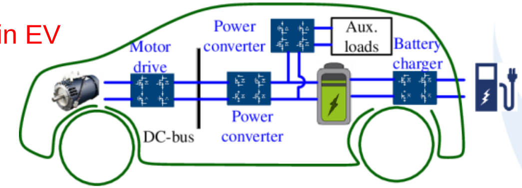


For e-mobility:

- High temperature: reduce cooling for on-board EV application
- High voltage: reduce device footprint and converter complexity
- High frequency: reduce passive components size and volume



Both can be applied in EV

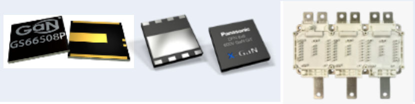


<u>*SiC:*</u>
- *High power converter (battery to DC-bus)*
- *Motor drive (200V-800V)*

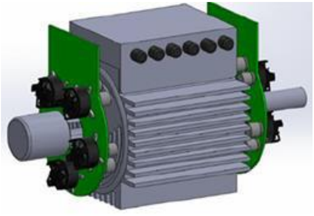
<u>*GaN:*</u>
- *Low power converter (battery to auxiliary power)*
- *On-board charger*
- *Motor drive (200V-400V)*

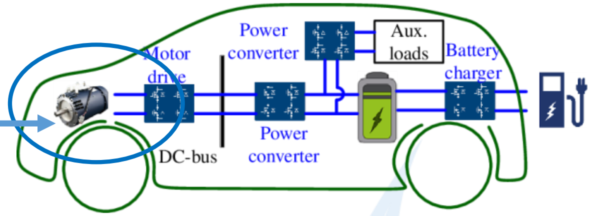
High efficiency and high power-density power electronics converters

Introduction

GaN power transistors
HEMT, GIT, Cascode

Device: 650V-900V/150-200A Module: 650V/300A

*





Integrated GaN power electronics circuit and systems

Step change on efficiency and power-density

Challenge:

- Device power losses (switching losses and dynamic R_{DSon} losses due to current collapse)
- Accurate device models and electro-thermal, electromagnetic simulation
- Model and simulation tool easy to use and fast

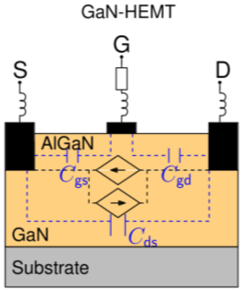
In this presentation

Objective: Compact model for GaN-HEMTs
1. Accurate and fast
2. Account for dynamic R_{DSon} losses

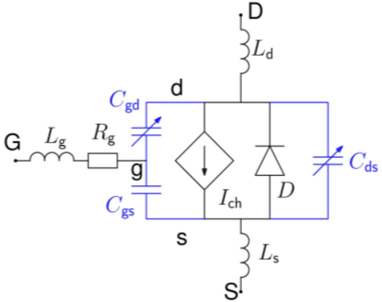
* "Tutorial - Integrated Drives: Power electronics and electrical machine challenges" EPE 2021.

Content

Modelling switching losses --- Model structure



Device structure



Equivalent circuit

- Bi-directional channel current I_{ch}
- Non-linear inter-electrode capacitances
- "Body-diode" like characteristic for reverse conduction
- Parasitic inductance due to packaging

	Literature	Advantages	Drawbacks
I_{ch}	Angelov, EKV MOSFET, Curtice model	Accurate	>20 parameters
Reverse conduction			
Capacitance	Look-up table	Accurate	Computation effort

Proposed method

- Adapted Angelov equations
- Classic p-n junction equation
- Tangent hyperbolic equations

Modelling switching losses --- Model structure

Ich modelling

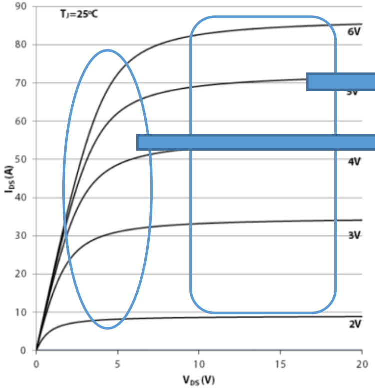


Figure 1 : Typical I_{DS} vs. V_{DS} @ T_J = 25 °C

$$I_{ch} = I_{ch1} + I_{ch2}$$

$$I_{ch1} = a \cdot (ln(1 + exp(b \cdot V_{gs} - c)))^{e} \cdot (1 + d \cdot V_{ds})$$

$$I_{ch2} = -a \cdot (ln(1 + exp(b \cdot V_{gs} - c - h \cdot V_{ds}^{g} \cdot tan(f \cdot V_{ds}))))^{e} \cdot (1 + d \cdot V_{ds})$$

- I_{ch1} is for transfer characteristics
- I_{ch2} is for Ohmic-Saturation region transition
- Use Logarithmic function to guarantee a V_{gs} continuity
- Parameter a and c are T_j dependent

