Sandeep Bala, Workshop on “High Pen PV through next-gen PE technologies”, NREL, 2016-10-12

# Next gen PV inverter systems – using WBG devices

## Challenges and research needs

# Agenda
## WBG-based PV inverter systems

Background: ABB solar inverters

Challenges for WBG-based PV string inverters

Research needs

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# ABB solar portfolio
## Factsheet

ABB in the solar business

- Has provided solutions **since the 1990s**
  - link
- Acquired **Power-One in 2013**
  - link
- Has worldwide solar inverter installed base of over **22 GW**
  - link
- Doubled installed base in India from **1 GW to 2 GW in 6 months in 2015**
  - link

# ABB solar portfolio

## From source to socket, no one provides more solar solutions

### Utility-scale

Low voltage products

Solar inverters

Turnkey stations

Medium voltage products

Transformers

Substations

Electrical balance of plant

Energy storage

Plant automation (Symphony Plus for Solar)

Remote monitoring (Aurora Vision)

Operations and maintenance

# ABB solar portfolio

## From source to socket, no one provides more solar solutions

### Commercial & Industrial

Low voltage products

Solar inverters

Building automation

Energy storage

### Residential

Low voltage products

Solar inverters

Energy storage

# Recent products launched
## PVS980

Basic specs:

- 1818…2000 kVA
- 1500 Vdc max
- 98.6% CEC efficiency
- 1-MPPT


System

- Dimensions: 2366H x 3180W X 1522D
- Weight: 3850kg


Highlights:

- Closed loop cooling system
  - phase transition and thermosiphon technology
  - no fillable liquids, pumps, valves, inhibitors or leaks
- Modular, industrial design

# Recent products launched
## TRIO-50

Basic specs:

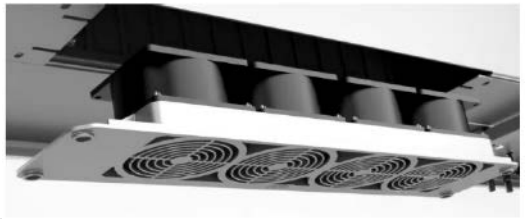
- 50 kVA
- 1000 Vdc max
- 98.0% CEC efficiency
- 1-MPPT

Power module

- Dimensions: 702H x 725W X 260D
- Weight: 66kg

Highlights

- Vertical or Horizontal mounting
- AC and DC Connection box options
- Field-replaceable fan tray



# Recent products launched
## UNO-3.6/4.2

Basic specs:

- 3.6/4.2 kVA
- 850 Vdc max
- 97.5% CEC efficiency
- 1-MPPT

System

- Dimensions: 553H x 418W X 175D
- Weight: 12kg

Highlights

- Single-stage topology
- Natural convection cooling

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## WBG-based PV inverter systems

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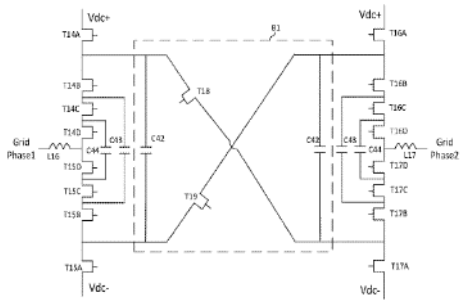
# Alternatives for WBG

