ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Fraunhofer IZM

ECPE Roadmap 2025 Workshop

Munich, March 26, 2015

Roadmap Power Electronics 2025

J.W. Kolar / E. Hoene* / Th. Harder**

Swiss Federal Institute of Technology (ETH) Zurich
* Fraunhofer IZM, Berlin
** ECPE, Nuremberg

Summary of 1st Roadmap Team Meeting

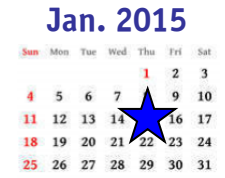
- → **Magnetic Components** are the Highest **Cost Factor** in Power Supplies
- → **EMI** and Semiconductor Oscillations are #1 Risk for **Time to Market**
- → **Robustness** is Often More Important than **Reliability**
- → **Modularity** Made it **Never Into the Market**
- → External Manufacturing Results in Too High Costs
- → **Only 6-8 Weeks Development Time** Requires Finished Building Blocks
- → Need for Fast Simulation Models
- → **Digital Control** Issues (Safety Requirements / **Redundancy**)
- → **Efficiency** is also a Political Issue / Depends on **Standardization**
- → **Efficiency is not a Selling Argument** (only for Last Person in Supply Chain)
- → **Ranking: Costs / Reliability /** Ease of Manufacturing / Robustness

→ Some Challenges / Limitations Identified

Summary of 2nd Roadmap Meeting

... see Summary presented by Th. Harder

Summary of 3rd Roadmap Team Meeting



Berlin

- → 2025 Performance Target Values
- → Evaluation of Current Research Level Technologies
- → Enabling Technologies
- → Technology / Research Gaps

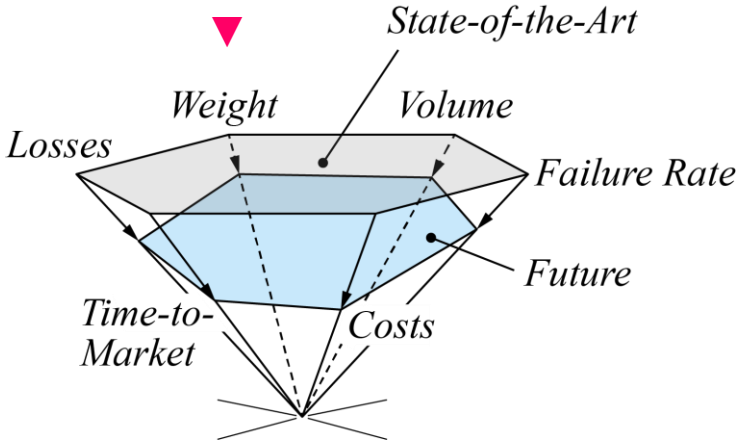
... see Following Summary

Discussion @ 3rd Meeting

- **Key Performance Indices which Must be Considerably Improved until 2025**

→ Costs
→ Power Density
→ Efficiency
→ Reliability / Robustness
→ Time-to-Market

Environmental Impact... $[kg_{Fe}/kW]$ $[kg_{Cu}/kW]$ $[kg_{Al}/kW]$ $[cm^2_{Si}/kW]$