Reverse conduction modelling

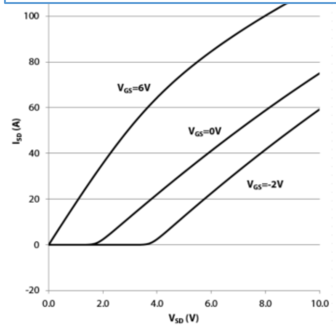
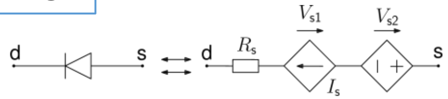


Figure 9 : Typical I_{SD} vs. V_{SD}



- I_s, V_{s1} is classic p-n junction equation
- R_s and V_{s1} are Tj dependent
- V_{s2} is negative V_{gs} voltage

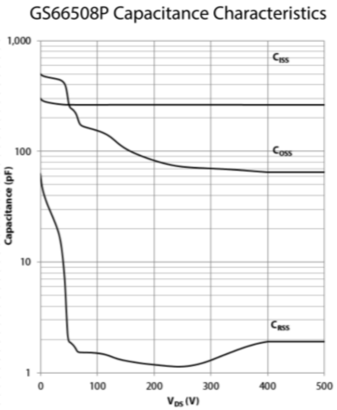


Figure 7: Typical C_{ISS}, C_{OSS}, C_{RSS} vs. V_{DS}

Capacitance modelling

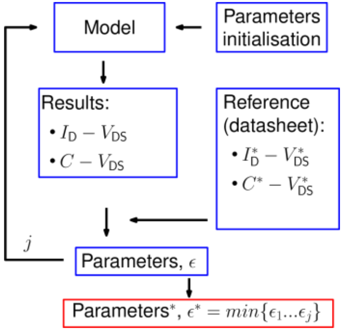
Using tangent hyperbolic functions

$$C_{xy} = a_1 - \sum_{1}^{n} b_i (1 + \tanh(c_i (V_{xy} + d_i)))$$

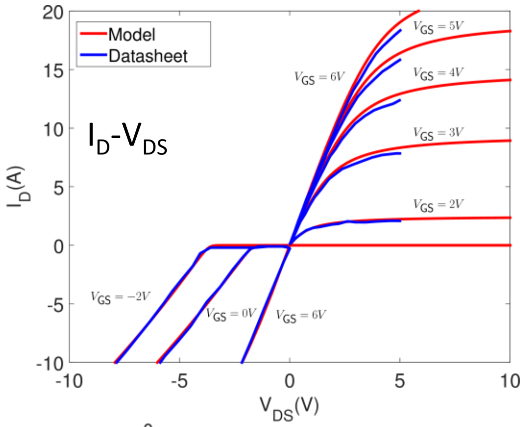
Parameters extraction

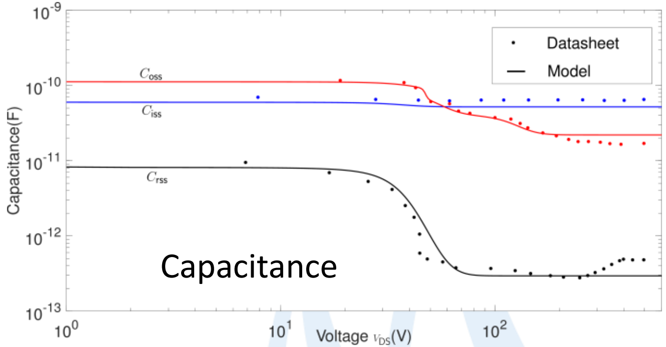
Modelling switching losses --- Parameters extraction

Optimisation approach based on curve fitting

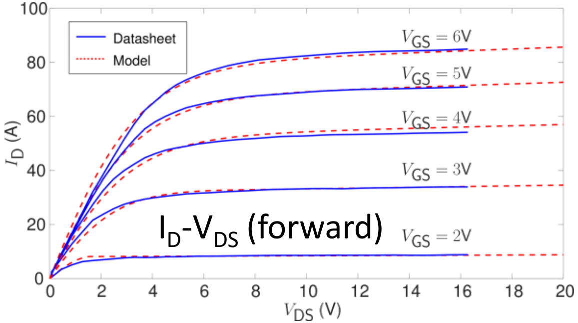


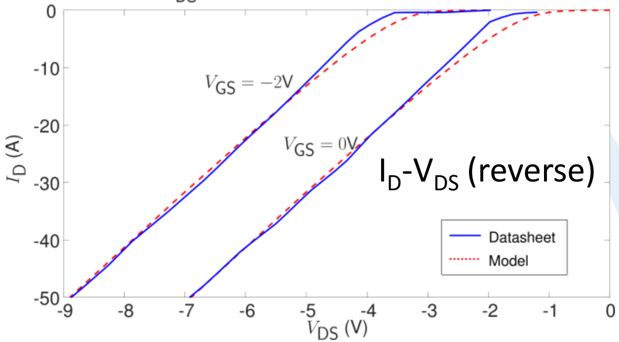
GS66502B (650V/7.5A)