## Continued innovation in Si-based converters

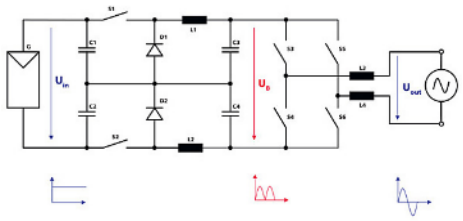
### Flying capacitor



SolarEdge

- US 9,318,974 B2

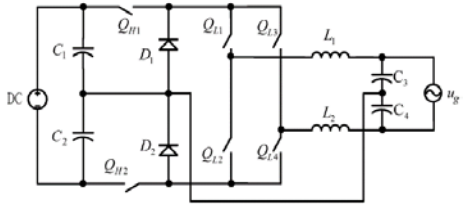
### Buck + unfolder



Steca

- Coolcept

### 5-level



Sungrow

- US 2016/0268925

**Si-based converters continue to evolve with lower cost to performance ratio**

# Alternatives for WBG
## ABB Si thyristor-based topology

Ongoing ABB R&D project

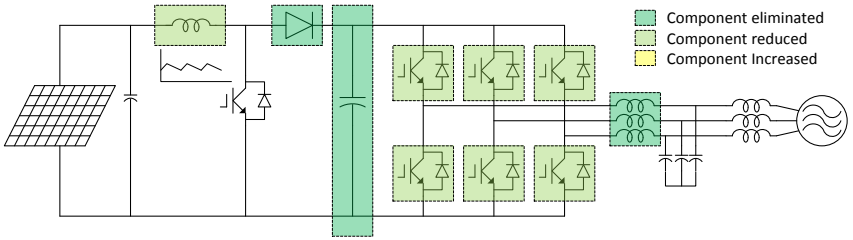
- Funded by DoE Sunshot

Approach to reduce cost and improve reliability

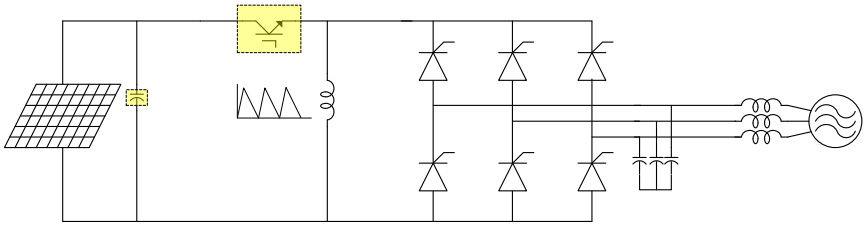
- Semiconductors
  - Only one IGBT
  - Replace: 6 IGBTs → 6 Thyristors
- Passives
  - No output inductor
  - No dc bus capacitor

Further improvements may be possible with:

- Wide bandgap devices
- Better thyristors

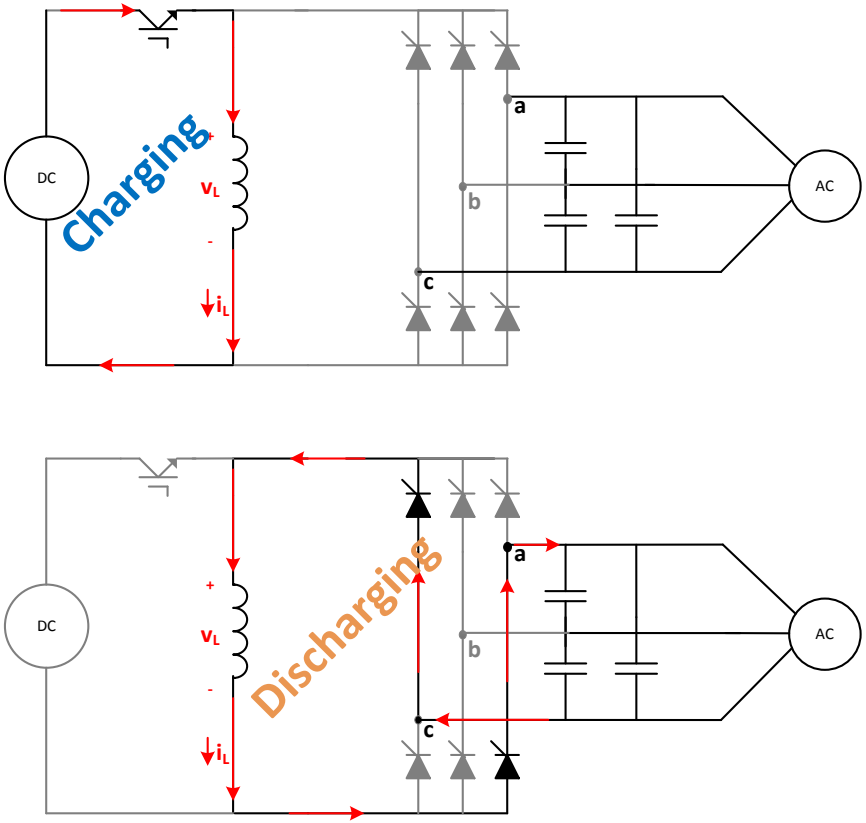



30% cost reduction
40% weight reduction



# Alternatives for WBG
## ABB Si thyristor-based topology

High frequency switching of thyristors enabled by Discontinuous Conduction Mode operation



# Challenges for SiC
## Reliability question marks

### Bias Temperature Stress (HTRB and HTGB) effects on Threshold Voltage instability

E.g. AECQ-101

- based on JEDEC JESD-22 A108C method
- "electrical testing shall be completed as soon as possible and no longer than 96 h after removal of bias from devices"

Standards have insufficient specs

- Measurement temperature
- Measurement time
- Measurement speed

| Measured at (temp) | Measured at (time) | Possible conclusion |
|---|---|---|
| high temp | stress time << $10^5$ sec | BTS improves VT stability |
| room temp | following rapid cooling | BTS degrades VT stability |
| room temp | after some time has passed | BTS has small effect on VT stability |

**Existing device testing standards inadequate to predict converter reliability**



AJ Lelis et al, "Basic Mechanisms of Threshold-Voltage Instability and Implications for Reliability Testing of SiC MOSFETs," IEEE Trans. on Electron Devices, Feb 2015

# Outlook for SiC

## ABB's first products being rolled out now

Battery charger for rail applications

Basic specs:

- Power: 10 kW
- Footprint: 360 x 220 mm

Highlights:

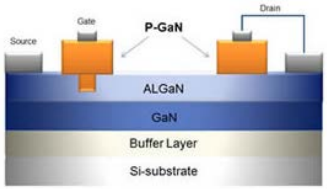
- Compatible with all rail voltages
- 10x smaller footprint
- 80% reduction in weight


Bordline BC

**Cost/benefit currently case-by-case… With a cautious eye on reliability**

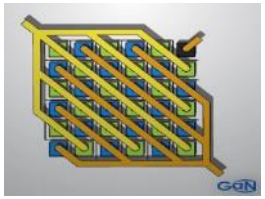
# Challenges for GaN
## GaN-world – a frontier location

### Gate injection transistor



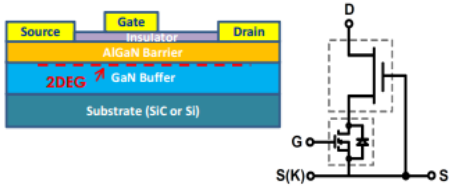

Infineon / Panasonic

### Large e-mode chips



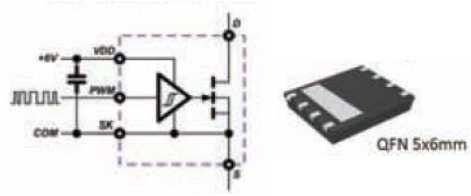

GaN Systems

### Cascode



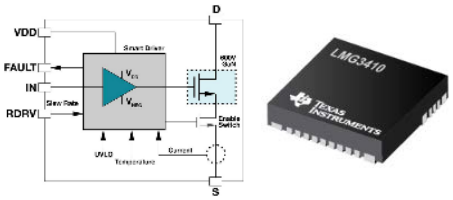

Transphorm

### Monolithic gate drive



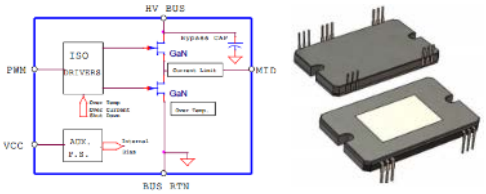

Navitas

### Co-packaged gate drive




Texas Instruments

### System-in-package




VisIC

**Device characteristics and packages evolving rapidly**

# Agenda
## WBG-based PV inverter systems

Background: ABB solar inverters

Challenges for WBG-based PV string inverters

Research needs

# Next gen PV inverters
## Setting a new, lower cost curve

How can WBG devices lower PV inverter cost?

