# Next-Generation Power Electronics Technology with Vehicle Electrification


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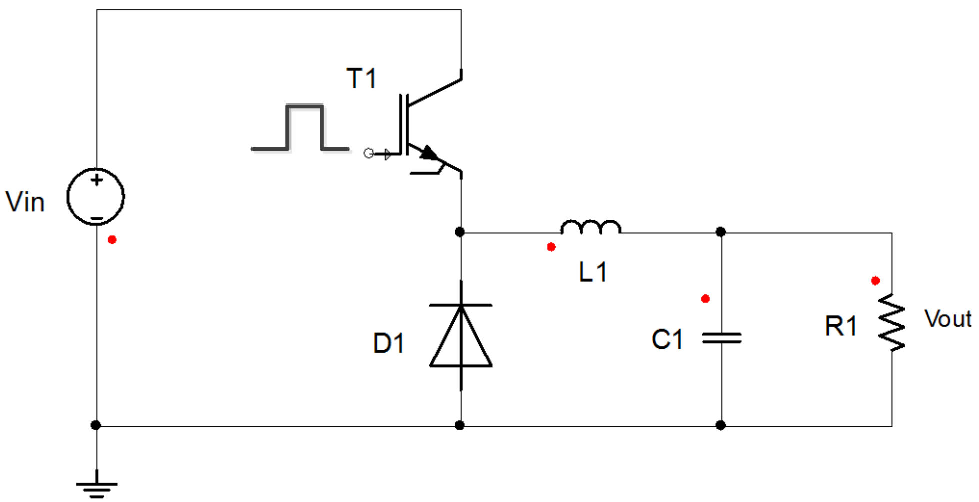
# Agenda

- **WBG Semiconductors vs Silicon Devices;**
- **WBG Semiconductors: Challenges and Opportunities;**
- **WBG Semiconductors in EVs;**
- **Conclusions.**

# Challenges of Power Electronics

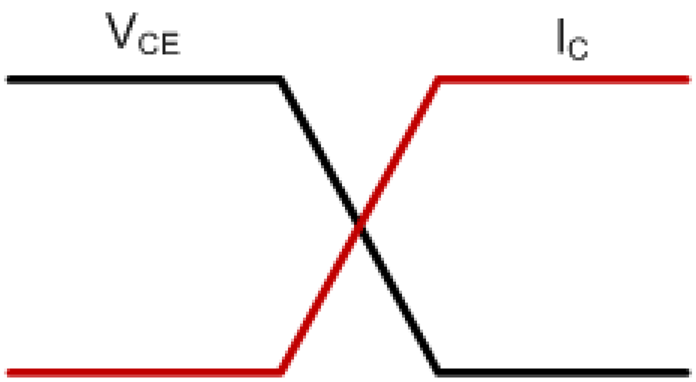



$$V_o = DV_{in}$$

$$L = \frac{V_o}{\Delta I_L f_s}(1-D)$$

$$C = \frac{V_o}{8L\Delta V_o f_s^2}(1-D)$$

**The higher fs the merrier.**




$$P_{swon} = \frac{V_{CE} I_C \Delta t}{6} f_s$$

**The lower fs the merrier.**

# 15 Years ago…

**We believed…**

1. **~10kHz is the best switching frequency for IGBTs;**
2. **MOSFET is good for <1kW application;**
3. **MV (>1000V) drive should use ~1kHz;**
4. **Wide-bandgap devices are far away.**

# Mega-Watt Motor Drive System

**An IGCT based Three-level Inverter was built to drive a 6000V/1.25MW Induction Motor.**

**4000V/4500A IGCT**

**6000V/1.25MW IGCT based Three-Level NPC Inverter**

Kevin Bai (Co-PI), China Significant NSF, “Transients of High-Voltage and High-Current Power Electronics System”, 2007~2011.

# Mega-Watt Motor Drive System

**An IGCT based Three-level Inverter was built to drive a 6000V/1.25MW Induction Motor.**

**6000V/1.25MW System**

**6000V/1.25MW Motors**

**1.25MW Waste Water Pumps**

**Waste-Water Tank**

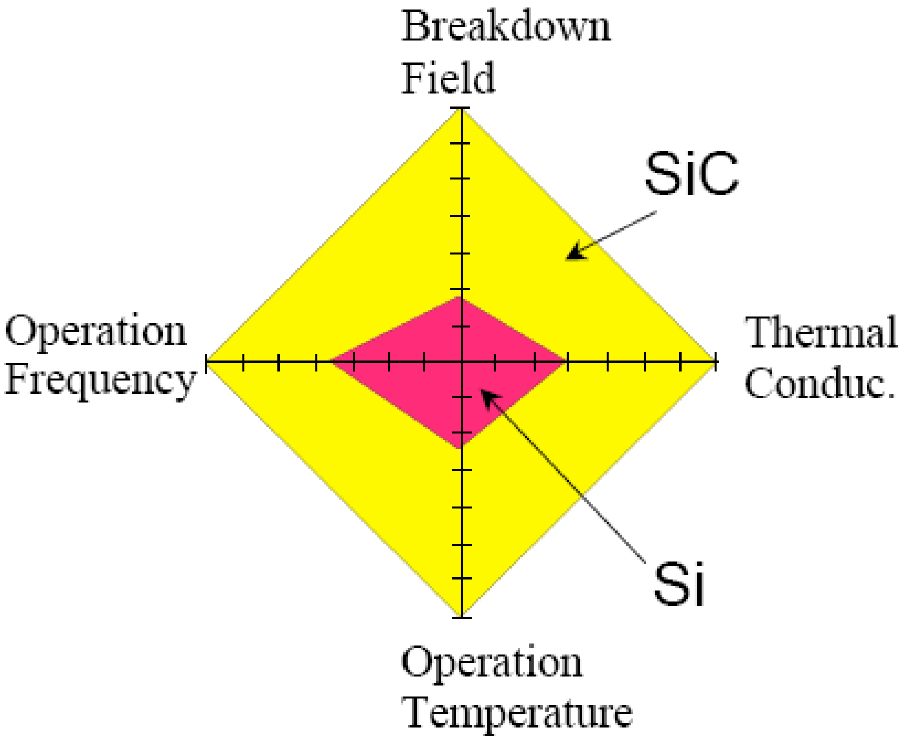
# 5 Years ago…

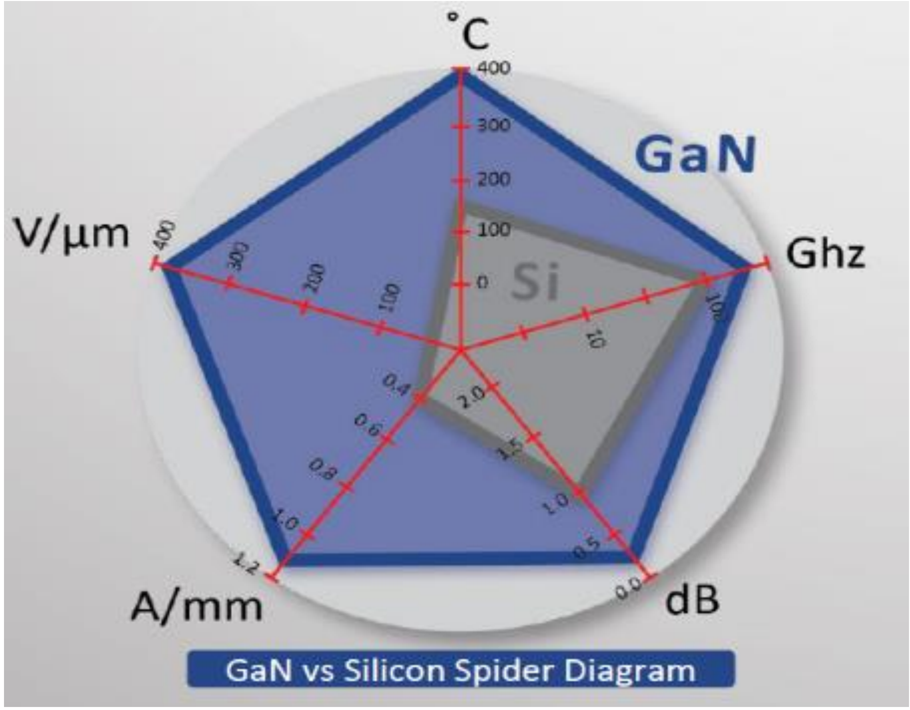
**We witnessed…**

1. **Fast-speed IGBTs (fs>50kHz) are on the market;**
2. **Cool MOSFETs can easily reach >10kW;**
3. **SiC devices enables higher fs for MV motor drive systems;**
4. **GaN are on the agenda.**