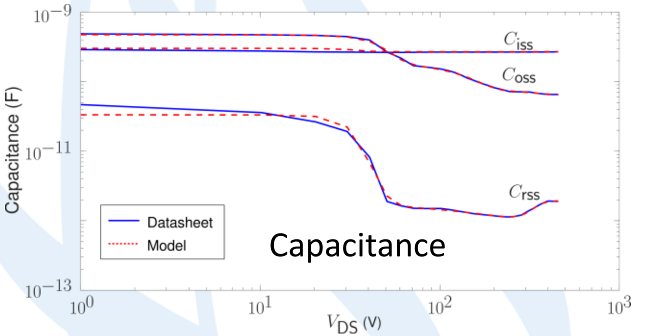




GS66508P (650V/30A)







- Parameters obtained around minutes
- Match datasheet values well

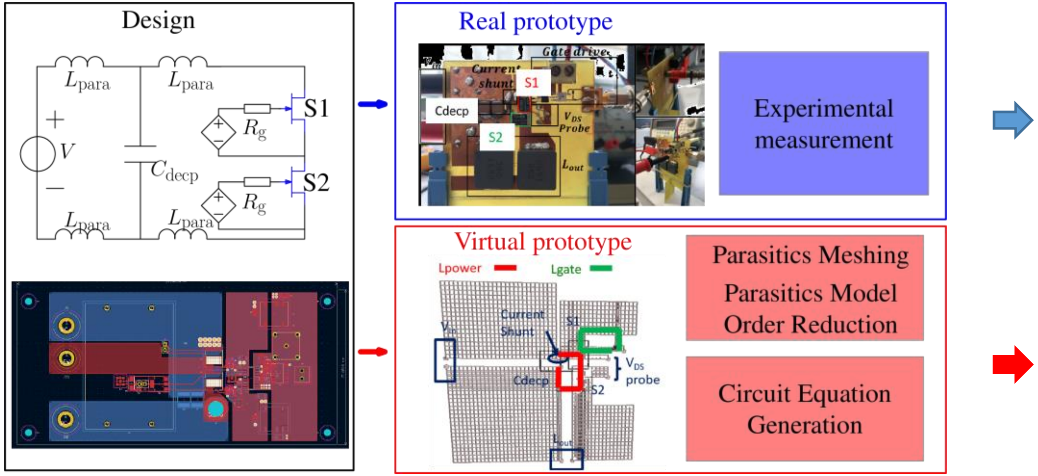
→ Switching waveforms validation

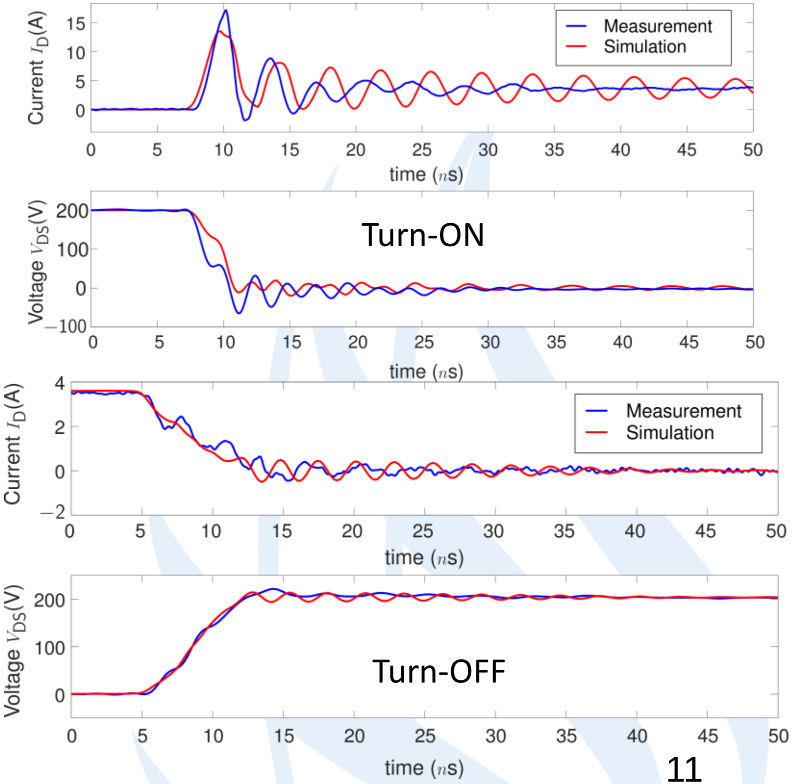
Modelling switching losses --- Experimental Validation

Applied to different simulation software: LTspice, ADS, Power Electronics Virtual Prototyping (PEVP) …

Power Electronics Virtual Prototyping (Dr Paul Evans, EP/K035304/1 & EP/R004390/1)

GS66502B (650V/7.5A)