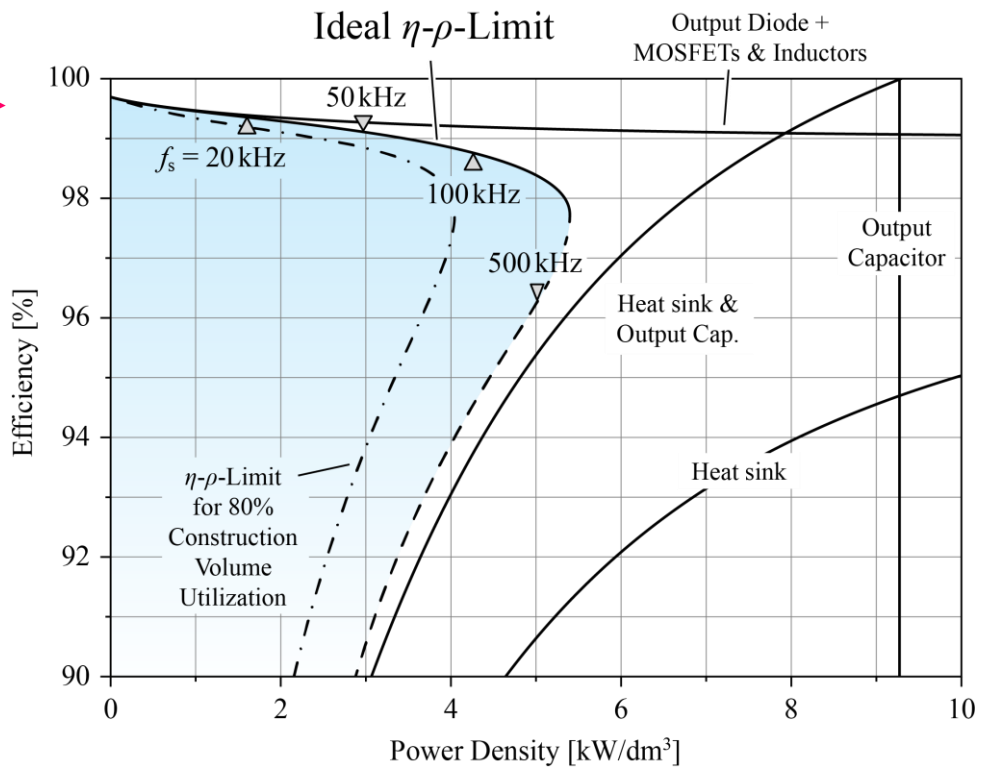


- **Performances are Mutually Coupled**

Main Components / Concepts / Processes Determining the Performance Limits

η-ρ-Pareto Limit

- → Switching Circuit
- → Transformers
- → Filter Components
- → EMI Filter Components
- → Interconnections
- → Heatsink
- → Sensors
- → Control Circuit
- → Package
- → Manufacturing



Roadmap Approach

Step #1

→ **Define 2025 Performance Targets**
... Considering Past Trend Lines

Step #2

→ **Current Research Level Technologies**
→ **High Switching Frequency**
→ **High Operating Temperature**
... Considered for Each Component in Order to Check for Potential Improvements of a Selected Performance Index

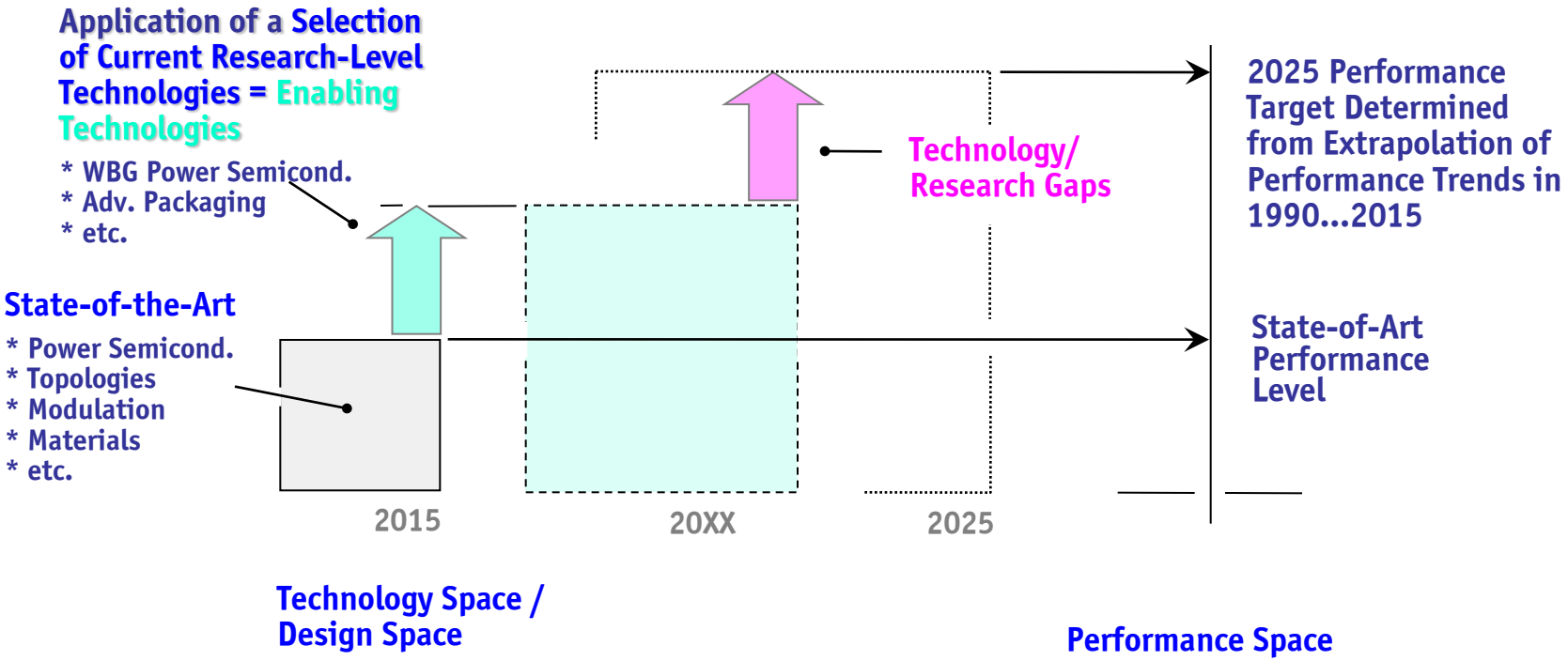
Step #3

→ **"Enabling Technologies"**
... Selected Subset of "Current Research Level Technologies" which Potentially Enable a Considerable Performance Improvement