# SiC and GaN

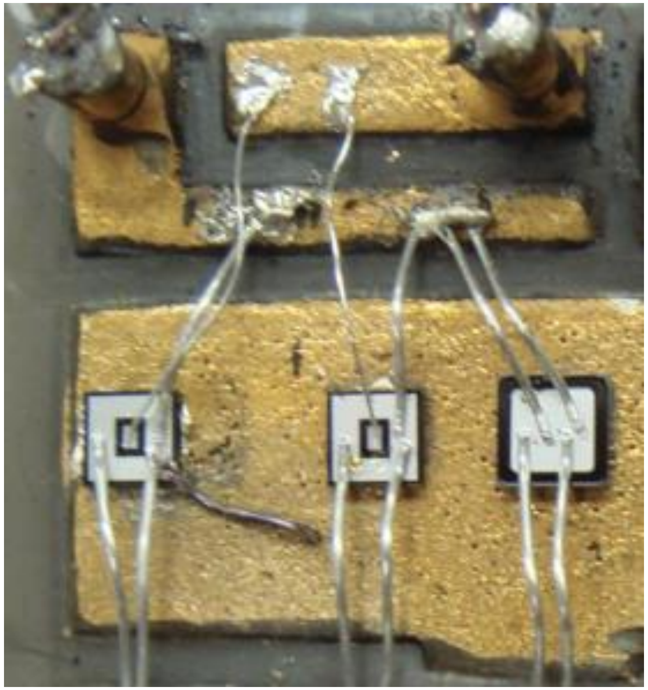
**Wide bandgap indicates higher thermal capability, which means less heatsink or higher switching frequency.**



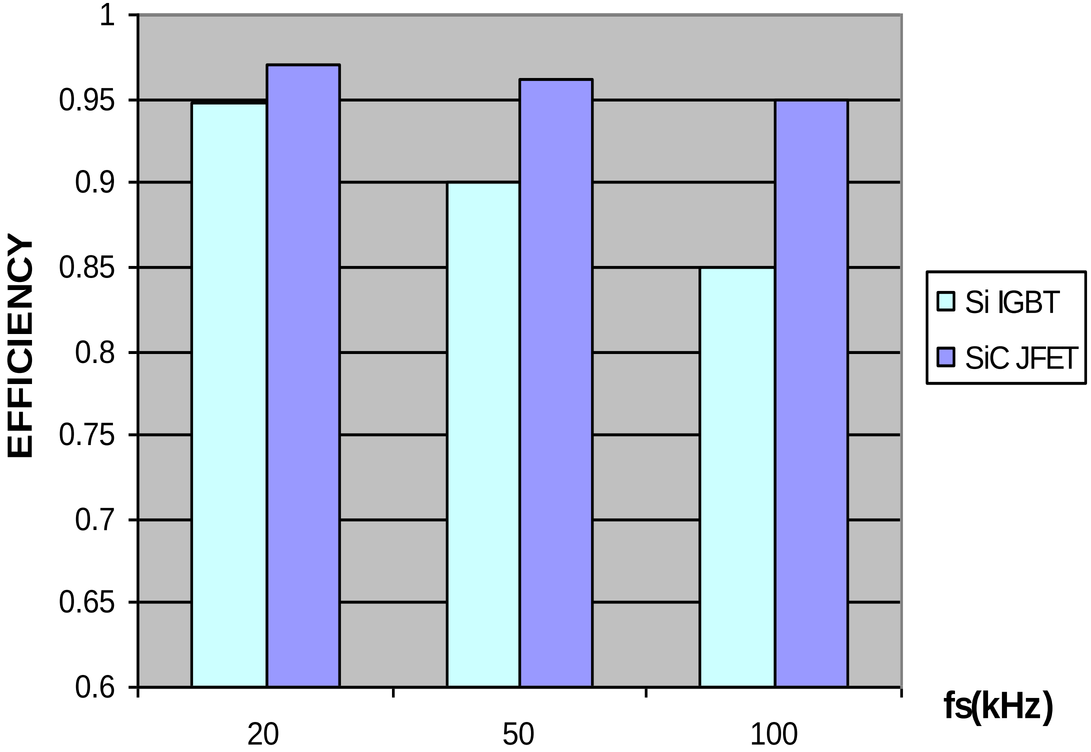




| | Si | SiC | GaN |
|---|---|---|---|
| **Bandgap** | **1.1eV** | **3.3eV** | **3.4eV** |
| **Dielectric** | **0.3MV/cm** | **2.5~3MV/cm** | **3MV/cm** |

# SiC JFETs



SiC JEFET Die




Efficiency

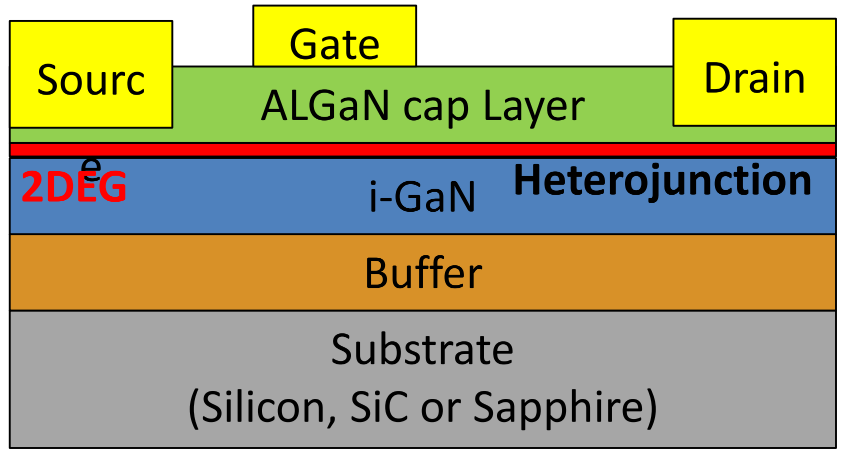
# Today…

**We witnessed**

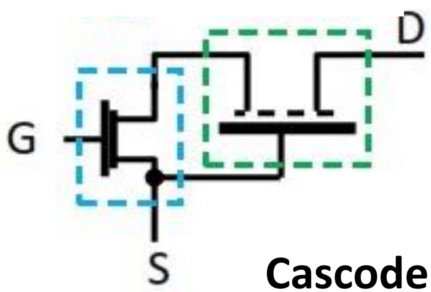
1. **Silicon devices keep enhancing their performance;**
2. **SiC MOSFET focuses on >1200V market;**
3. **GaN devices emerge in <650V applications;**
4. **Wide-bandgap devices are believed as the future.**

# GaN Devices

**normally on**

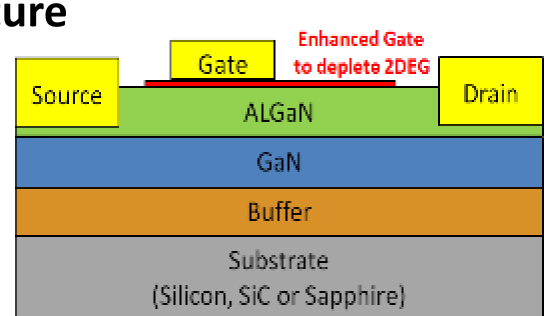



**normally off**




transphorm FUJITSU
Infineon micro GaN GmbH

**Cascode Structure**




GaN Systems Infineon HRL
SanKen Panasonic EPC
FURUKAWA ELECTRIC SHARP NEC

**Enhanced Mode GaN**

# GaN Devices

**Material Property**

- **High electron mobility**
- **Wide band gap**
- **High breakdown field**
- **High electron velocity**

