pcim ASIA *Hybrid Platform*

Thermal Management for Buck Converters Using Co-Packaged GaN Power HEMTs

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Current research interest: Power devices (IGBTs, LDMOST, GaN HEMTs)

2015 – Present	**Ph.D.**	**Electrical Engineering**	**UESTC**
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OUTLINE

1. Introduction
2. Proposed GaN Power Module
3. Thermal Considerations for Modules
4. Conclusions and Future Work

1. Introduction

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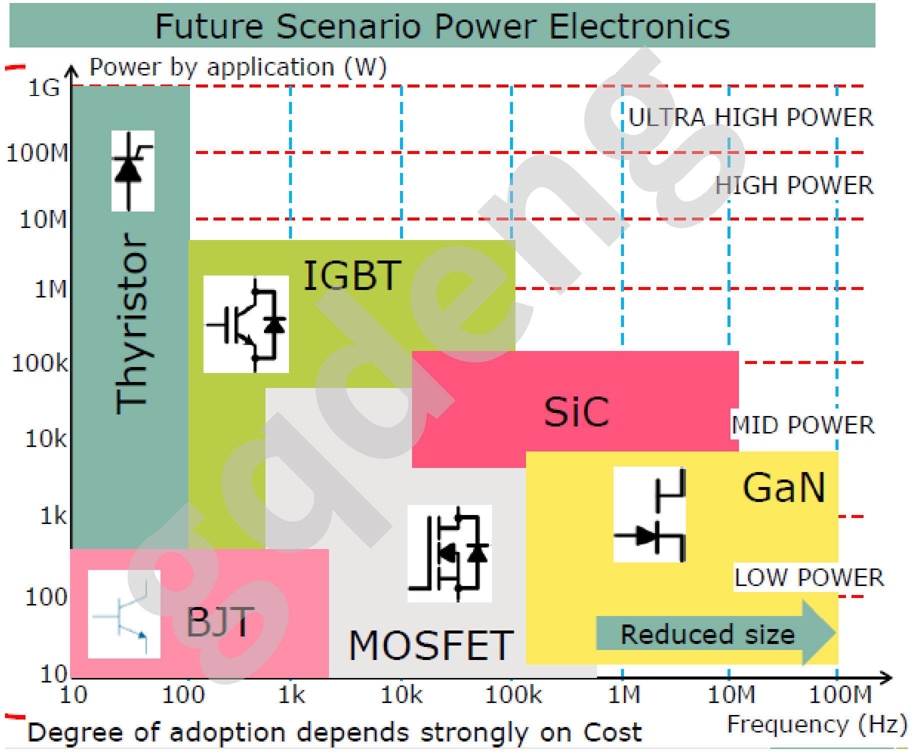
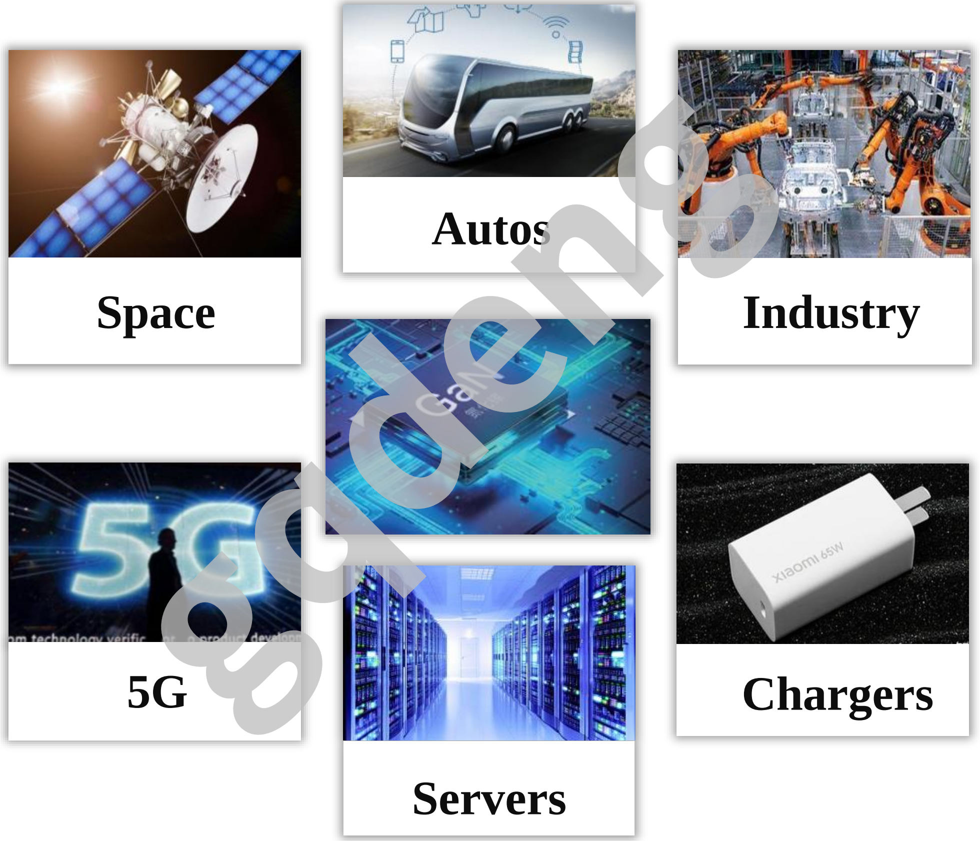
Applications for GaN devices





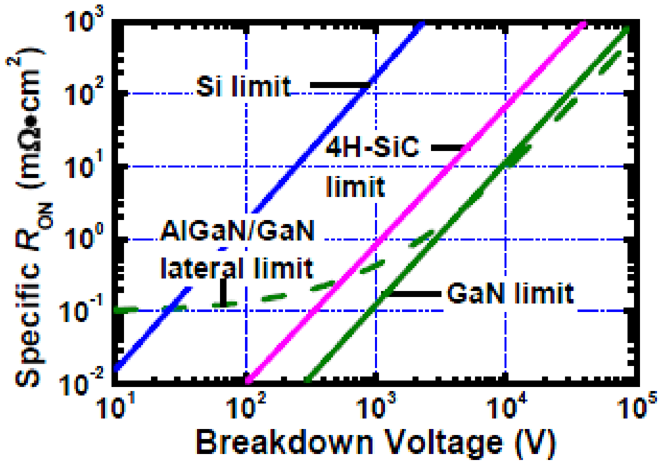
Low / medium power, High frequency

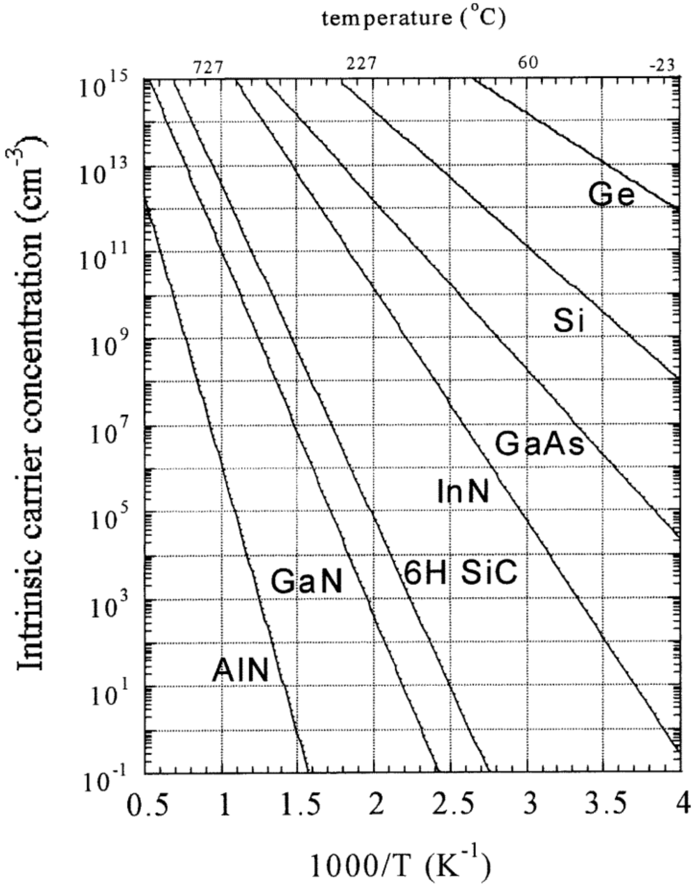
Market size will be $300M in 2021 and $424M in 2023, estimated by Yole Développement.

1. Introduction

GaN power devices break the performance limit of Silicon power devices!

Material	Critical Field E_{crit} (MV/cm)	Electron Mobility μ_n (cm^2/Vs)	Band gap E_g (eV)
Silicon	0.3	1400	1.12
SiC	2.2	700	3.25
GaN(HEMT)	**3.3**	**1800 (2DEG)**	**3.44**





S.M.Sze, "Physics of Semiconductor devices", Chapter 1

Material

- **High** Critical Field
- **High** Mobility
- **Wide** Band gap

→

Devices

- **High BV**
- **Low** $R_{on,sp}$
- **High** T_j

1. Introduction

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GaN-based power conversion systems