- Use less material
  - higher frequency switching reduces size of passives
  - higher temperature operation (SiC) reduces size of heat sinks
- Simpler circuit designs
  - two-level instead of three-level inverters needs fewer auxiliary components
  - use of monolithic gate drives (GaN) reduces parts count

What are the other non-traditional pathways for cost reduction?

- Advanced manufacturing
  - fewer, cheaper, and more automated processing and assembly steps
  - leaner supply chain

# PCB integrated power electronics
## System in board

Why integrate?

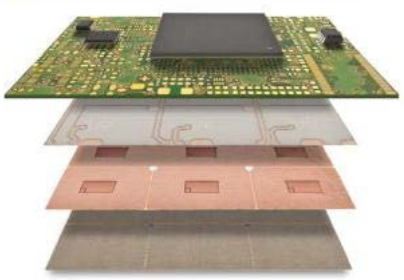
- Increase electrical performance, functionality and efficiency
- Reduced parasitic inductance/resistance
- Improved $R_{TH}$
- Low cost potential

Challenges with integration

- Increased power density → thermal management from outset
- Increased complexity → package becomes more application specific

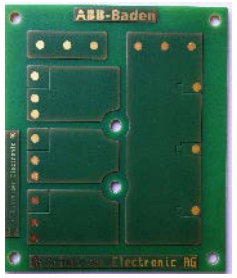
Applications

- PV string invertor
- EV car chargers
- Switched mode power supplies
- Integrated drives (robotics, HHEV)




Schweizer Electronic $p_2$Pack

Commercially available power module



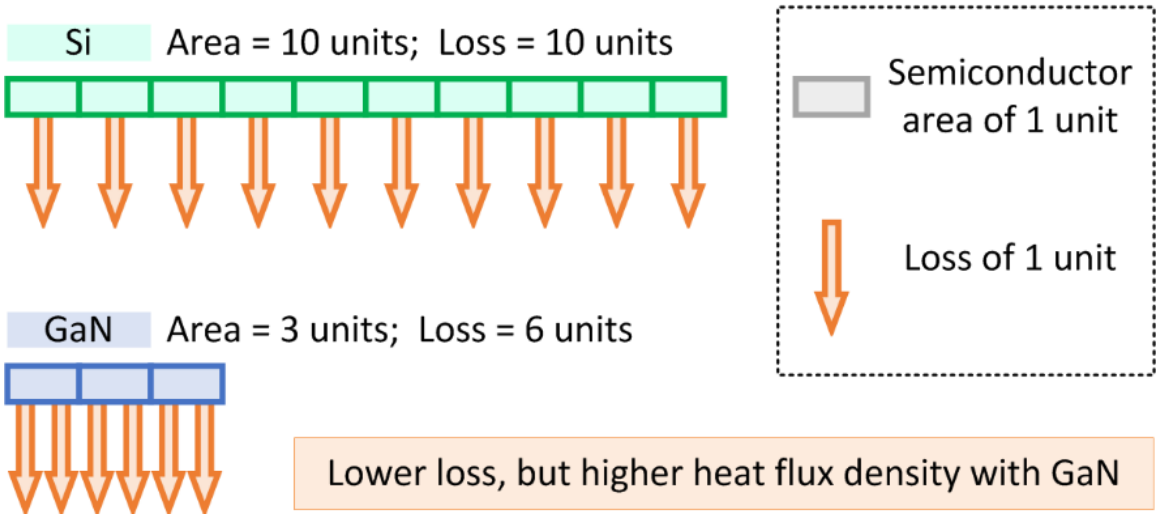

Next generation power electronics package



D Kearney, “PCB Embedded Power Electronics for Low Voltage (<1.2kV) Applications” at CIPS 2016