**Electrical Performance of E-mode HEMTs**

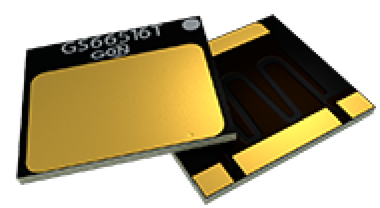
**Reverse Conduction**

- **No reverse recovery**
- $V_{sd}=V_{sg}+V_{th\_gd}+R_{dson}*Ids$

**2DEG**

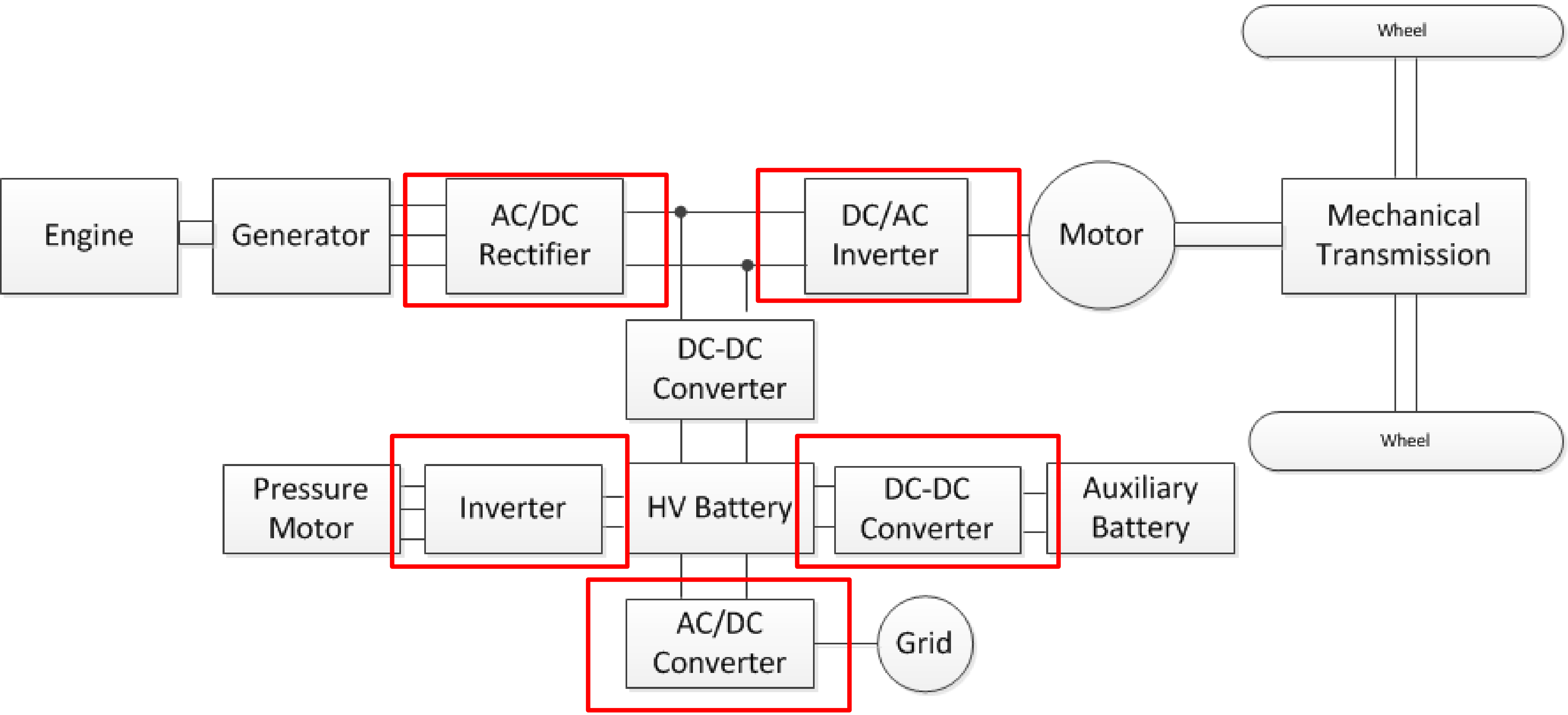
- **Low Rdson**
- **Dynamic $R_{dson}$**

- **Fragile gate**
- **Low Threshold Voltage**
- **low Capacitance**
- **High transition speed**
  - **Low Switching loss**
  - **High di/dt**

Jones, E. A., & Wang, F. (n.d.). Application-Based Review of GaN HFETs.

# WBG devices in PHEV

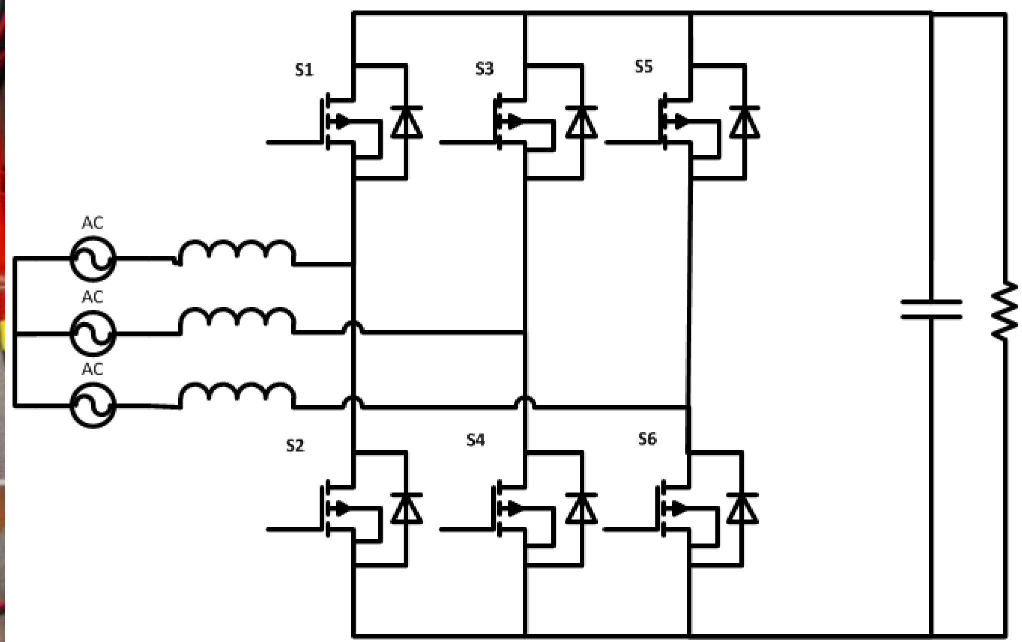


# 1. SiC Based Dual Inverters for E-Truck

- **120kW dual inverter;**
- **All SiC devices;**
- **All Hard switching;**
- **Bidirectional power for V2G and G2V;**
- **>3.3kW/L.**

Sponsored by ARPA-E agency of the U.S. Department of Energy, 02/01/2016-01/31/2017.