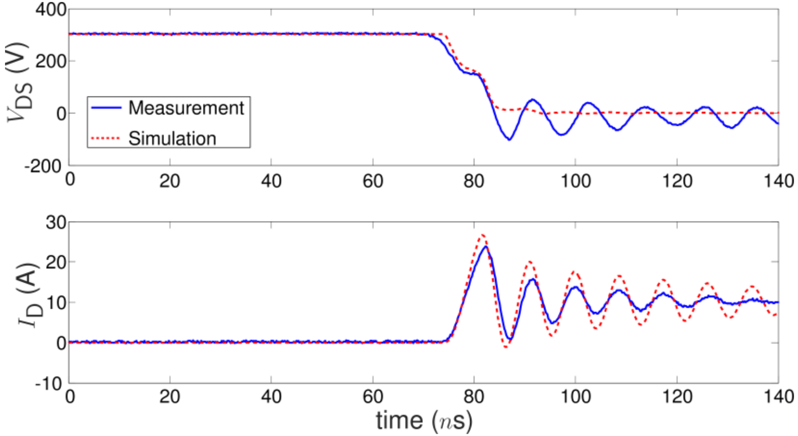




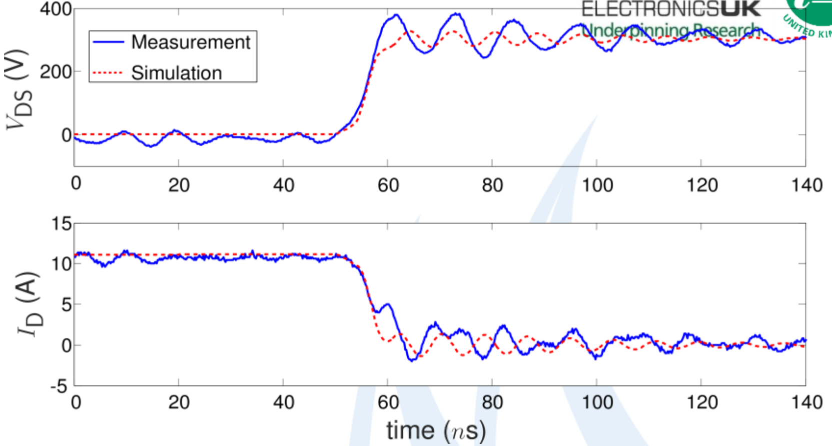
Software	L_{gate}	L_{power}	Simulation time
ADS	9.6nH	5.7nH	100 mins
PEVP	9.7nH	5.4nH	<1 min

Modelling switching losses --- Experimental Validation

GS66508P (650V/30A)



Turn-ON



Turn-OFF

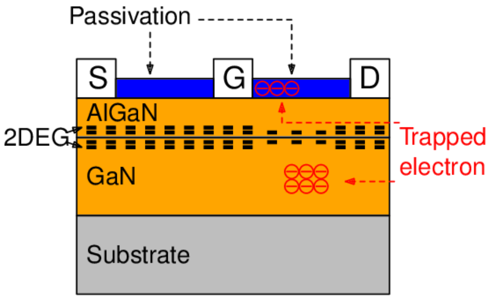
Condition	Measurement (uJ)	Simulation (uJ)	Error
300V/10A ON	16	19	19%
300V/10A OFF	6	5.6	6.7%
200V/15A ON	16	14	12.5%
200V/15A OFF	9	7	22%

- Relative error 10-20%
- Absolute error is around 1-3uJ (measurement methodology challenge)
- Probe impedance and loop needs to be considered

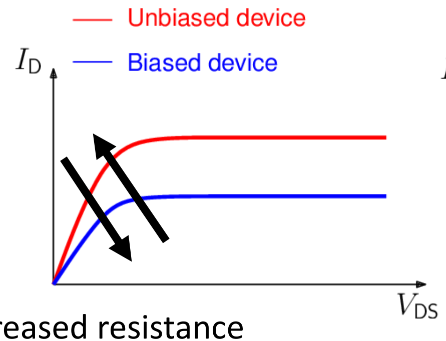
Content

Modelling conduction losses --- Model structure

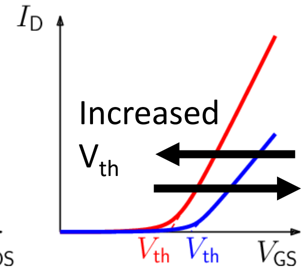
- GaN current collapse: trapped charge to reduce current in ON-state



GaN-HEMT structure



Increased resistance
(dynamic R_{DSon})

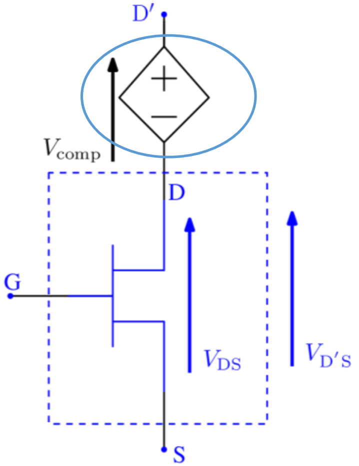


- Unbiased device: device original characteristics, datasheet value
- Biased device: biased V_{DS} voltage, switching losses, duty cycle, frequency and temperature
- Biased characteristics recoverable (trapping, detrapping)

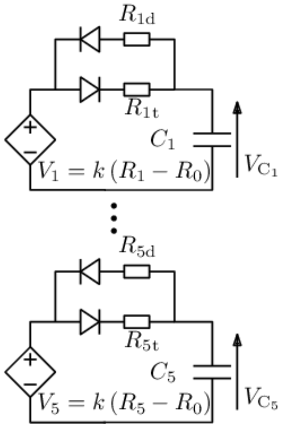
Research challenge:
1. Quantify and predict losses for power converters under different frequencies and duty cycles
2. Model this effect to accurately design power converters