Step #4

→ **"Technology / Research Gaps"**
... Technologies Crucial for Reaching the 2025 Performance Target but Currently Not Considered in Research

Roadmap Approach



General Remark

→ Pragmatic Approach
→ Only Already Known Research Concepts are Considered
→ No Speculations on Unknown Disruptive Concepts (e.g. Nanomaterials)

→ Identified Barriers are Indicating Future Research Needs

→ Trivial Requirements (e.g. Higher Energy Density of Caps) are not Listed

Power Density - Expected Impr. until 2025 – Factor 2 ... 5 (10)

■ Filter Components (→ Minimize Volume)

→ Increase Switching Frequency

Challenges:	* Higher Switching Losses * Higher HF Losses of Passives / Thermal Managmnt * Increased EMI Noise (for Hard Switching)
Enablers:	* Low Switching Loss WBG Semiconductors * Adv. Inductor Concepts (e.g. Distributed Gaps) * Adv. Packaging – Min. Parasitics (Gate & Power) * ZVS / Resonant Converter Concepts * High Clock Frequency Digital Control
Barriers:	* Mag. Materials (Permeability /Losses at HF) * Conductor Types / Winding Arrangements * Thermal Management * Adv. Design Tools (Layout, Magnetics) * Adv. Measurem. Tools Integrated with Simulation * Engineering Experience
Detour:	* Interleaving for Frequency Multiplication
Remark:	* Only Basic Converter Topologies are of Interest

→ „Enablers“ are Taken from the List of „Current Research Technologies“
→ „Barriers“ are Indicating „Technology Gaps“

→ Increase Operating Temp.

Challenges:
* Reliability of Interconnection Technologies
* Higher Losses

Enablers:
* High Temperature Passive Components
* Interconnection Technologies for Higher Temp.
* WBG Semiconductors

Barriers:
* Requirement to Enable all Used Components and Technologies for High Temp.

Remark:
* Especially Effective for High Temp. Environment

→ Change from CCM to DCM

Challenges:
* Higher Conduction Losses
* Higher Filtering Effort

Enablers:
* Low On-Resistance Power Switches (CoolMOS, WBG)
* Advanced Digital Control
* Interleaving for Red. of Filter Effort

Barriers:
* New Circuit Topologies / Modulation Schemes
* Magnetic Materials (High Flux Swing, High Frequ.)
* Conductor Types / Winding Arrangements

Remark:
* Only Basic Conv. Topologies with Modified Control / Min. Auxiliary Circuits are of Interest

→ etc., etc.

EMI Filter (→ Minimize Volume)

→ Increase Switching Frequ. Beyond 500kHz

Challenges: ....
Enablers: ....
Barriers: ....
Remark: ....

→ etc., etc.

- Heat Sink (→ Minimize Volume)
- Interconnection / Packaging (→ Minimize Volume)
- etc.

Efficiency - Expected Loss Reduction until 2025 – Factor 2 ... 3

- Evaluation of Contributions to Loss Reduction of the Main Components Employing Current Research Level Technologies

→ Switching Circuit and Gate Drive
→ Transformers
→ Filter Components
→ EMI Filter Components
→ Heatsink
→ Interconnections
→ Sensors
→ Control Circuit

- Utilized Current Research Concepts – Enabling Technologies
- Required Additional New Technologies – Technology Gaps

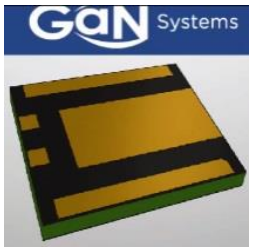
Costs - Expected Reduction until 2025 – Factor ... 2

- Evaluation of Contributions to Loss Reduction of the Main Components Employing Current Research Level Technologies
  - → Switching Circuit and Gate Drive
  - → Transformers
  - → Filter Components
  - → EMI Filter Components
  - → Heatsink
  - → Interconnections
  - → Sensors
  - → Control Circuit
- Utilized Current Research Concepts – Enabling Technologies
- Required Additional New Technologies – Technology Gaps

Examples of Enabling Technologies

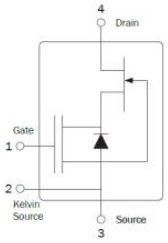
Enabling Technologies (1)

→ **Wide Bandgap Semiconductors**
  * Low Switching Losses
  * Low Conduction Losses
→ **Next Generation (LV) Si Semiconductors**
  * Low Conduction Losses