# PCB integrated power electronics
## Considerations for WBG devices

Simplified visualization of thermal management challenge with WBG devices

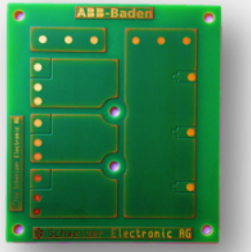




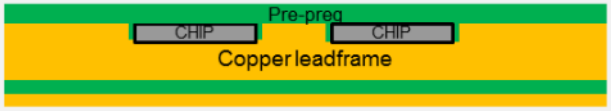

J Xu et al, "The Promise of GaN in Power Converters," in ABB Research Center United States, Technical Review 2015

# PCB integrated power electronics
## Potential for better heat spreading

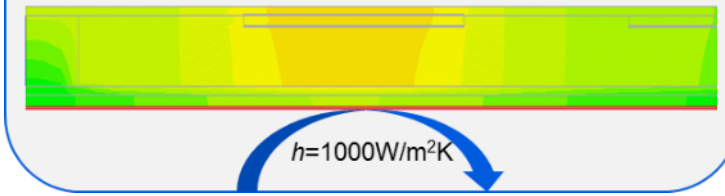
- IGBT=32.6W
- Diode=6.8W
- *h*=1000W/m²K

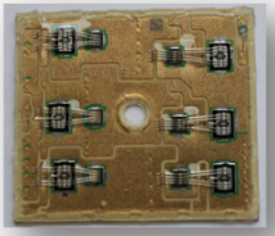



mPIPE package heat spreading

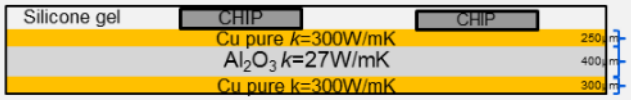



HTC applied to base 1000W/m²K

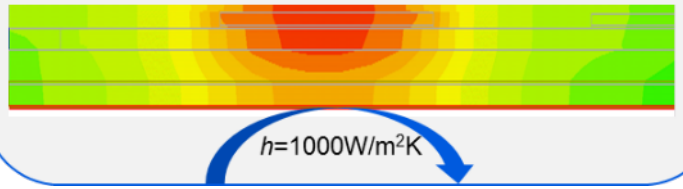


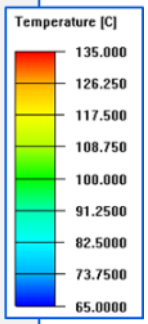



Traditional package stucture




HTC applied to base 1000W/m²K






D Kearney, "PCB Embedded Power Electronics for Low Voltage (<1.2kV) Applications" at CIPS 2016

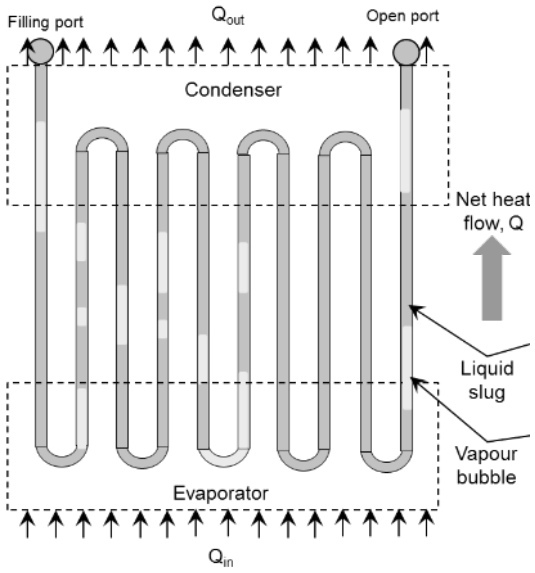
# PCB integrated power electronics
## Summary of results of embedding Si chips