Device size comparison

Small device area

⇩

Low capacitance

⇩

High f_{sw} & power density

SJ based 130KHz

GaN based 350KHz

System comparison

- **Frequency** 2.7×
- **Volume** 34%
- **Power Density** 2.8×

Source: Infineon_CoolGaN_ProductSelectionGuide.2019

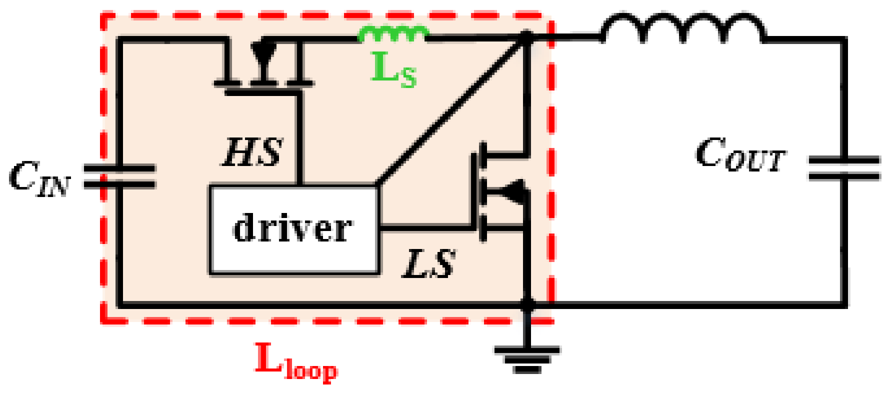
ggdeng

1. Introduction

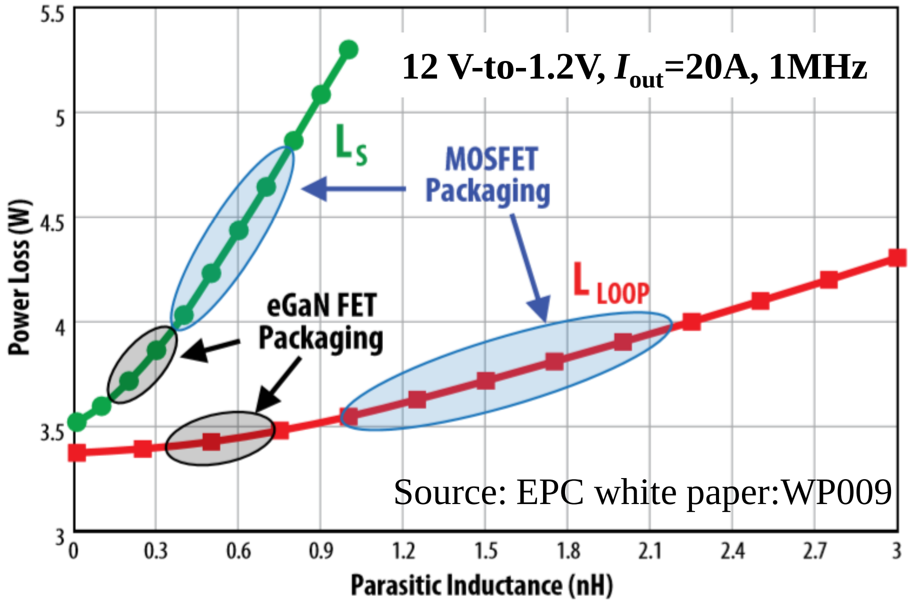
Packaging matters !

- Less parasitic inductance and resistance
- Lower thermal impedance
- Smaller footprint and physical size

The higher the device frequency, the more important the consequences of parasitic inductance.



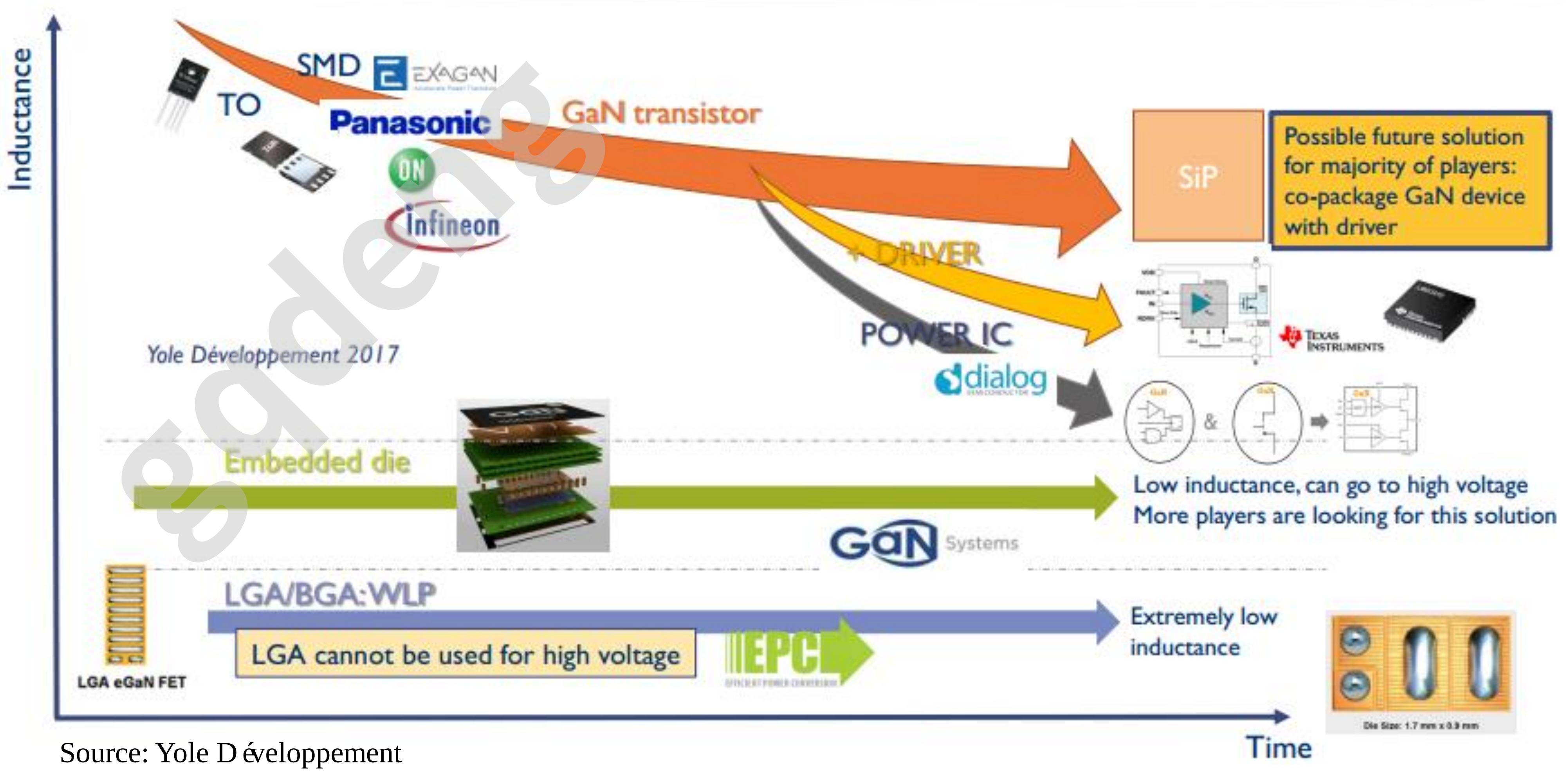
Synchronous buck converter with parasitic inductances



Parasitic inductance impact on power loss

1. Introduction

Packaging roadmap for GaN transistors



Source: Yole Développement

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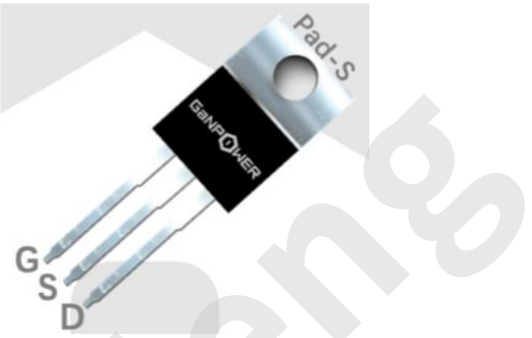
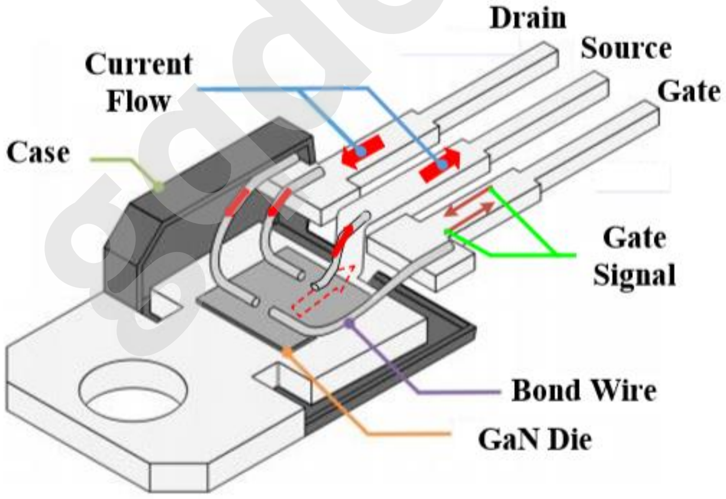
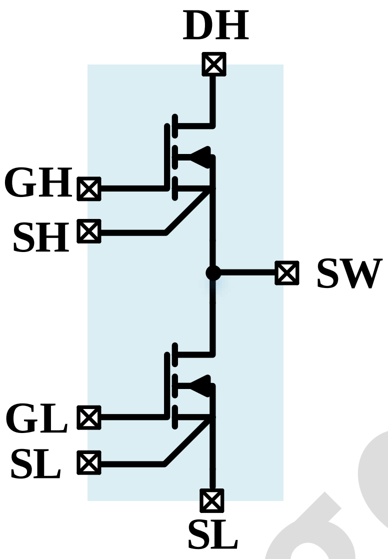
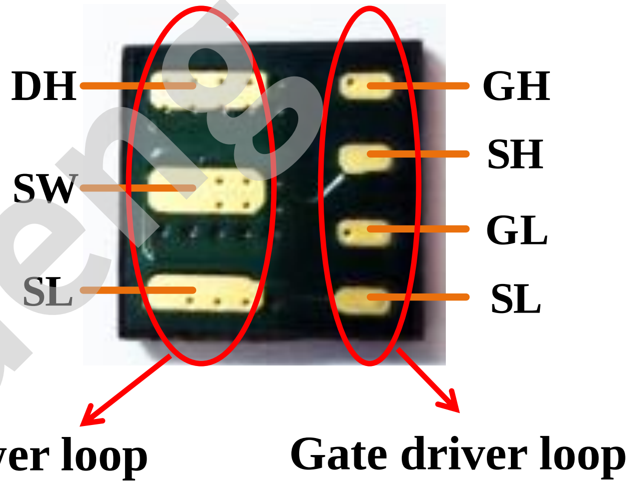
GaN transistor in TO-220 package