# 2. Magna 11kW Battery Chargers

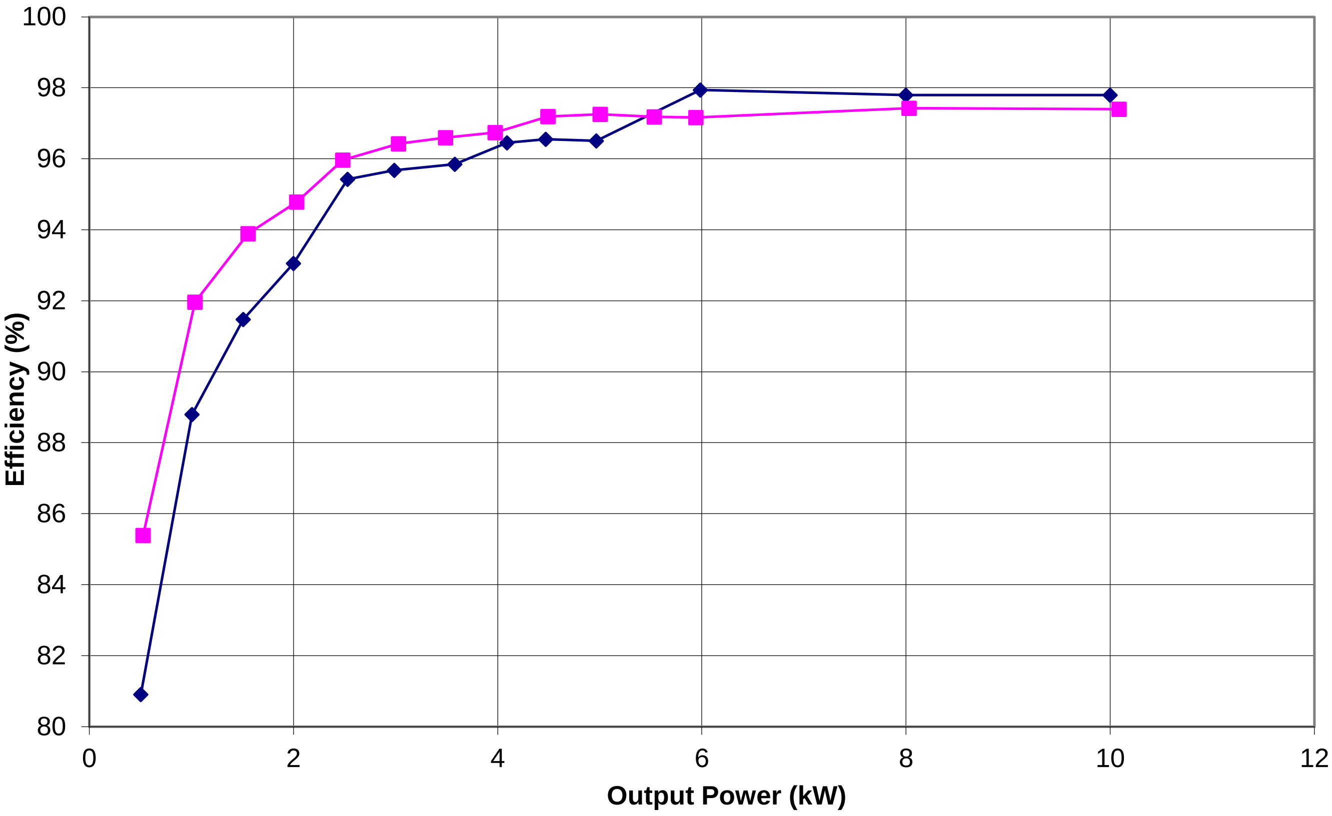



**11kW/208VAC 97%-efficiency PFC**

**Topology**

# 2. Magna 11kW Battery Chargers

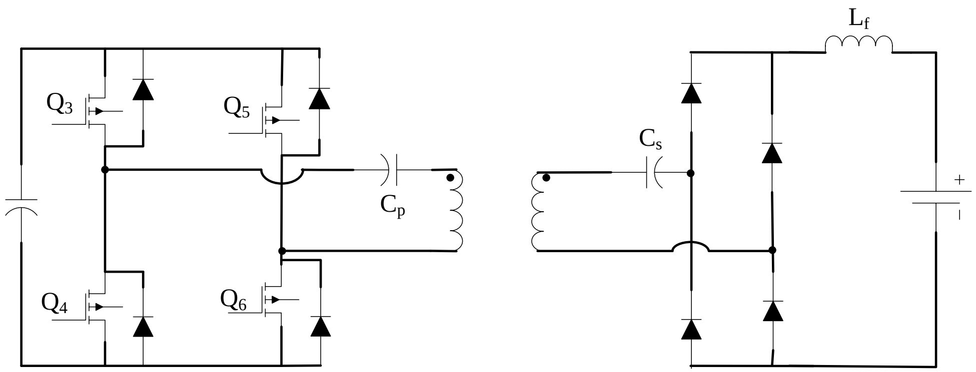
## Kettering / Magna PFC Experimental Efficiency Data