| # | Activity | Status | Comment/Result |
|---|---|---|---|
| 1 | **Chip metallization**<br>• Cu metallization | ☺ | • Chip metallization of small gate pads challenging. More difficult for smaller gates for WBG. |
| 2 | **Die attach**<br>• Chip alignment fixture<br>• Silver film sintering<br>• Thermo-shock test | ☺ | • Acceptable alignment achieved<br>• Agromax 8020 sinter foil identified as a suitable candidate material. Successful sintering and thermo-shock cycling to leadframe |
| 3 | **Embedding**<br>• $p_2$Pack lamination and top contact | ☺ | • Successful embedding and top contact |
| 4 | **Switching**<br>• Switching behaviour<br>• Double pulse test | ☺ | • Comparable to standard module (not optimized). IEEE journal |
| 5 | **Insulation**<br>• Breakdown<br>• Partial discharge | ☺ | • Break down non-aged 5.3kV$_{rms}$ → 6.5kV$_{rms}$<br>• Partial discharge ok<br>  • up to 3.6kV$_{rms}$ in air (3x nominal operating voltage)<br>  • 4.7kV$_{rms}$ potted in gel |
| 6 | **Thermal**<br>• Heat spreading<br>• $R_{th}$ | ☺ | • PCB embedded module Rth -cooler = 0.50°C/W – 0.61°C/W<br>• SkiiP Rth j-cooler = 0.89 °C/W – 0.96°C/W (data sheet Rth IGBT=0.9°C/W)<br>• PCB embedded module **30-44%** lower $R_{th}$.<br>• Thermal simulations highlighted superior heat spreading |
| 7 | **Reliability**<br>• Active power cycling | ☺ | • 30A 120% $I_{nominal}$ dT=42-45°C **1M cycles no failure**<br>• 35A 140% $I_{nominal}$ dT=70-75°C **2M cycles no failure**<br>• 40A 160% $I_{nominal}$ dT=90-93°C 400k cycles |

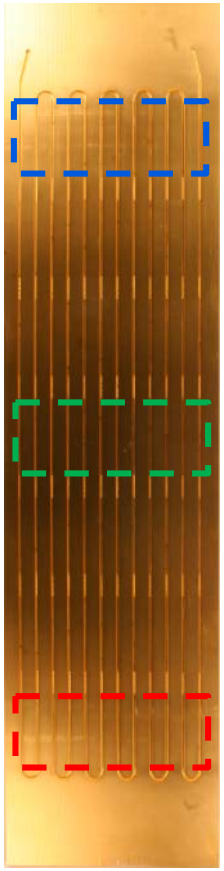
# PCB embedding of pulsating heat pipes
## Basics

Properties / Features

- Sensible and latent heat transfer
  - liquid slugs and vapour plugs
- PHP is wickless
  - easier to integrate
- Operates independent of gravity
  - depends on capillary forces, surface tension of fluid and channel diameter
- Flexible integration
- Operate at sub-ambient pressures
- Lower cost/easier to manufacture compared to traditional wicked heat pipe
- Dielectric working fluids
  - **direct chip cooling possible**




**Open loop PHP**





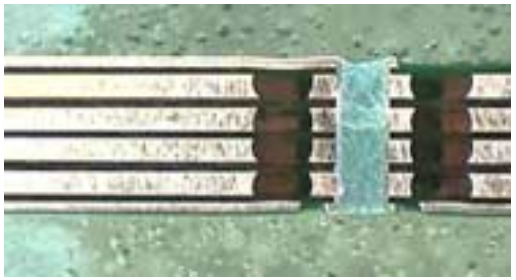
D Kearney et al, “An Integrated Passive Cooling Solution for PCB Substrates,” in 8th IMAPS workshop on Micropackaging and Thermal Management, 2013