Modelling conduction losses --- Model structure

Method: Adding V_{comp} on drain



$$V_{DS}^{eff} = V_{D'S} = V_{DS} + V_{comp}$$



$$V_{comp} = \sum_{k=1}^{n} V_{Ci}$$

V_{comp} increases when device is OFF (V_{DS}=V_{DC} , with stress) and decreases when device is ON (V_{DS}=V_{DSON} , without stress)

Static $R_{DSon} = \frac{V_{DS}}{I_D}$

Dynamic $R_{DSon} = \frac{V_{DS}+V_{comp}}{I_D}$

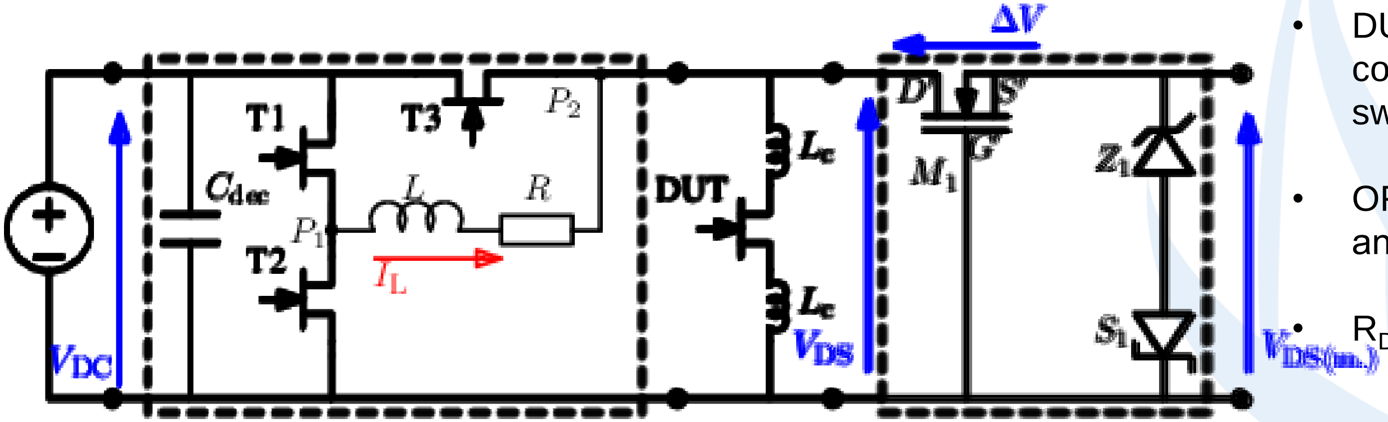
Parameters extraction

Modelling conduction losses --- Parameters extraction

Power converter soft switching:
1. Reduced switching losses 2. Only V_{DS} biased voltage as stress effect

Challenge:
- DUT trapping/detrapping time constant
- V_{DS} measurement resolution
- Sensitivity (L_c, probe deskew, T_j)

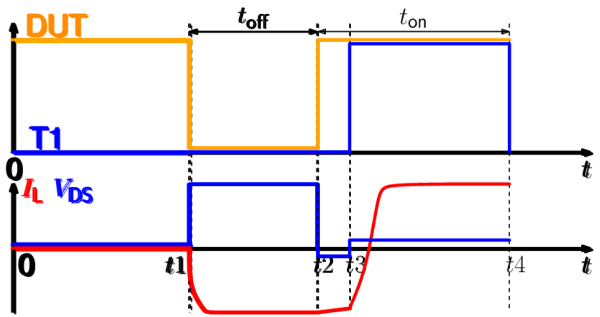
Solution:
- Full H-bridge
- Voltage clamping circuit to measure $V_{DS(m.)}$
- Constant current under single pulse



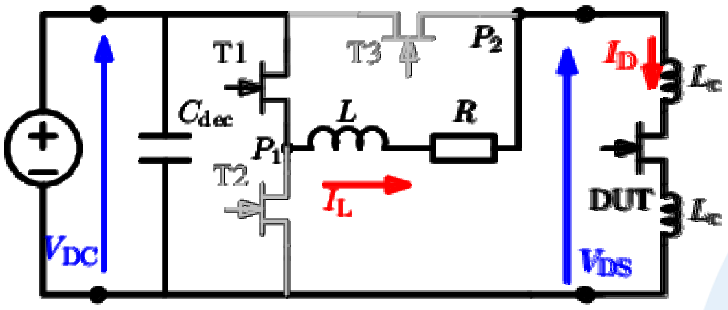
Proposed measurement circuit

- DUT t_{off}, t_{on} accurately controlled under soft switching
- OFF-state: $\Delta V=V_{DC}$; reverse and forward conduction: $\Delta V=0$
- $R_{DSon}=V_{DS(m.)}/I_L$