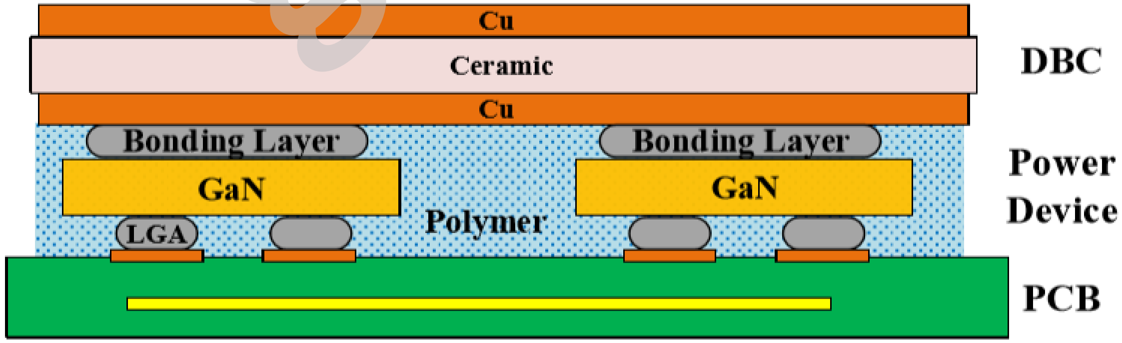




Custom Half-Bridge Module for this work



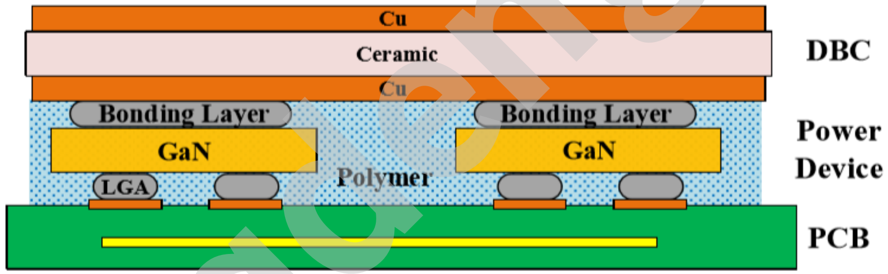


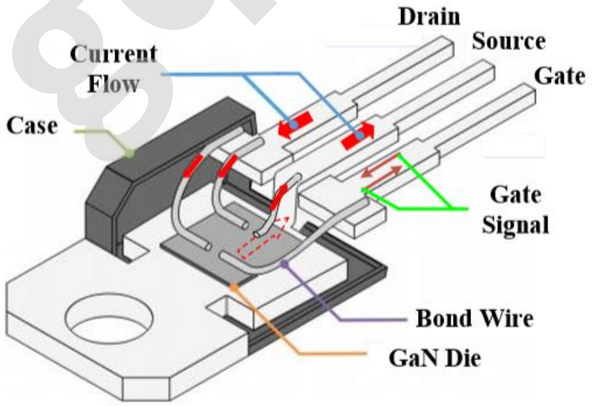


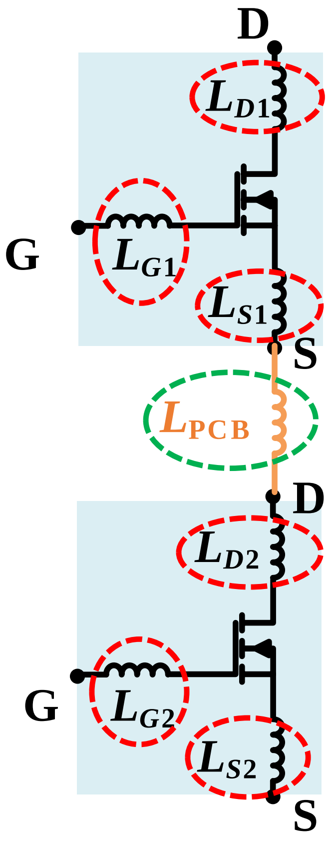
2. Proposed GaN Power Module

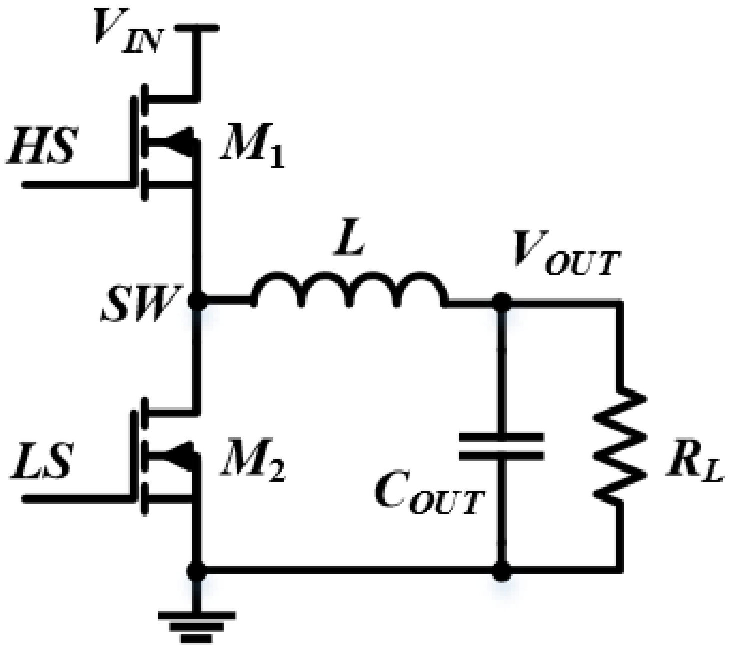
How the GaN power modules minimize the parastics:

- Eliminate bond wire by flip-chip assembly
- Shorten the wire connection on PCBs by co-packaging





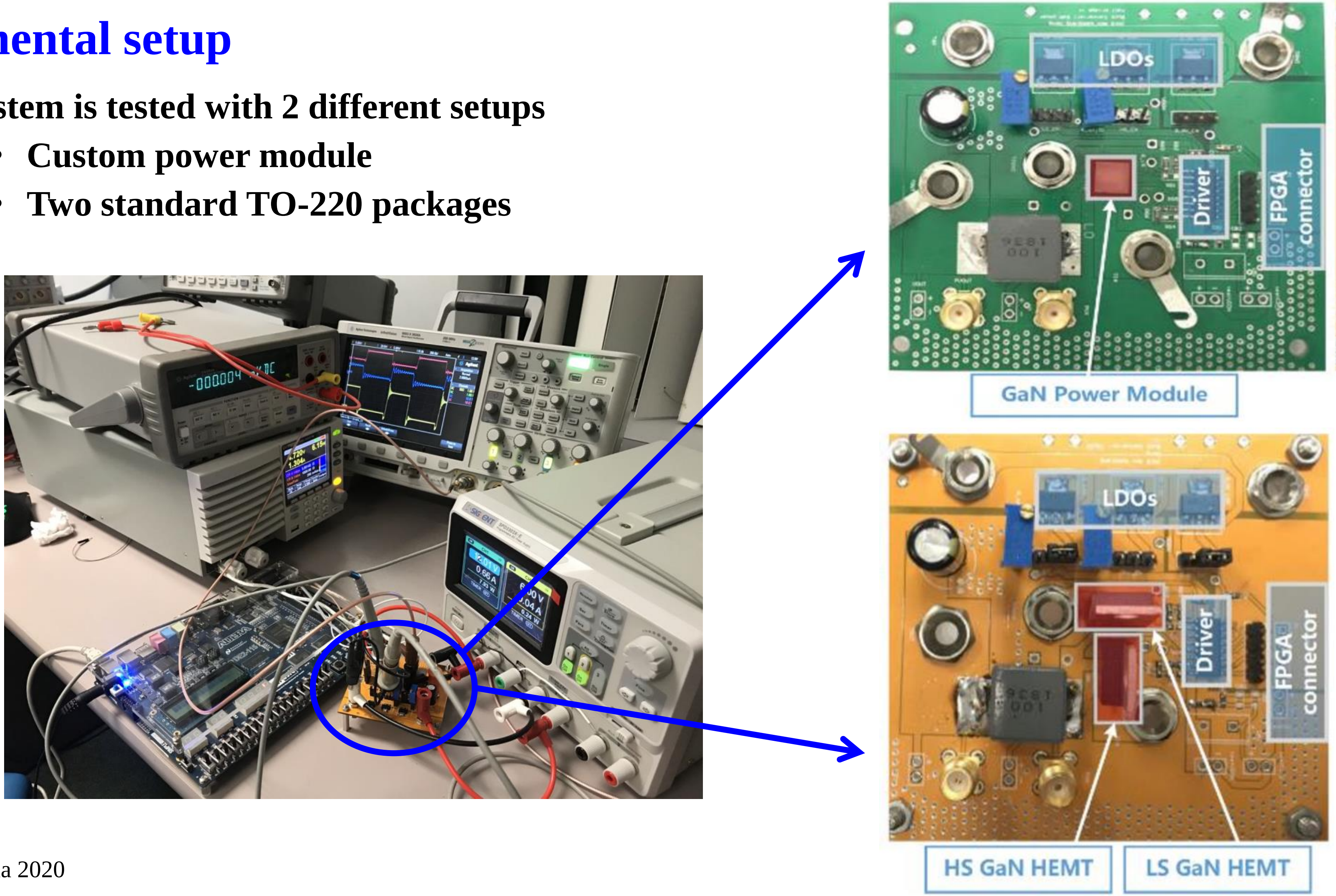




2. Proposed GaN Power Module

Experimental setup

- System is tested with 2 different setups
  - Custom power module
  - Two standard TO-220 packages



2. Proposed GaN Power Module

Component list for the test PCB

Component	Value	No.	Model number	Description
Module	15A	1	Custom prototype	Switch
HEMT	15A	2	GPI65015TO	Switch
Driver	4A	1	Si8273	Gate driver
Inductor	10µH	1	SRP1265A-100M	Filter inductor
Capacitor	220µF	1	EEU-FM1V221L	Filter capacitor
LDO	Adjustable	2	NCP1117STAT3G	Power for drivers
Diode	100V	1	MBR1H100SFT3G	Bootstrap diode