# PCB embedding of pulsating heat pipes
## Example of performance dependence on design parameters

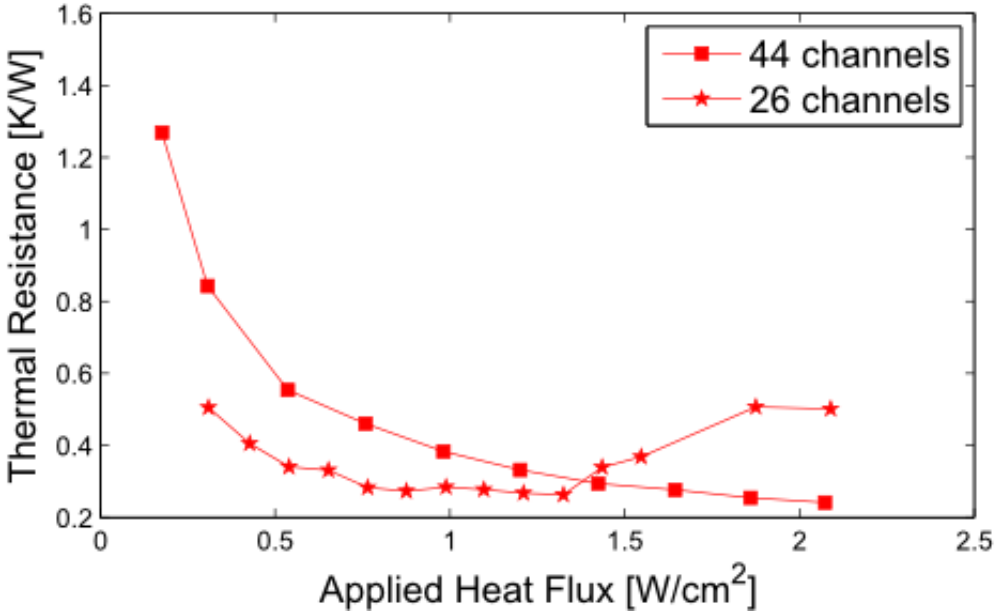
**Minimum $R_{TH}$ for tested conditions: 0.20°C/W**

- Similar to values reported in literature
- >10x improvement  vs. copper

$$R_{th} = \frac{T_{evap} - T_{cond}}{Q_{in}}$$



**Schweizer Thick Copper Board**

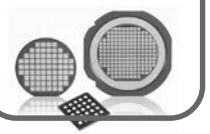



D Kearney et al, “An Experimental Analysis of an Open Loop Pulsating Heat Pipe Operating with a Dielectric Working Fluid for Embedded Power Electronics Applications” in IHTC ‘15

# A vision for the future
## PCB-integrated WBG-device based PV inverter

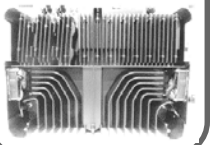
Commercial state-of-the-art

Silicon semiconductors



Press-in module

Heat sink & fan



Less losses, smaller passives

Improved layout and EMI

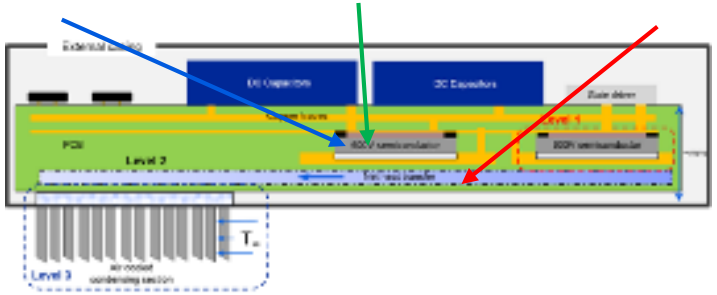
Reliable and effective cooling

Proposed technology

WBG semiconductors

PCB embedding

Passive two-phase cooling



Higher efficiency

Higher power density

Higher reliability

Power and productivity
for a better world™