Modelling conduction losses --- Parameters extraction



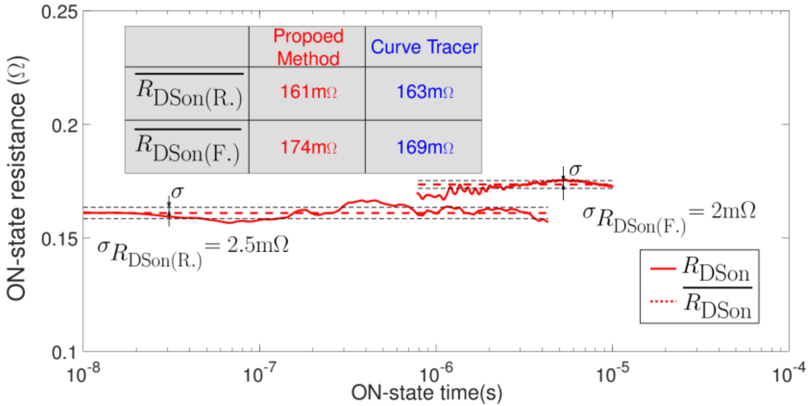
Control signal



Measurement circuit

- 0-t1: I_L=0, V_{DS}=0
- t1-t2: DUT OFF-state
- t2-t3: DUT **reverse** conduction (ZVS turn-ON at t2)
- t3-t4: DUT **forward** conduction

- Measurement results of 170mΩ SiC-MOSFET (C2M0160120D)

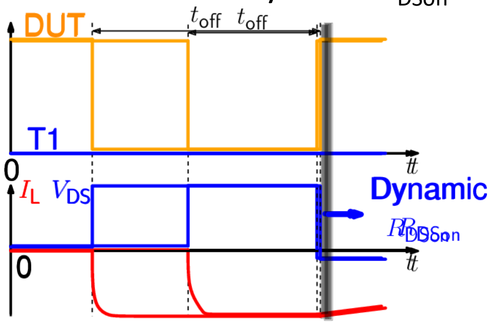


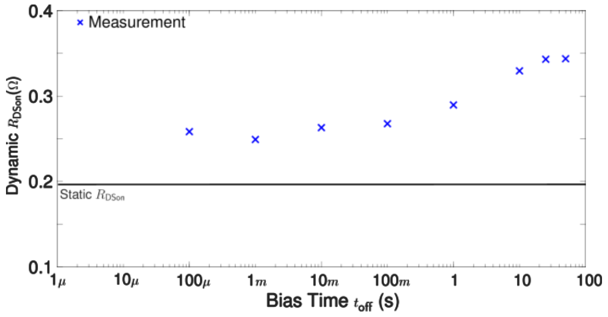
- Accuracy validated by comparison with device curve tracer results
- Fast response (~10ns)
- To measure GaN-HEMT dynamic R_{DSon}

Modelling conduction losses --- Parameters extraction

DUT: 200mΩ GaN-HEMT (GS66502B, 650V/7A)

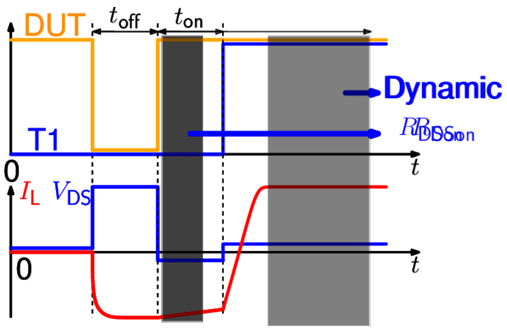
- GaN-HEMT dynamic R_{DSon} under different t_{off}

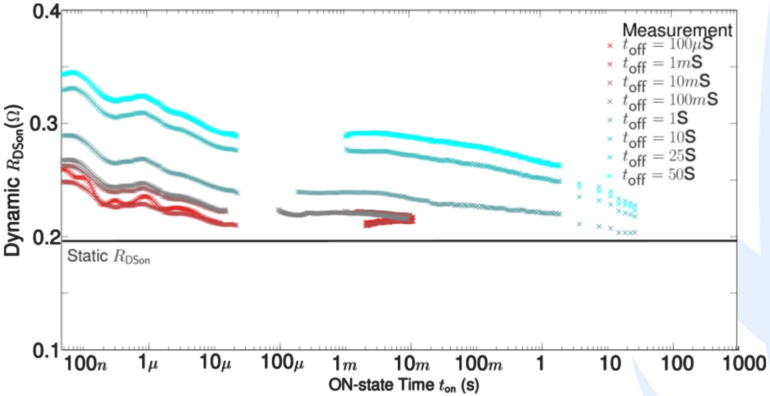




- Average value within 50ns
- Different toff time constant
- More than 50s to stabilise
- Dynamic R_{DSon} increasing 75%

- GaN-HEMT dynamic R_{DSon} under different t_{on}





- Reverse and forward conduction
- Different ton time constant
- More than 100s to stabilise (decrease to static R_{DSon} value)