Apparatus used for the test

Oscilloscope: *Agilent Technologies MSO-X 3024A*

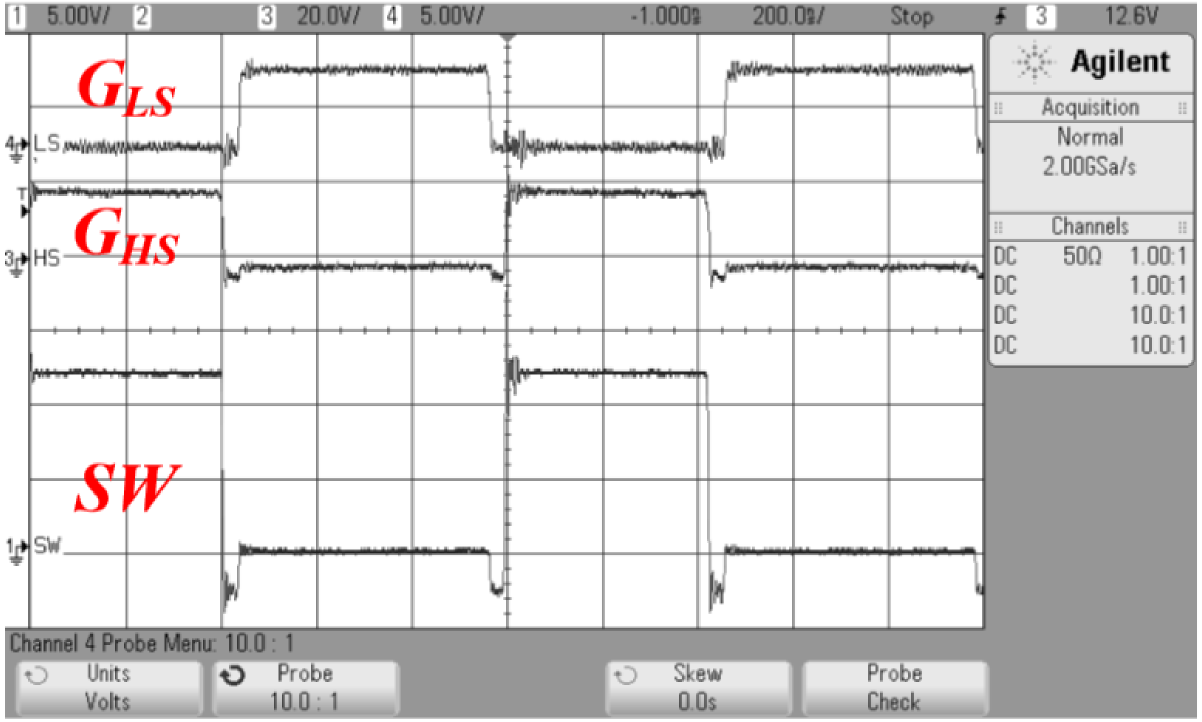
DC Power Supply: *SIGLENT SPD3303X-E*

DC Electronic Load: *GWINSTEK PEL-3031E*

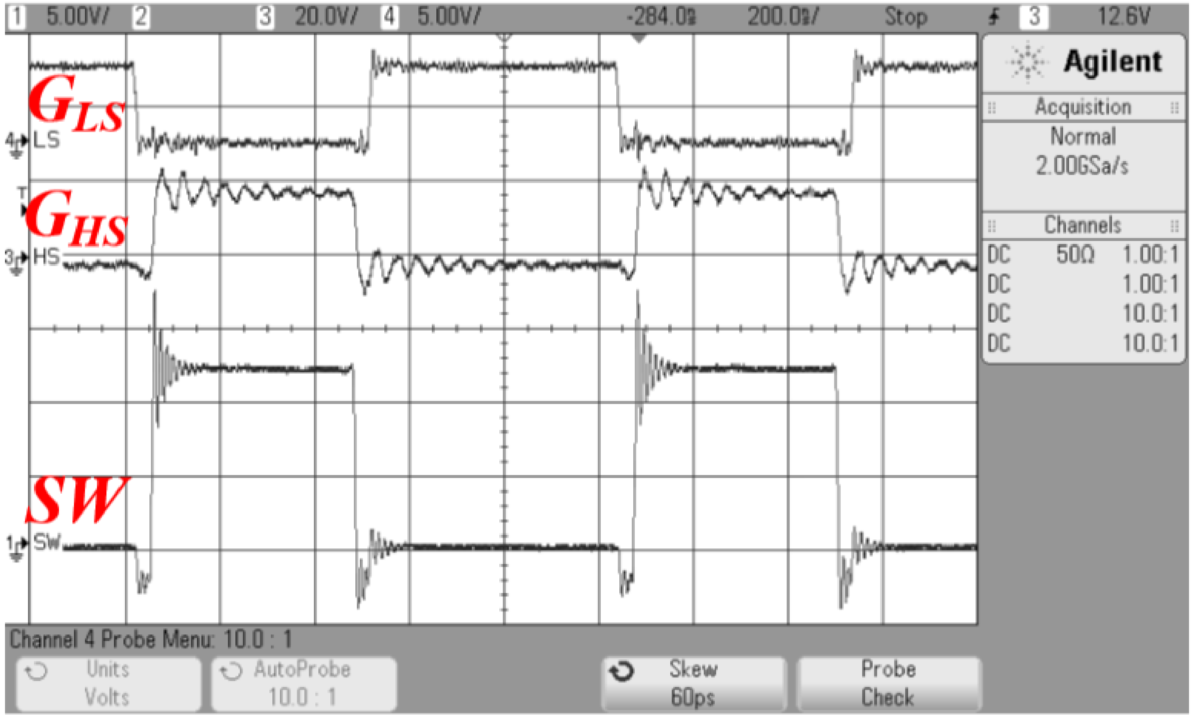
2. Proposed GaN Power Module

Experimental results

- **Waveforms comparison** (Buck converter, V_{IN} = 12 V, V_{OUT} = 5 V, f = 1 MHz)



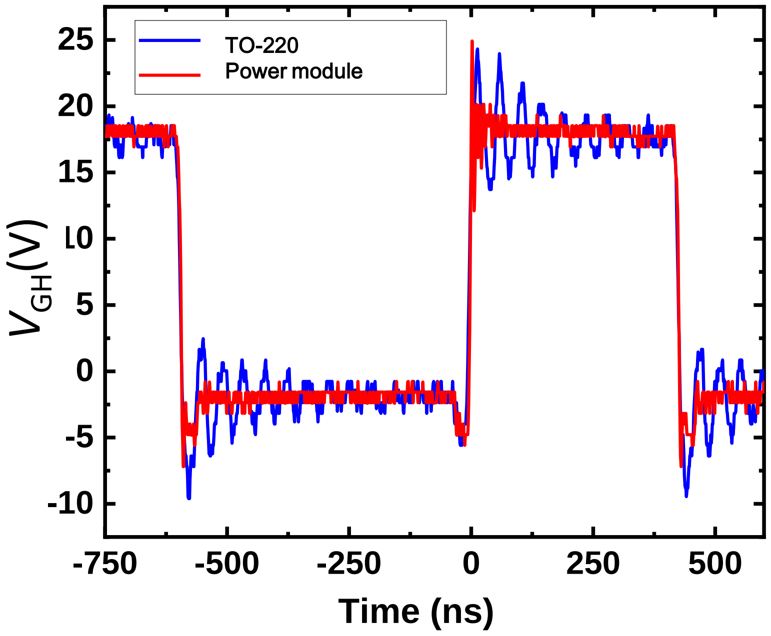
GaN power module



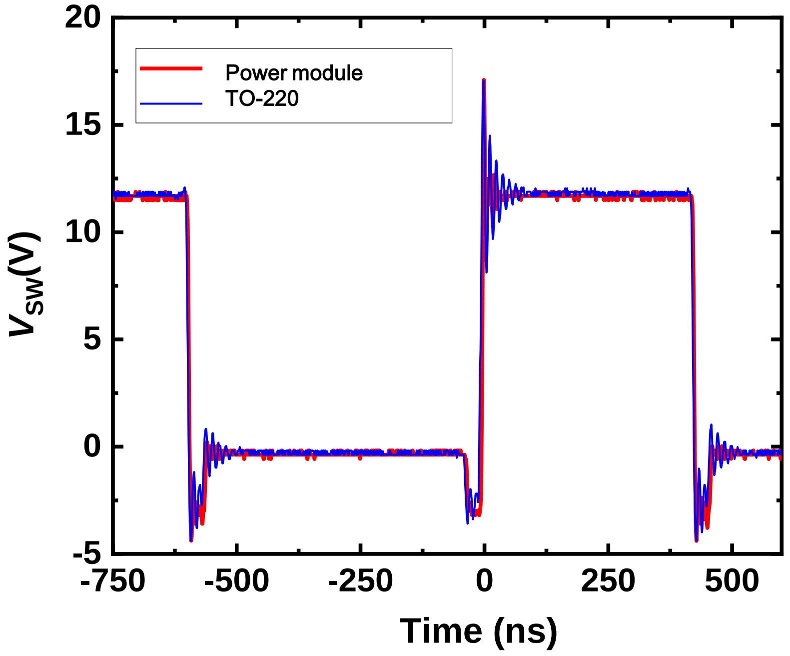
TO-220 packages

Experimental results

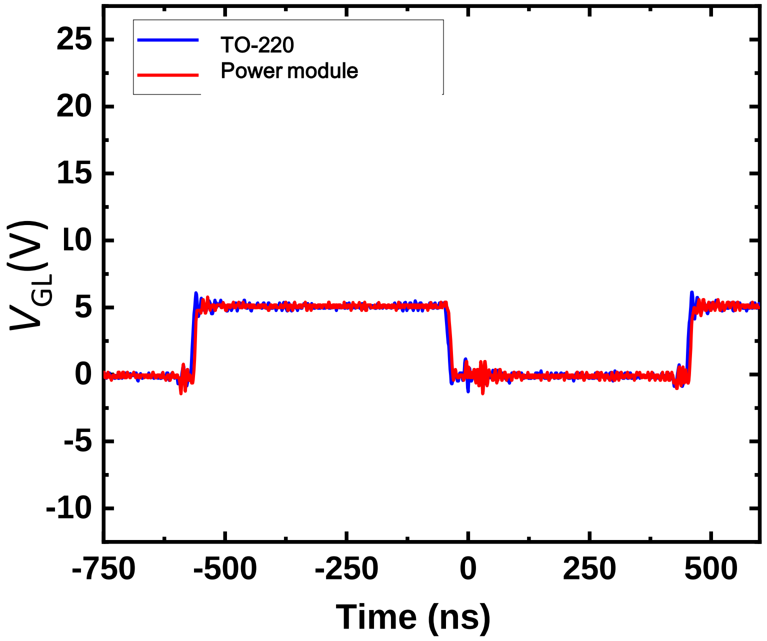
- **Waveforms comparison** (Buck converter, V_{IN} = 12 V, V_{OUT} = 5 V, f = 1 MHz)