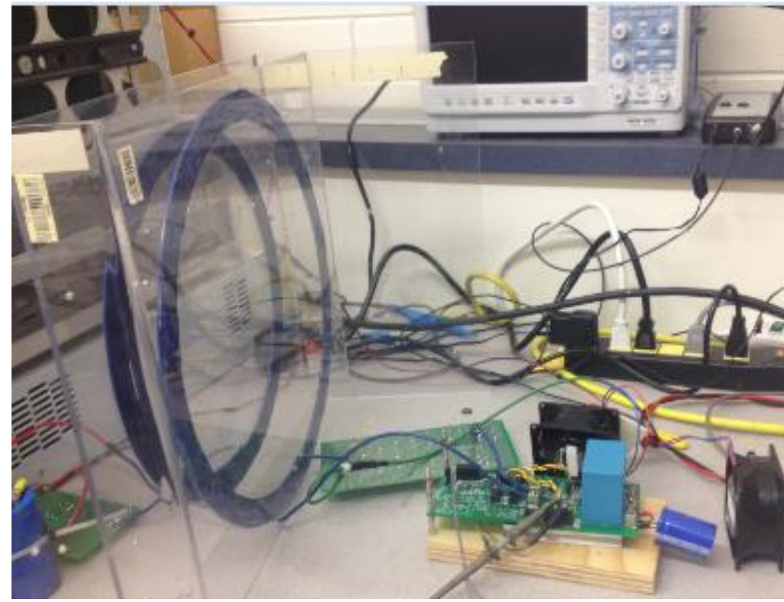

**#1. with FRR**

**#2. With SiC Skottky Diode**

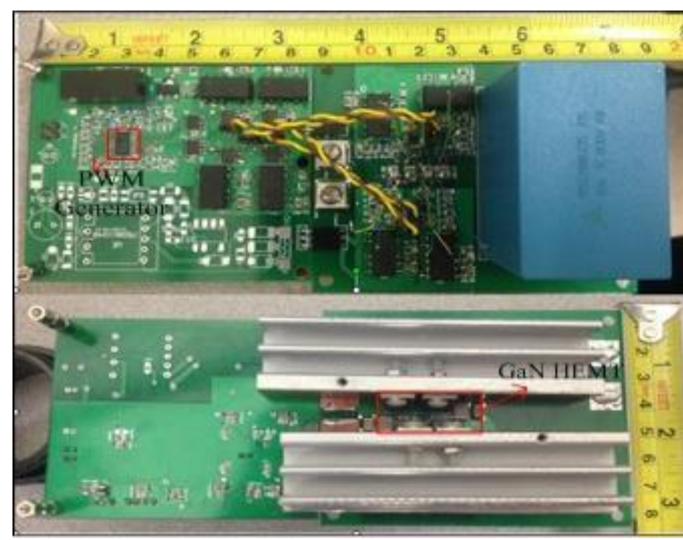
# 3. GaN Based Wireless Charger




**WBG based wireless charger**

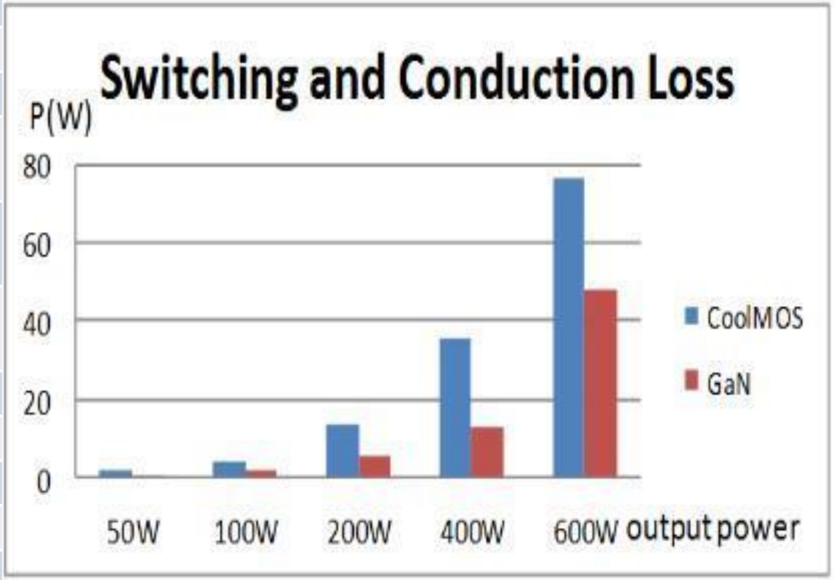


**G2 Wireless Charger, D=20cm**



# 3. GaN Based Wireless Charger

| Parameter | Value | Unit |
|---|---|---|
| Switching frequency | 813 | kHz |
| Dead time | 90 | ns |
| PWM duty cycle | 43% | |
| Turn on/off resistance for GaN HEMT | 8.2 | Ω |
| Self-inductance of primary side | 30.87 | uH |
| Self-inductance of secondary side | 25.62 | uH |
| Mutual inductance | 5.52 | uH |
| Input voltage | 150 | V |
| Input average current | 1.34 | A |
| Output voltage | 48 | V |
| Output current | 3.8 | A |



# 4. GaN based Cell-phone Wireless Charger

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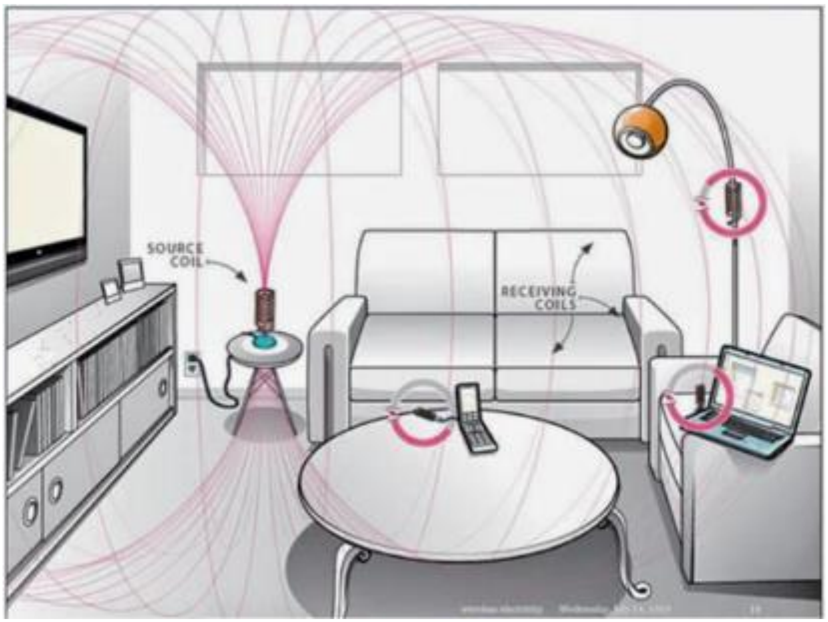


# 4. GaN based Cell-phone Wireless Charger

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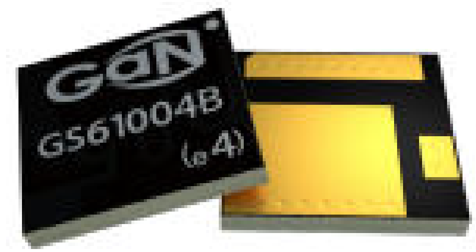
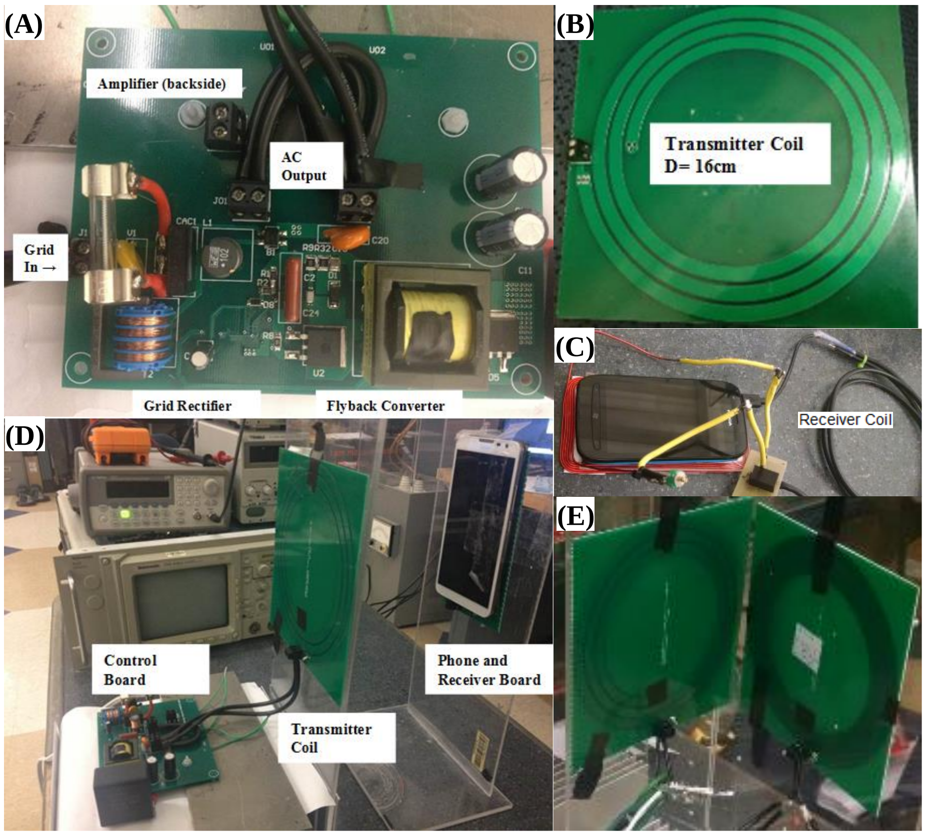
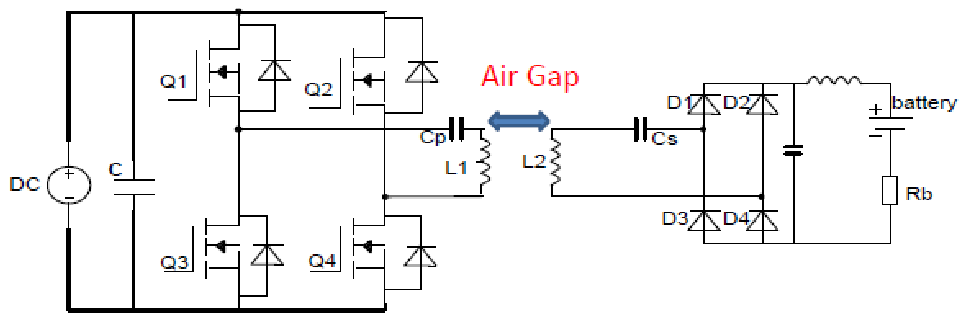