Curve fitting to extract parameters

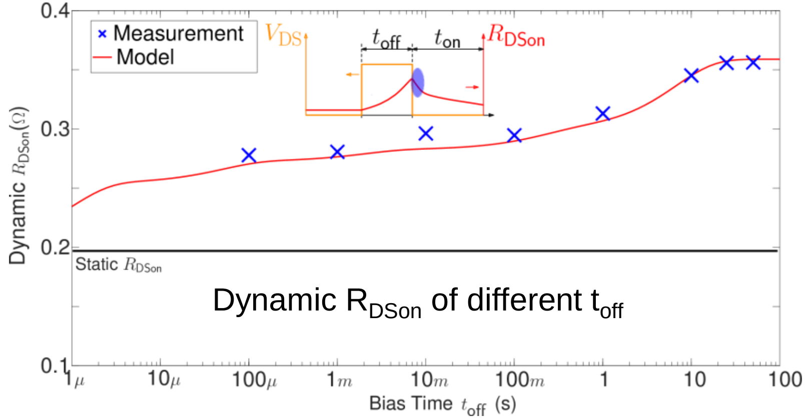
Modelling conduction losses --- Parameters extraction

$$R_{DSon}(t) = \sum_{i=1}^{n} \underbrace{(R_i - R_0)(1 - e^{-\frac{t_{off}}{\tau_{off_i}}})}_{\text{Trapping effect}} \underbrace{e^{-\frac{t_{on}}{\tau_{on_i}}}}_{\text{Detrapping effect}} + R_0$$

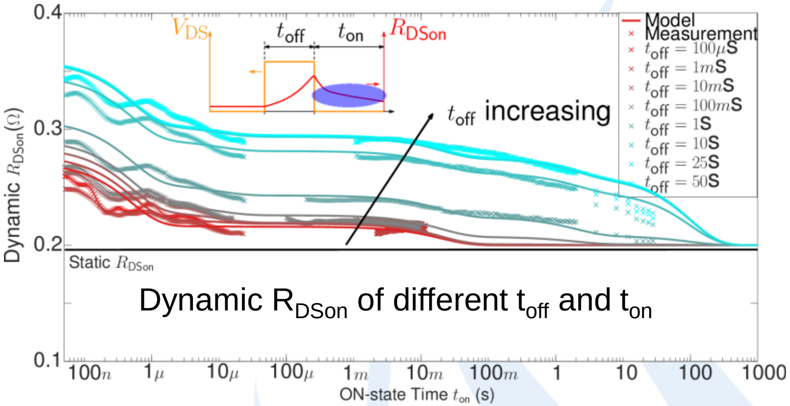
R_i, τ_{off_i}, τ_{off_i}: parameters to obtain;

R_0: static R_{DSon};

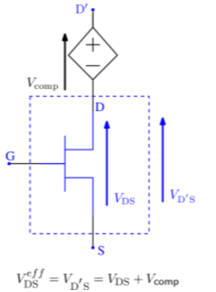
5 cells are chosen

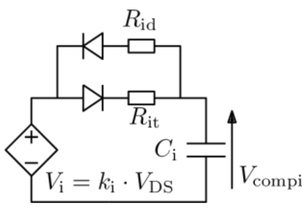


Dynamic R_{DSon} of different t_{off}



Dynamic R_{DSon} of different t_{off} and t_{on}





Implemented into model and validation under repetitive mode

Modelling conduction losses --- Experimental validation

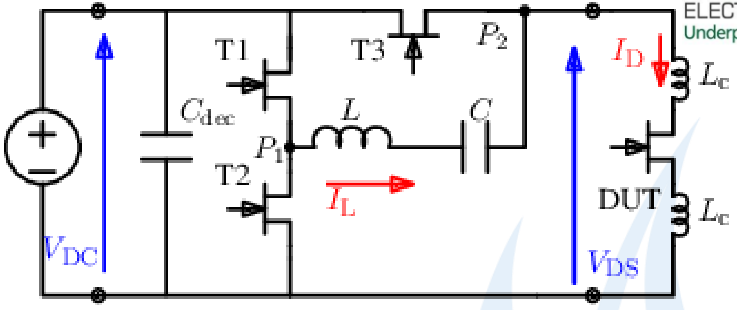
DUT: 200mΩ GaN-HEMT (GS66502B, 650V/7A)

- Measurement under repetitive mode

Challenge: $L_c \cdot \frac{dI_D}{dt}$ on measurement accuracy

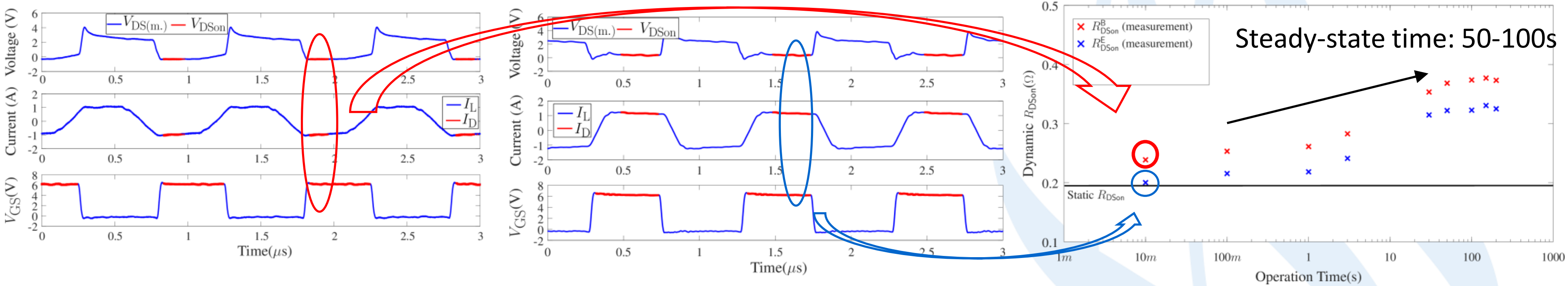
Solution:

- Trapezoidal current waveform
- Phase-shift between two legs
- Whole H-bridge in soft switching ($T_j \approx T_c$)



Measurement circuit

- Measurement results

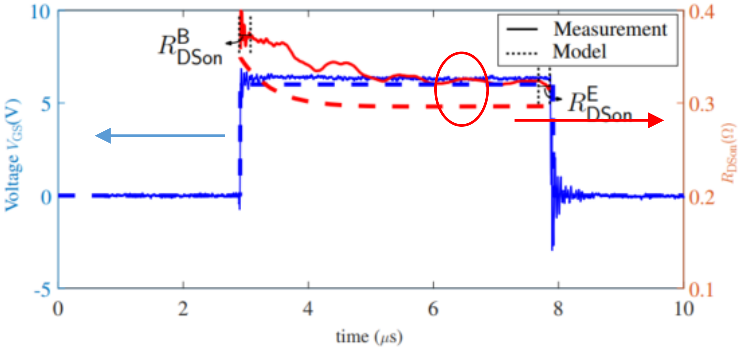


Measurement at the beginning of each duty cycle (f_{sw}=1MHz)

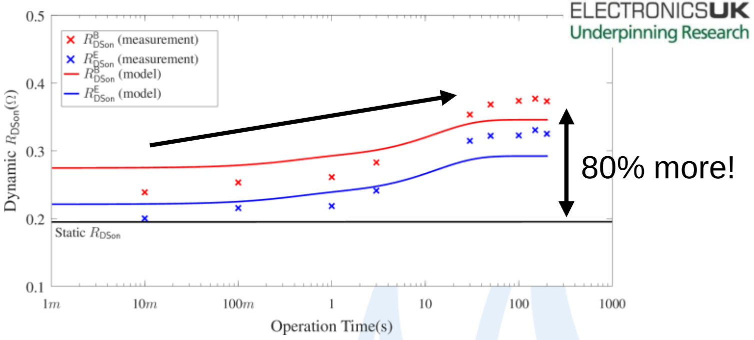
Measurement at the end of each duty cycle (f_{sw}=1MHz)

Modelling conduction losses --- Experimental validation

- Model validation for transient and steady-state values (100kHz, D=50%)

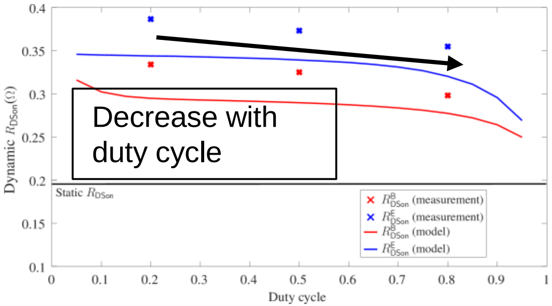


R^{B}_{DSon} and R^{E}_{DSon}

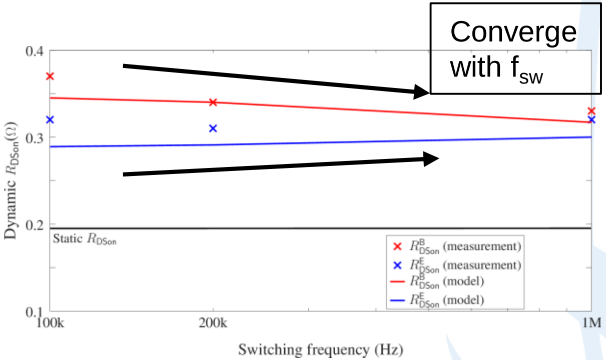


Dynamic R_{DSon} at transient and steady-state

- Model validation for different duty cycles and f_{sw}



Different duty cycles (f_{sw}=100kHz)



Different f_{sw} (D=50%)

- <10% difference between model and measurement
- 80% maximal dynamic Ron increases (V_{DS}=200V)
- Model validated

Content

Summary

1. A compact model based on behavioural equations and equivalent circuits for GaN-HEMTs
2. Less than 10 parameters needed for channel current, reverse conduction and capacitance
3. Switching waveforms validated by experimental measurements under different operation conditions
4. A drain voltage compensation circuit proposed to model dynamic R_{DSon} for power electronics converters
5. Dynamic R_{DSon} are validated by experimental measurements under different frequencies and duty cycles (soft switching at 200V)

Acknowledgement

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- Technical support by University of Nottingham and University of Lille

References

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Thank you for your attention.
Any questions?