Waveforms at HS gates



Waveforms at switching nodes

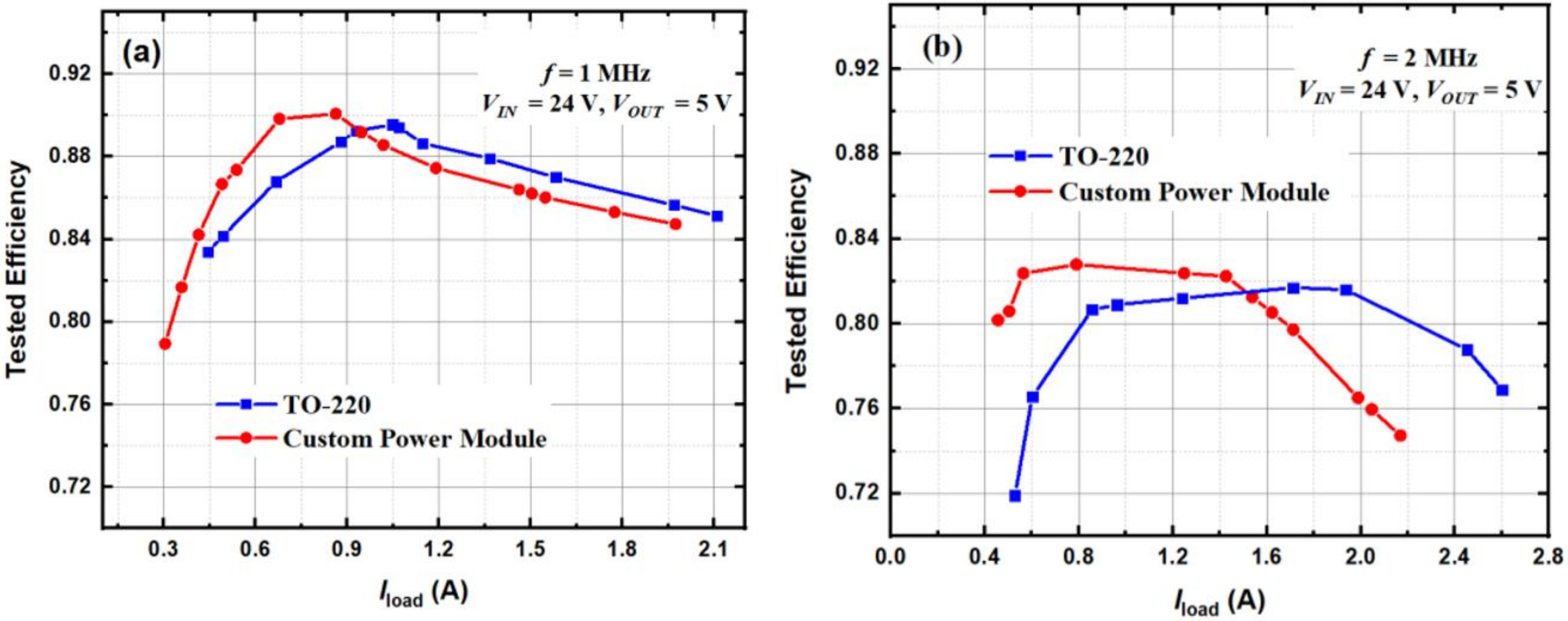


Waveforms at LS gates

2. Proposed GaN Power Module

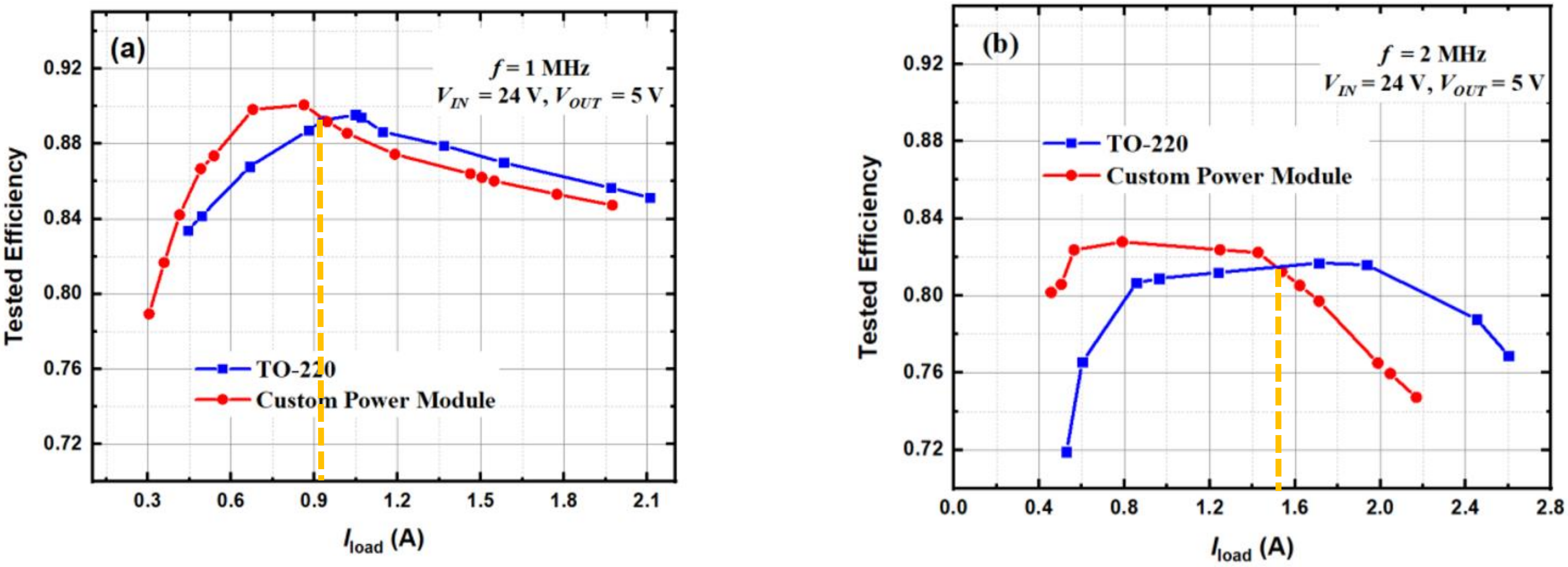
Experimental results

- Efficiency plot (Buck converter, V_{IN} = 24 V, V_{OUT} = 5 V, Dead-time 40ns)



f = 1MHz f = 2MHz

2. Proposed GaN Power Module



- Light load: Power module shows higher efficiencies owing to suppressed ringing oscillation
- Heavy load: Power module shows lower efficiencies owing to large heat transfer
- The higher the switching frequency, the more advantageous the power module will be!

OUTLINE

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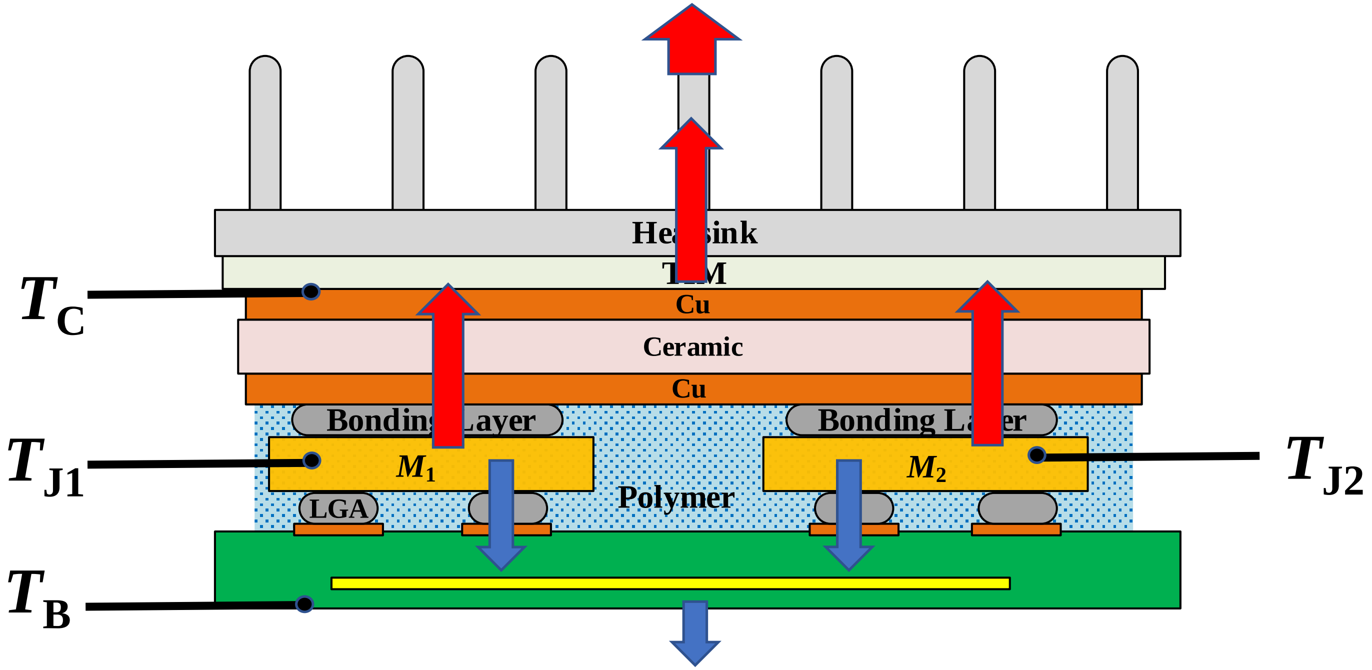
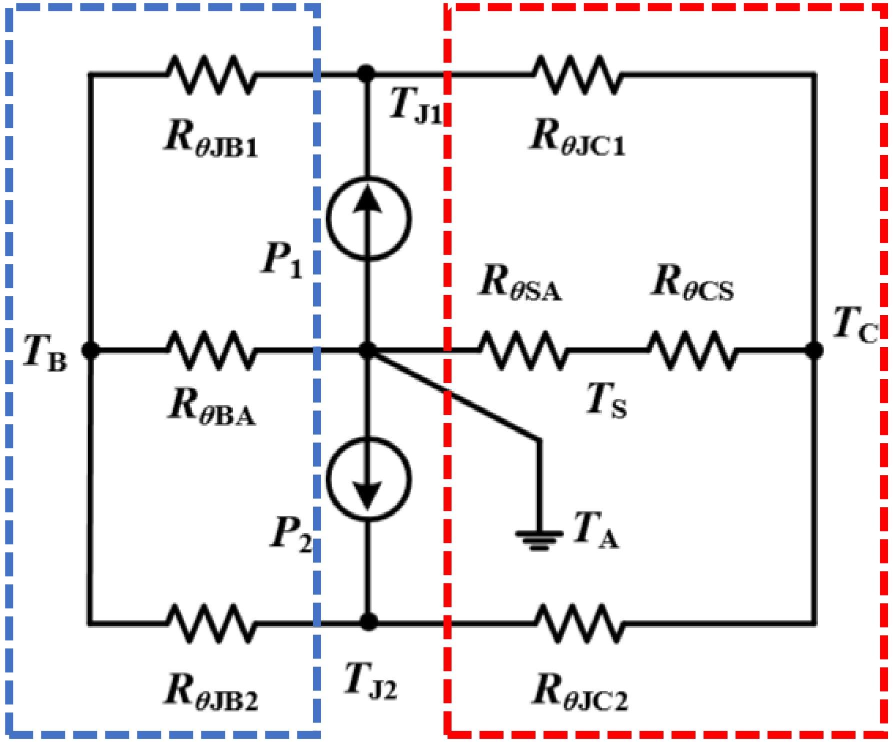
3. **Thermal Considerations for Modules**
4. Conclusions and Future Work