**Switching frequency 6MHz;**

**Overall efficiency ~40%;**

**>10W per phone;**

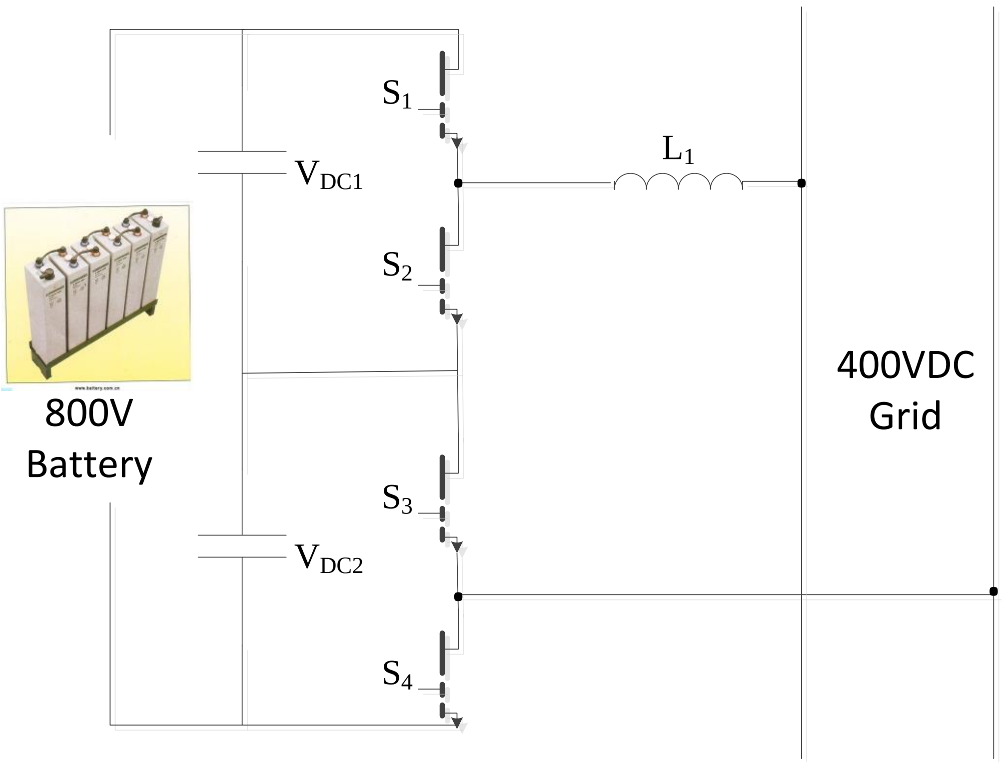
**Multiple phone charging**

**……**

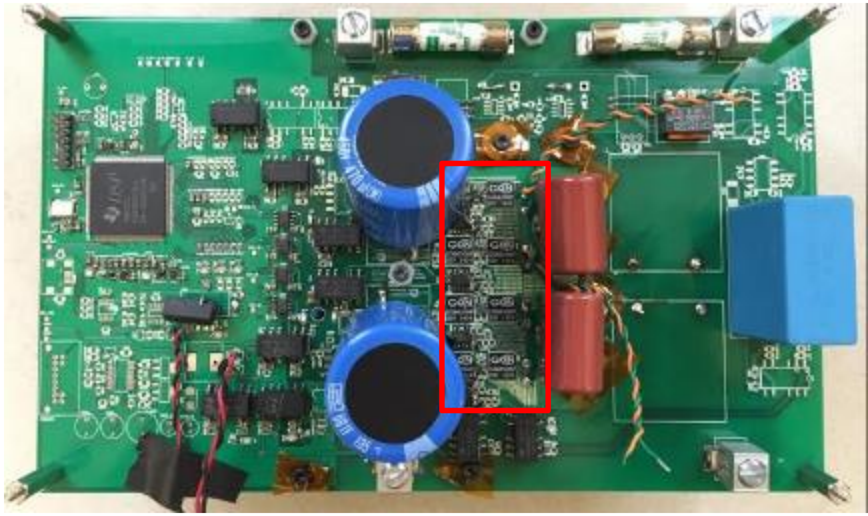
# 5. GaN based Smart Grid System

BOSCH

GaN System



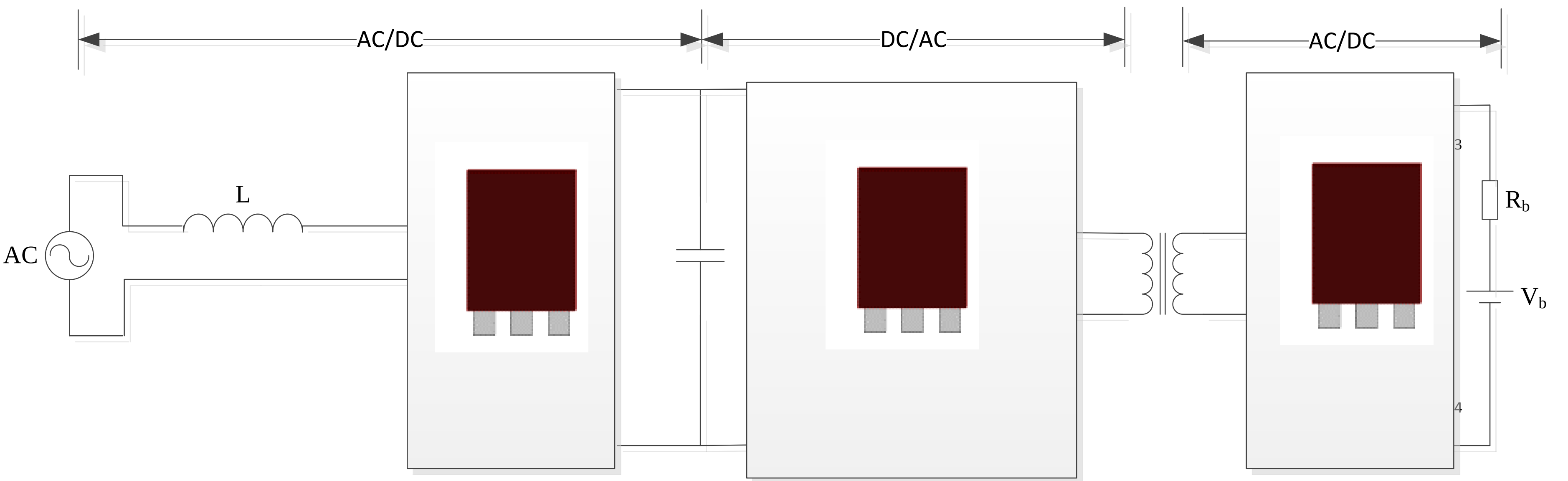




**Smart-Grid Infrastructure**

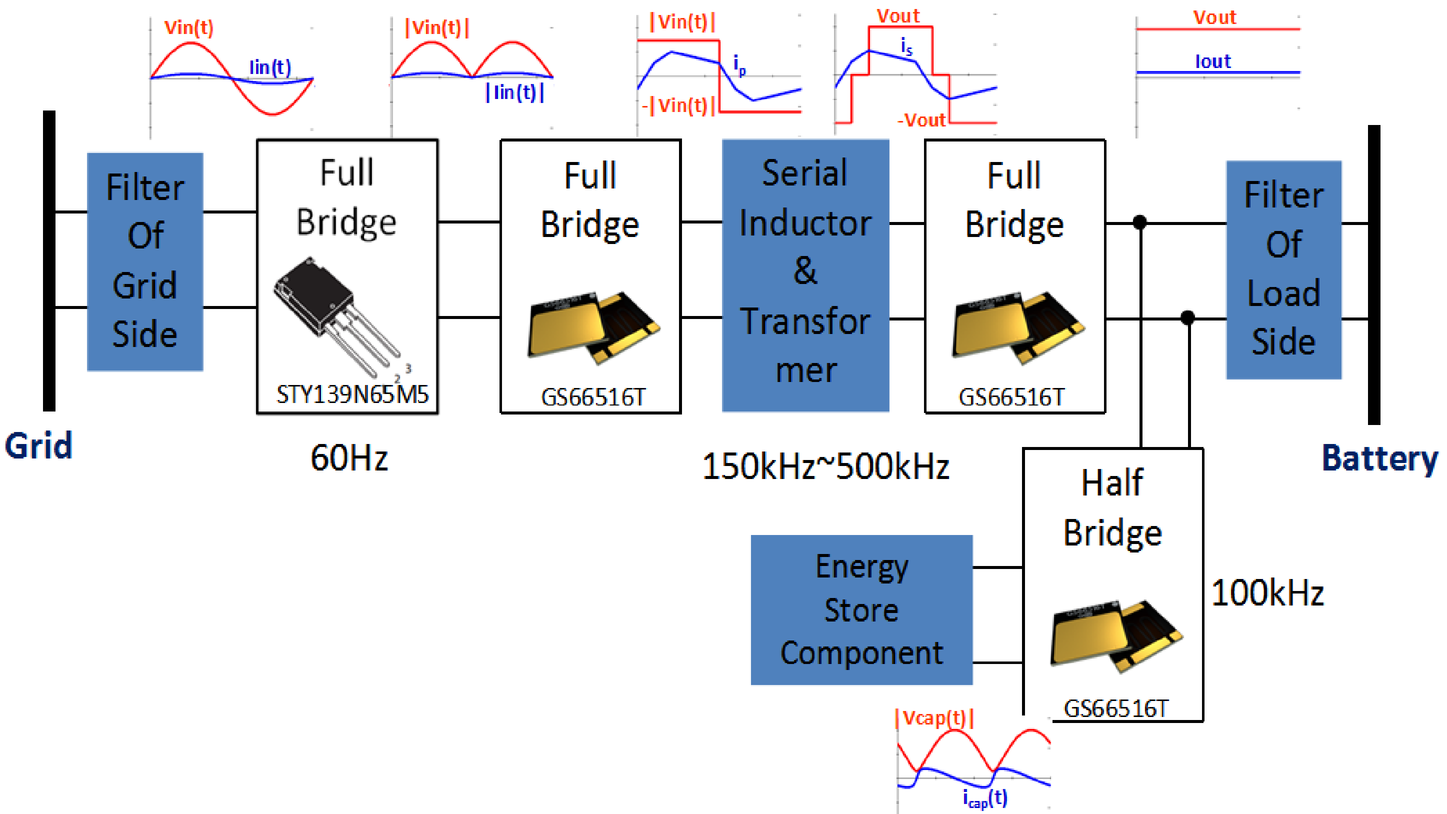
**Bidirectional DCDC Converter using GaN**

# 6. GaN based 97%-efficiency Charger



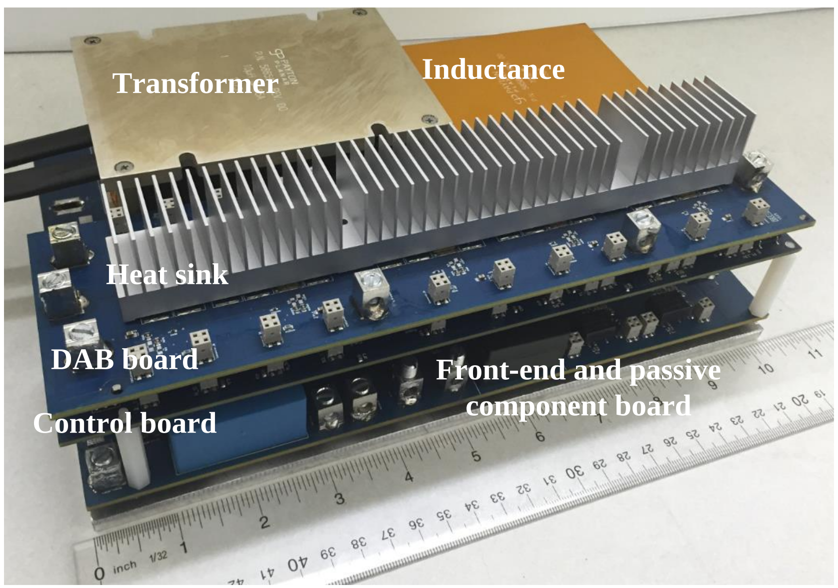