3. Thermal Considerations for Modules

Thermal equivalent circuit



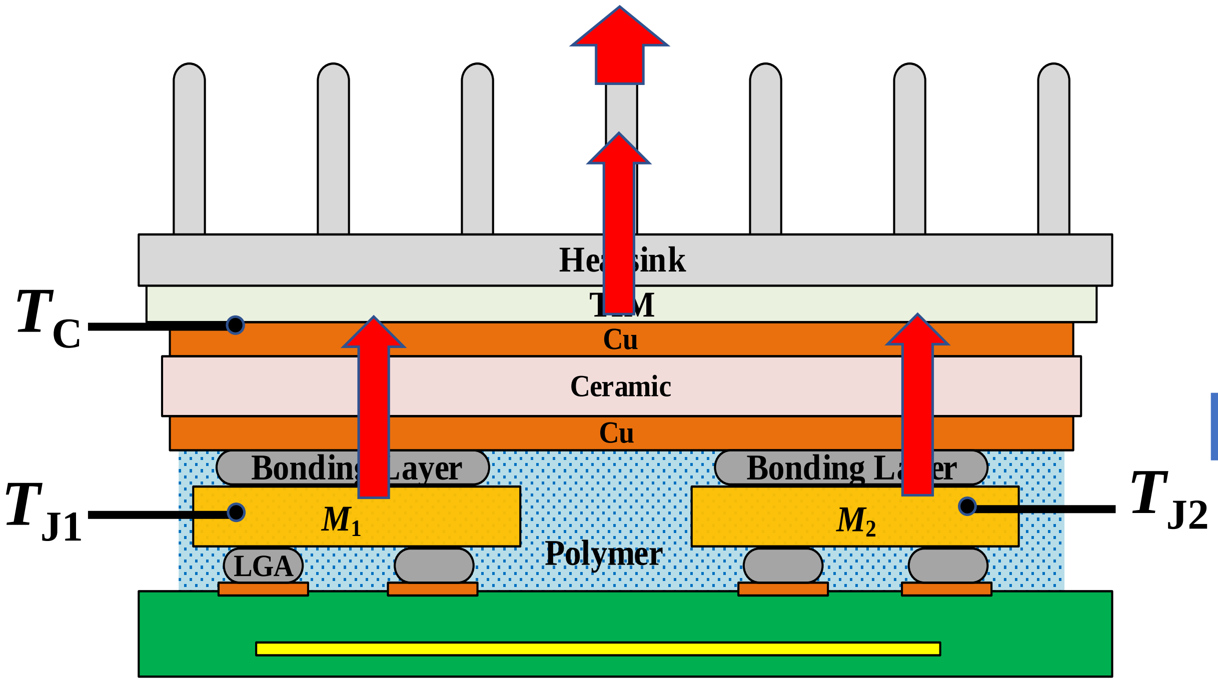


Upwards: Junction-to-Case ($R_{\theta JC}$), Case-to-Sink ($R_{\theta CS}$), Sink-to-Ambient ($R_{\theta SA}$)

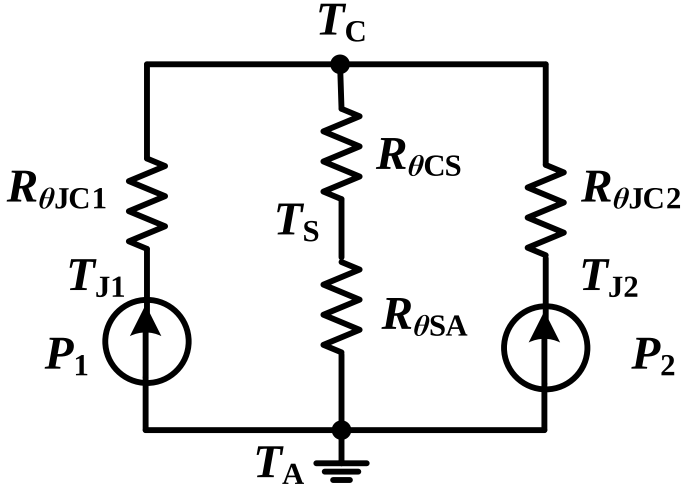
Downwards: Junction-to-Board ($R_{\theta JB}$), Board-to-Ambient ($R_{\theta BA}$)

3. Thermal Considerations for Modules

Simplified thermal equivalent circuit



Heat mainly dissipates upwards !



$$T_{J1} = DP_{switch}R_{\theta JC1} + T_C$$

$$T_{J2} = (1-D)P_{switch}R_{\theta JC2} + T_C$$

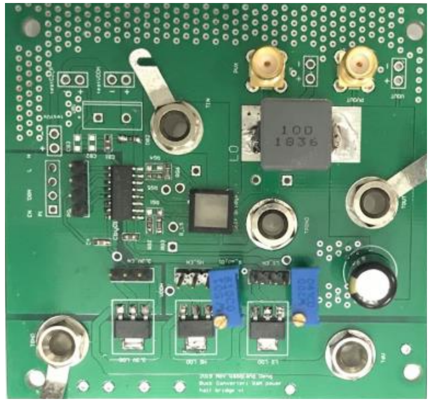
$$T_C = R_{\theta CA}P_{switch} + T_A$$

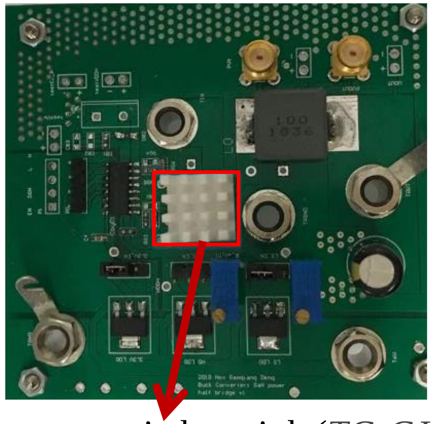
$$R_{\theta CA} = R_{\theta CS} + R_{\theta SA}$$

$$T_S = R_{\theta SA}P_{switch} + T_A$$

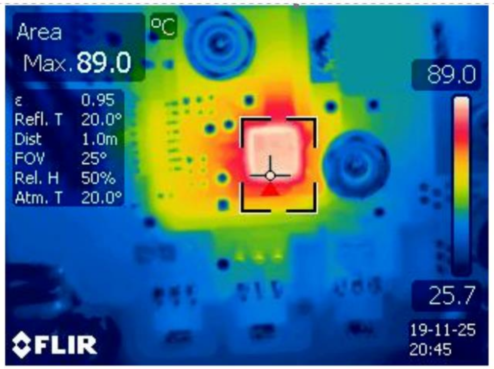
3. Thermal Considerations for Modules

Measuring $R_{\theta CA}$ & $R_{\theta SA}$

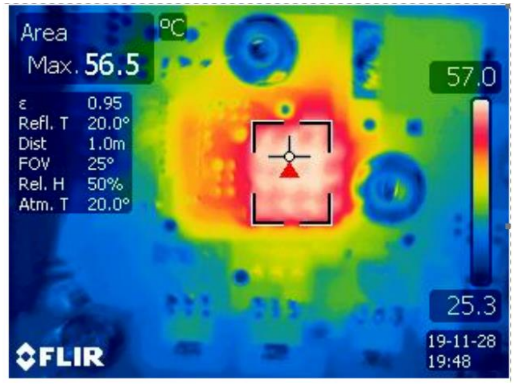




Top-mount ceramic heatsink (*TG-CJP-12-LI98*)

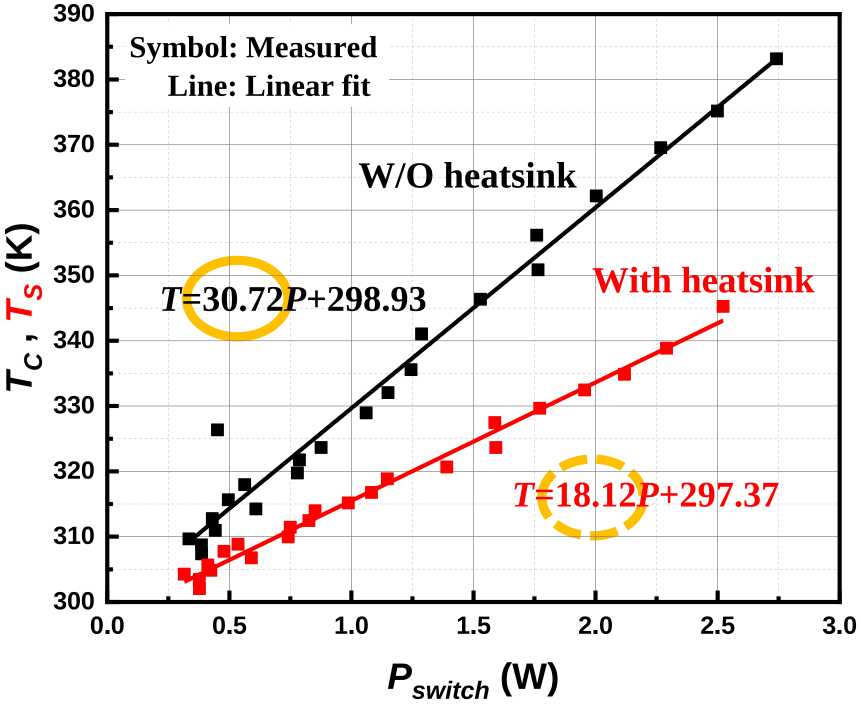


Without a heatsink



With a heatsink

Convection cooling, Output power 9 W



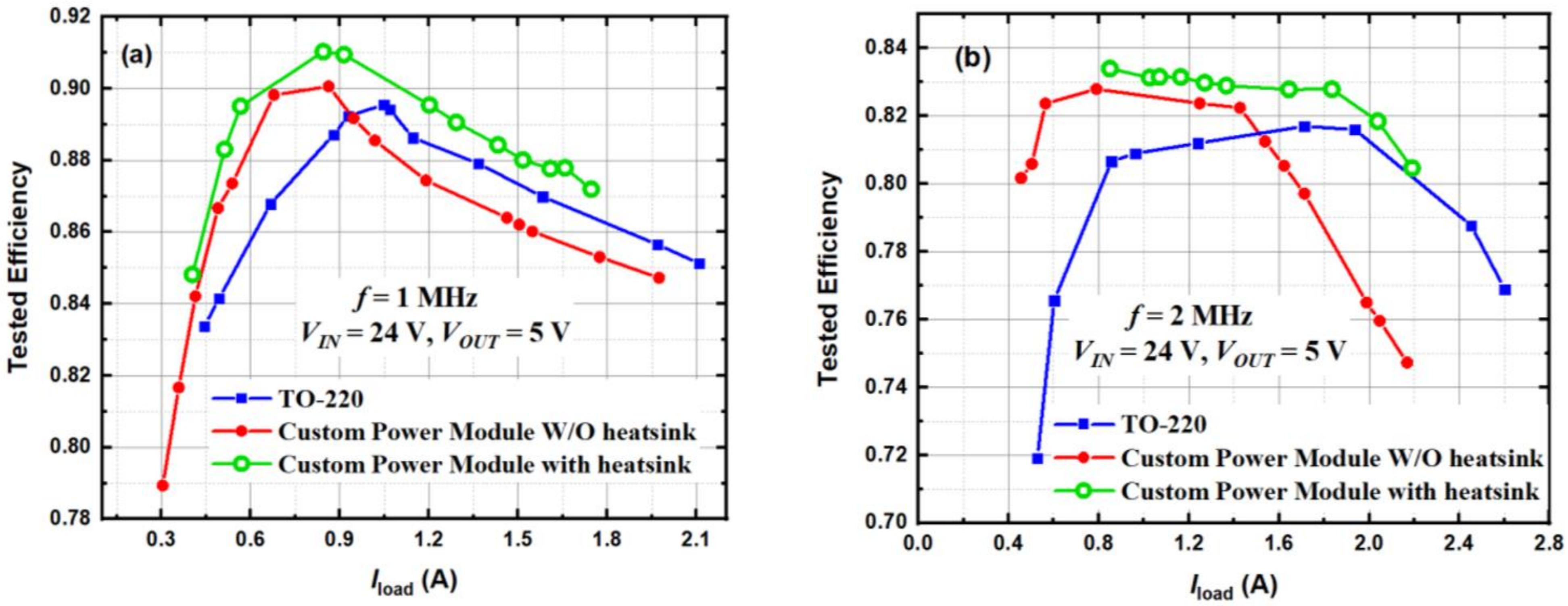
$$P_{\text{switch}} = P_{\text{in}} - P_{\text{load}} - P_{\text{ESR}} - P_L$$

$$T_C = R_{\theta CA} P_{\text{switch}} + T_A$$

$$T_S = R_{\theta SA} P_{\text{switch}} + T_A$$

3. Thermal Considerations for Modules

Efficiency plot (Buck converter, V_{IN} = 24 V, V_{OUT} = 5 V, Dead-time 40ns)

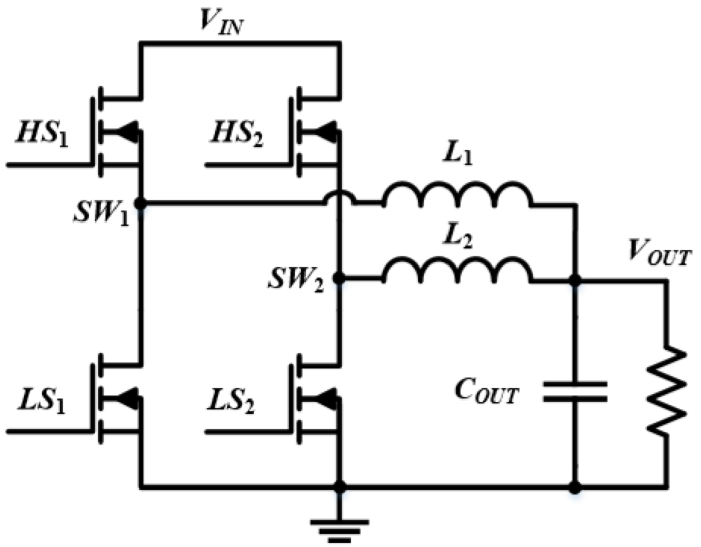


Improved efficiency at heavy load due to decreased junction temperature!

3. Thermal Considerations for Modules

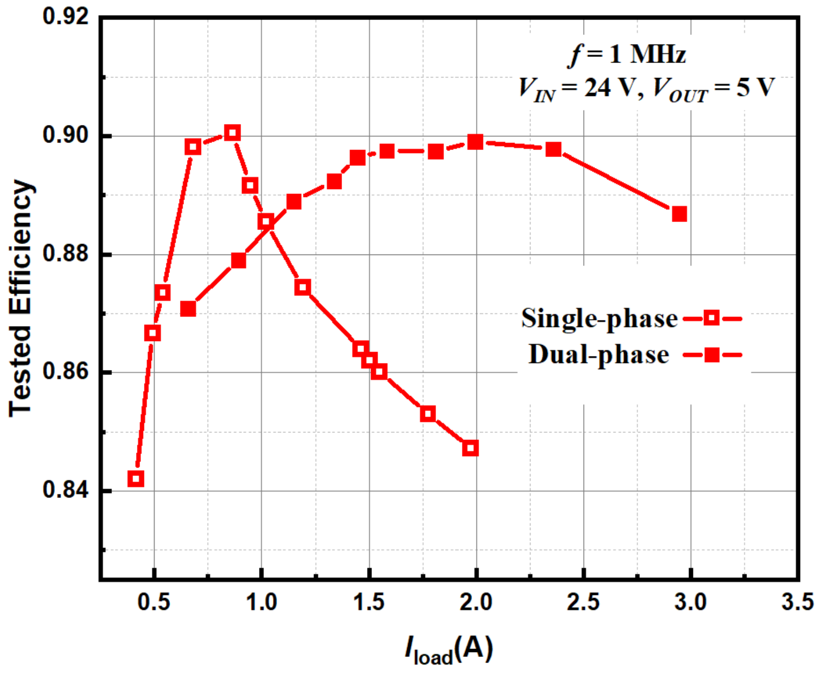
Multi-phase buck converter

-- Higher efficiencies are realized over a wider load current range !



Dual phase buck converter output stage

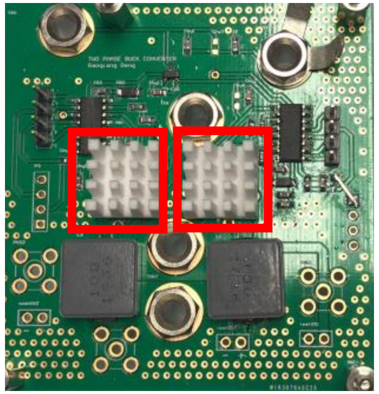
Test-bench using two modules



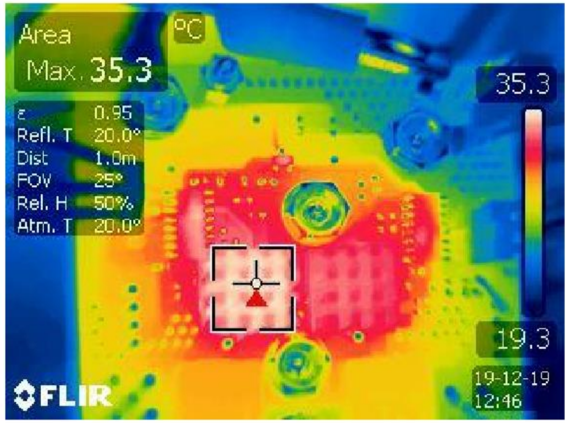
Efficiency plot

3. Thermal Considerations for Modules

Dual phase buck converter

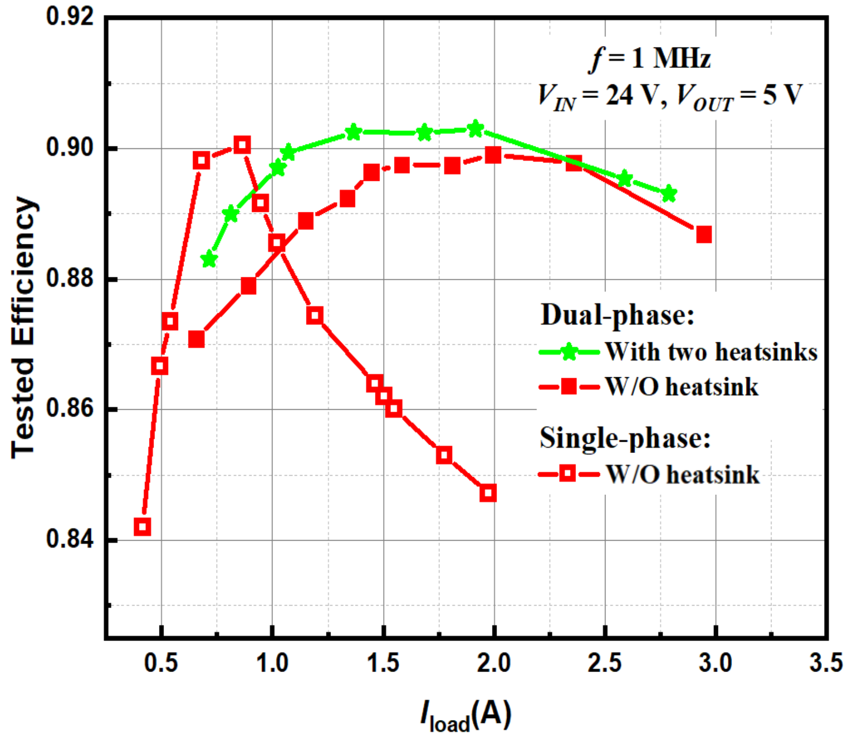


Without heatsinks



With two heatsinks

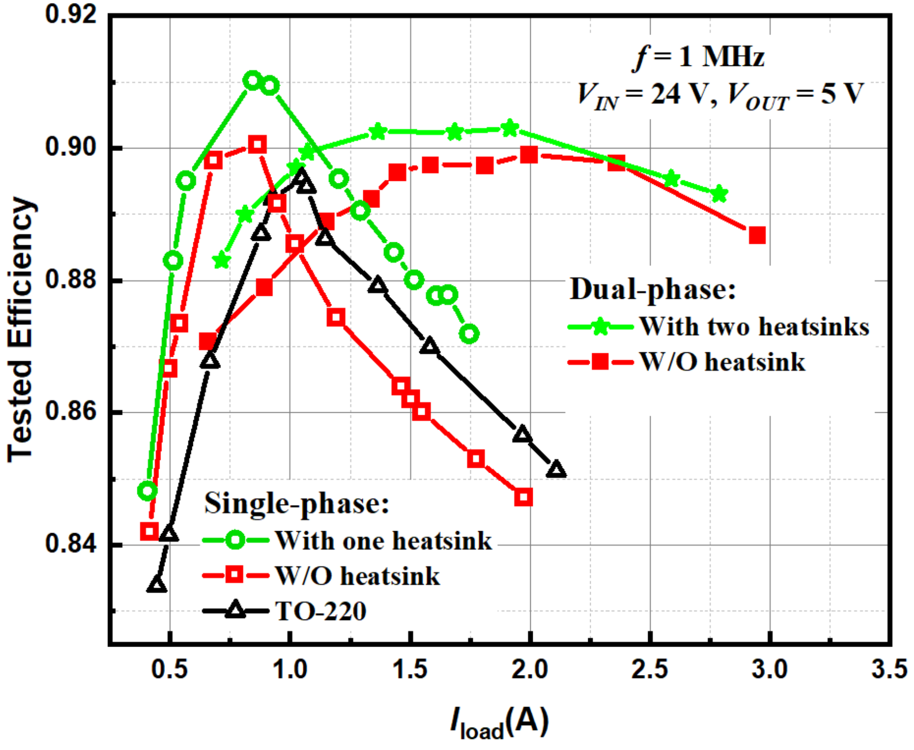
Convection cooling, Output power 9 W



Efficiencies are further increased by attaching heatsinks.