**94%-efficiency Conventional Charger**

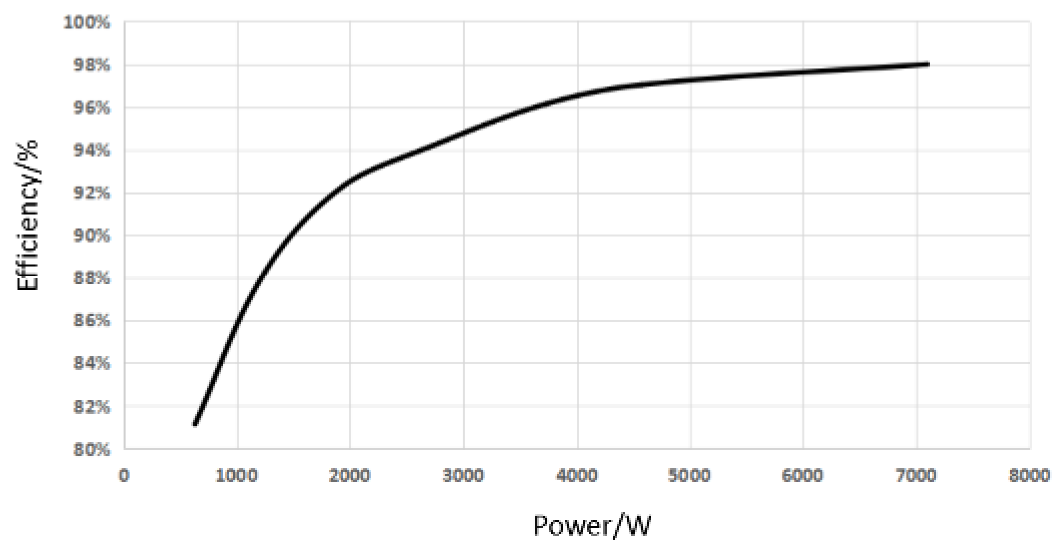
# 6. GaN based 97%-efficiency Charger




97%-efficiency Charger

# 6. GaN based 97%-efficiency Charger

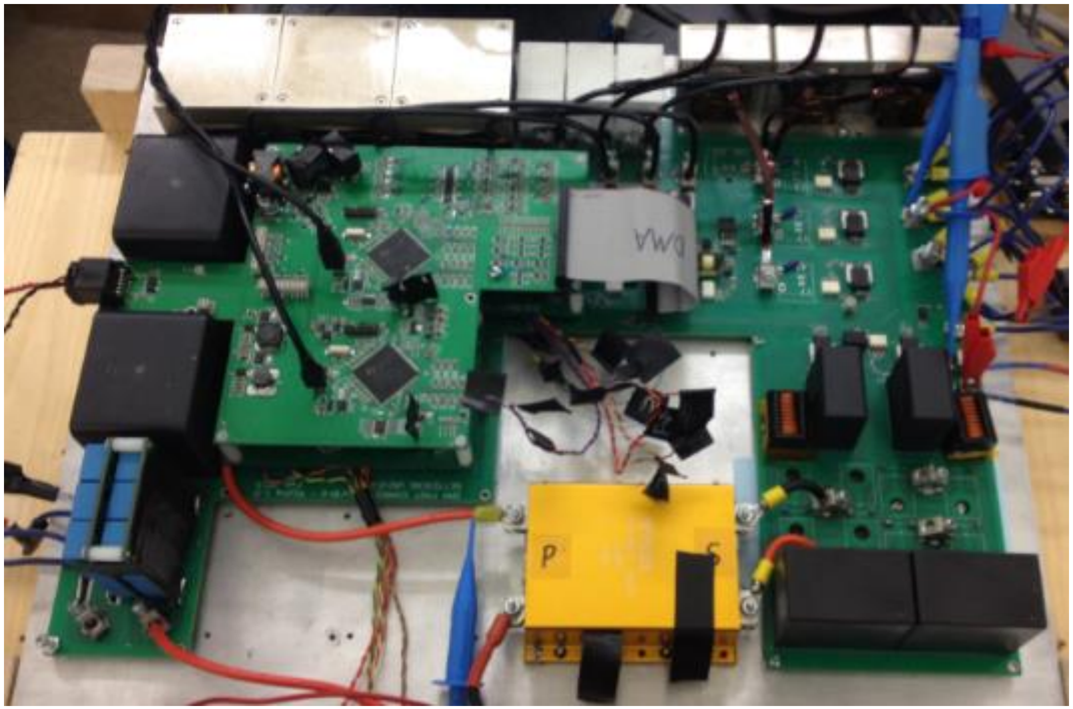



**1st version charger (>2.6kW/L)**
**2nd version charger (>4kW/L)**

**Efficiency Curves**

# 7. SiC 24kW On-board Charger




- **24kW charging power;**
- **96% efficiency at 20kW;**
- **All SiC devices;**
- **Hard switching at PFC;**
- **Soft switching at DCDC;**
- **>2.4kW/L.**

# 8. SiC 120kW Charging Station

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## Xuntuo Wang

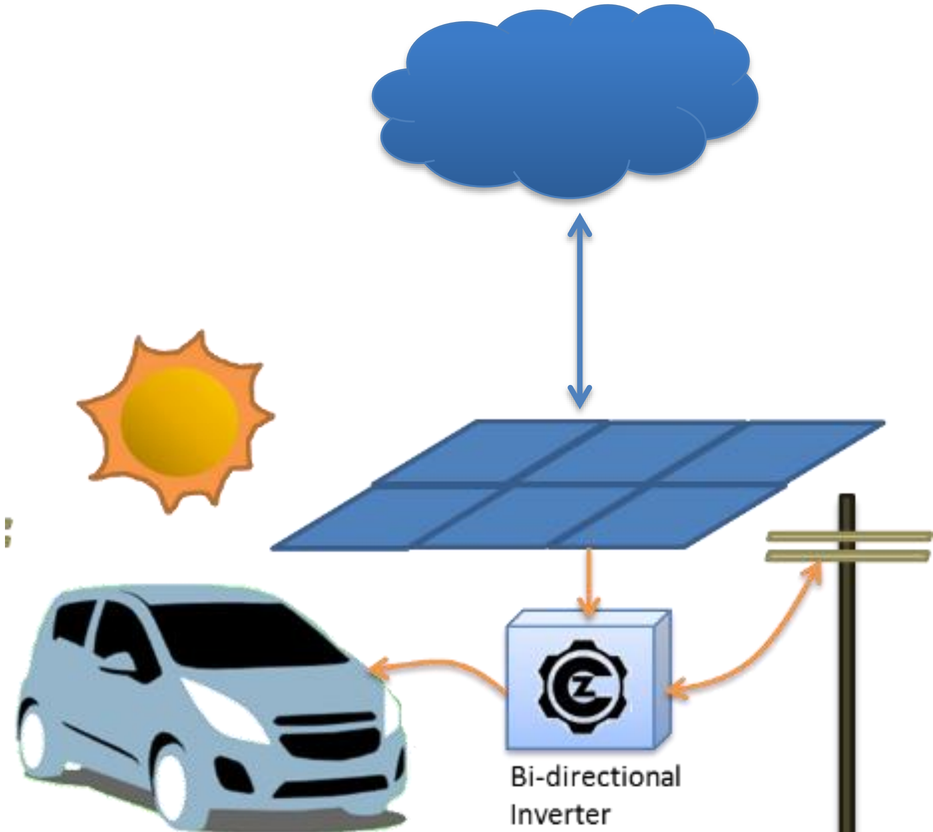
Xuntuo (Nelson) Wang is currently a 3nd year Ph.D. Candidate and Irwin Mark Jacbos and Joan Klein Jacobs Presidential Fellow in the Department of Electrical Engineering and Computer Science at MIT. He has two years research experience in the EV field. Nelson is honored to serve as President and CTO of CZAR-POWER and is committed to future collaboration with industry and research universities.

## Dr. Hua (Kevin) Bai

Hua (Kevin) Bai received BS and Ph.D. from Department of Electrical Engineering of Tsinghua University, Beijing, China in 2002 and 2007, respectively. He is the author of 1 book (Transients of Modern Power Electronics), 35 peer-reviewed IEEE journal papers, 18 conference papers, and he holds 5 industrial patents.

## Dr. James L. Kirtley Jr.

Dr. James L. Kirtley Jr. is of Professor of Electrical Engineering at the Massachusetts Institute of Technology. Dr. Kirtley attended MIT as an undergraduate and received the degree of Ph.D. from MIT in 1971. Dr. Kirtley is a specialist in electric machinery and electric power systems. He served as Editor in Chief of the IEEE Transactions on Energy Conversion from 1998 to 2006 and continues to serve as Editor for that journal and as a member of the Editorial Board of the journal Electric Power Components and Systems. Dr. Kirtley was made a Fellow of IEEE in 1990. He was awarded the IEEE Third Millenium medal in 2000 and the Nikola Tesla prize in 2002. Dr. Kirtley was




**Charge the vehicle**

**Support the grid**

**Cloud technology**

**Renewable energy**

**……**

# 8. SiC 120kW Charging Station

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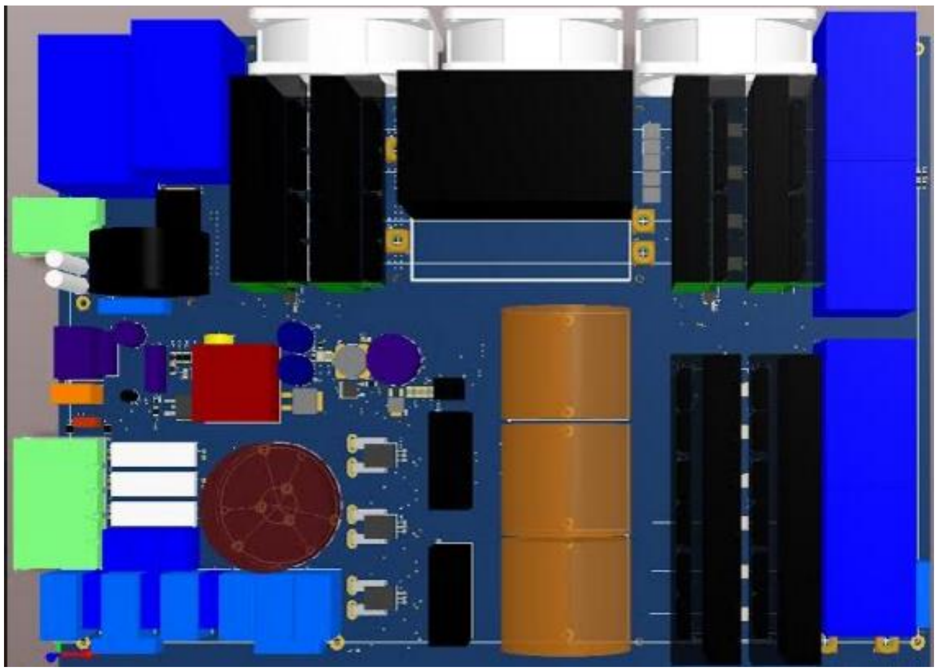

Final Charger Module
(~3.3kW/L)

- 24kW bidirectional ;
- 96% efficiency at 20kW;
- All SiC devices;
- Hard switching at PFC;
- Soft switching at DCDC;
- >3.3kW/L;
- Incorporating solar energy

# Summary

1) **Higher efficiency and high power density are always the pursuit of power electronics engineers and scholars;**

2) **Wide-bandgap devices are the present hot point and might replace present Si devices once the cost drops;**

3) **Wide-bandgap devices will push Silicon device to enhance its performance continuously;**

4) **Simply replacing Silicon devices with wide-bandgap devices on the presently existing systems won't work.**

# Acknowledgement

MAGNA

Mahindra genZe

SINOEV TECHNOLOGIES

CHRYSLER

TENNECO

JING-JIN ELECTRIC

FEV

transphorm

GaN System

HELLA®

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

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Ford

Thank you!

Questions?