3. Thermal Considerations for Modules

Test-benches for all buck converters



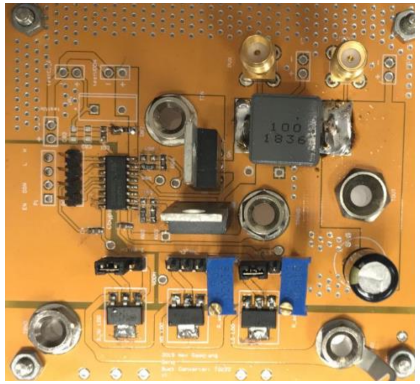
Convection cooling

Dual phase

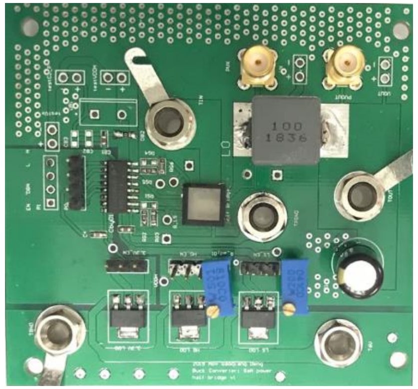
W/O heatsinks

With heatsinks

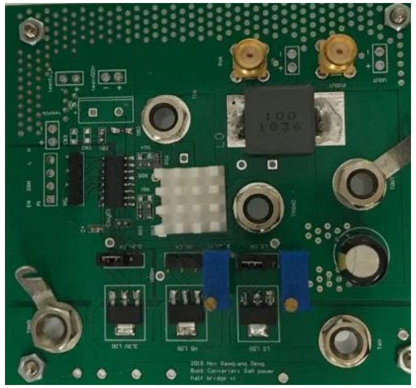
Single phase



TO-220



Module

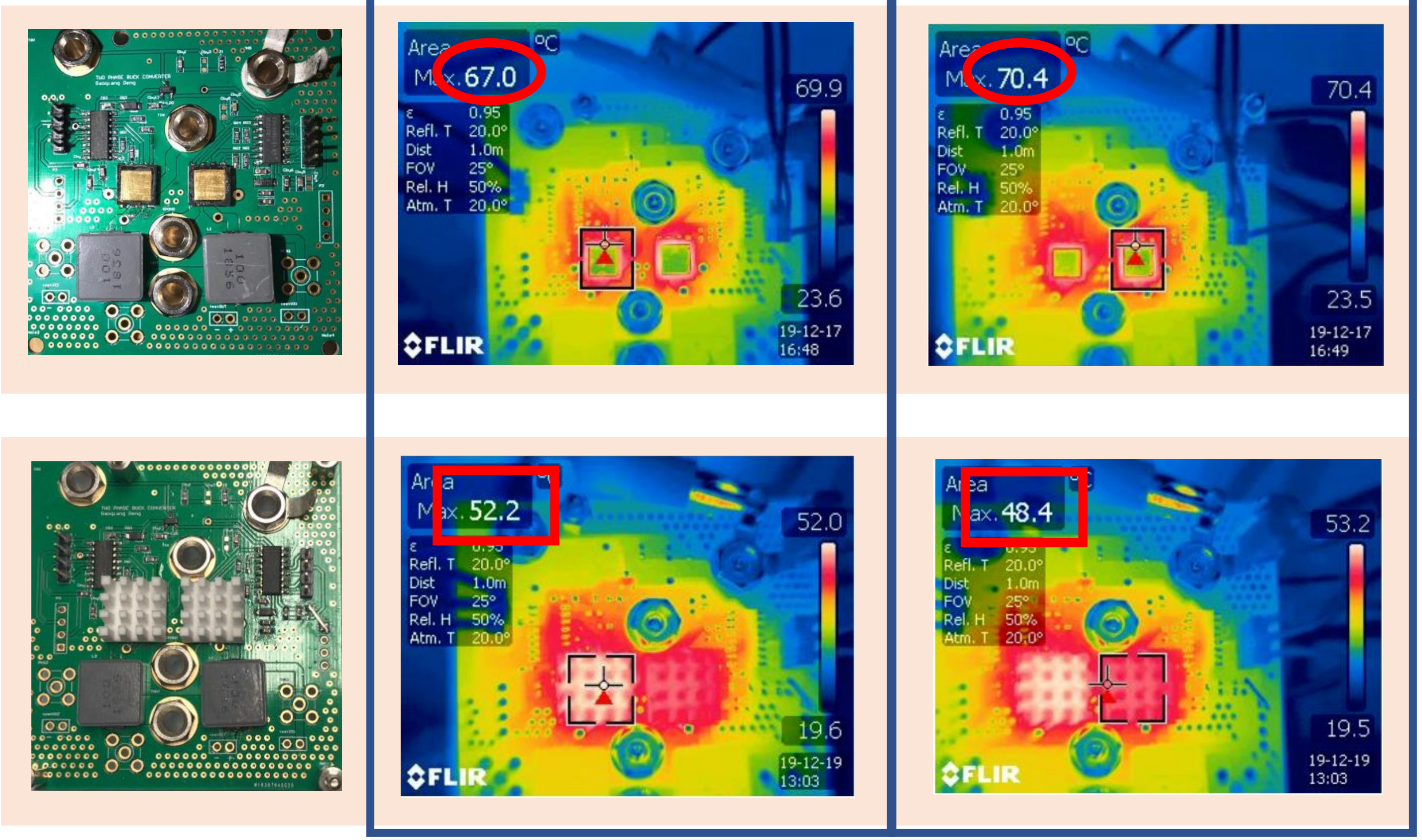


Module with one heatsink

3. Thermal Considerations for Modules

Temperature differences between phases

Phase 1	Phase 2



Convection cooling, Output power 18 W

Uneven convection airflow & current sharing

⇩

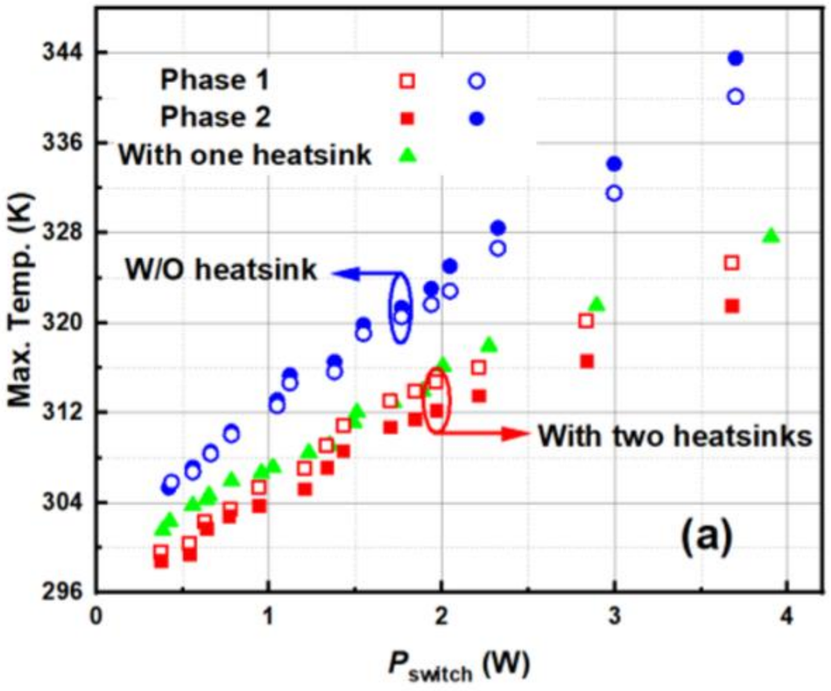
Increased peak temperature of PCB

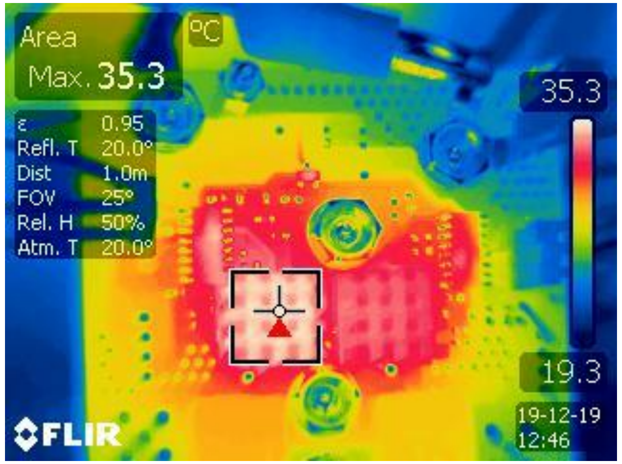
⇩

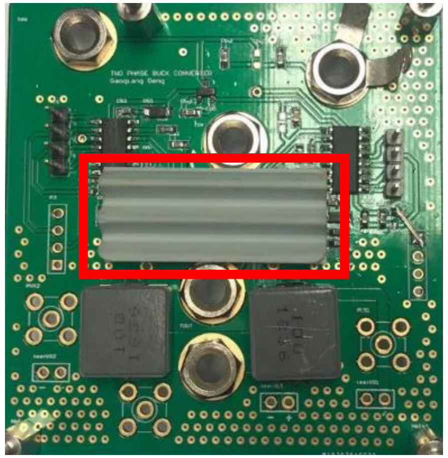
Reduced mean-time-before-failure & Reliability issues

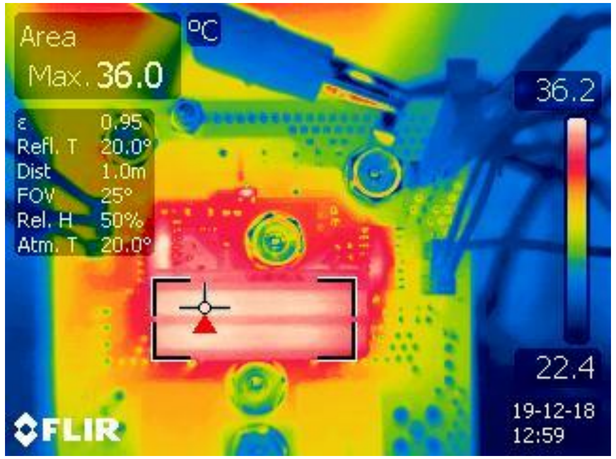
How to eliminate temperature variations

- Attach one heatsink on both modules
- Detect each phase's temperature and build a thermal management circuit









OUTLINE

4. Conclusions and Future Work

The proposed GaN power module

- Increased the power conversion efficiency under light loads
- Suppressed the ringing oscillation during high-frequency operation by minimizing the parasitics
- Conduction losses in the module are very sensitive to temperature

Future work includes

- Optimizing the module package for better heat dissipation
- Building a thermal management circuit for multi-phase buck converters