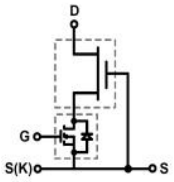
EPC
EFFICIENT POWER CONVERSION

RFMD
rfmd.com

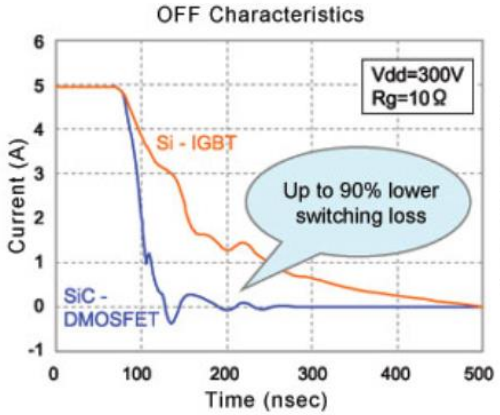


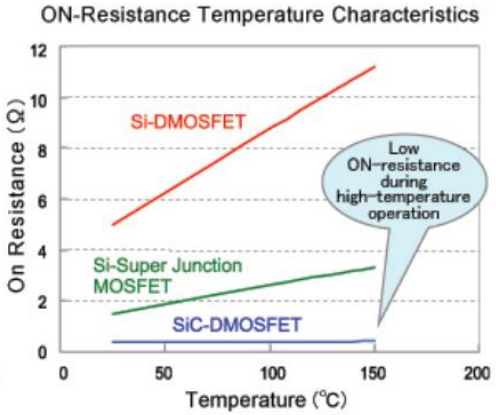
ROHM SEMICONDUCTOR

transphorm



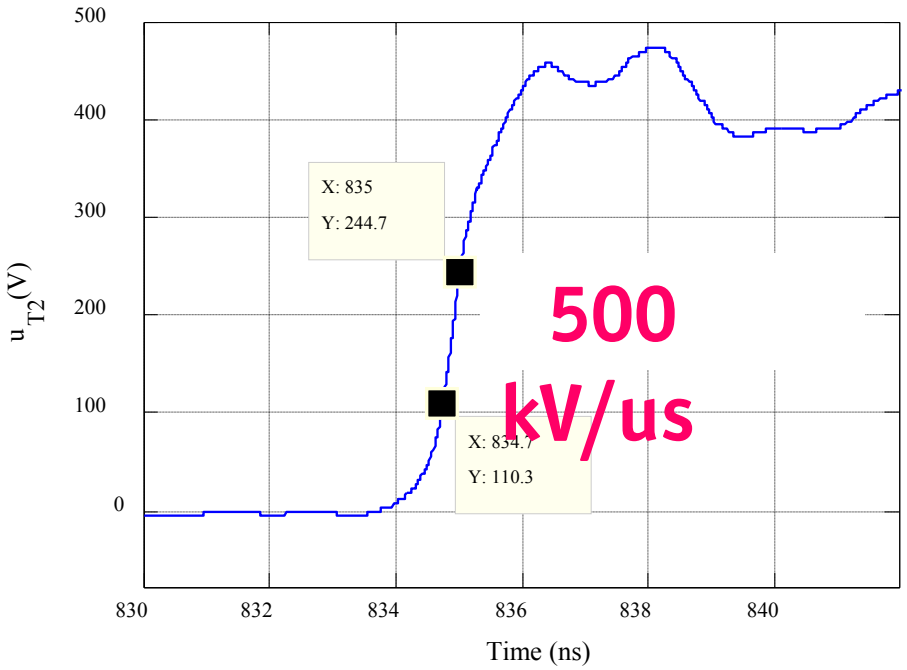
8x8 PQFN Package
(bottom view)





Enabling Technologies (2)

→ Wide Bandgap Semiconductors
  * Low Switching Losses
  * Low Conduction Losses
→ Next Generation (LV) Si Semiconductors
  * Low Conduction Losses

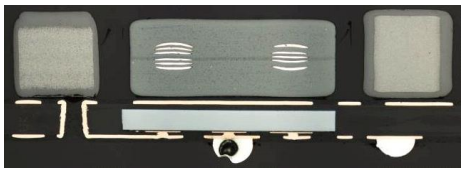


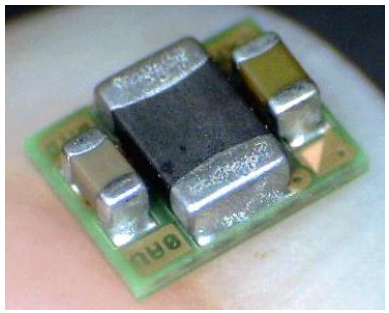
→ 600V GaN Switching Behavior
→ Main Challenges in Packaging (!)

Enabling Technologies (3)

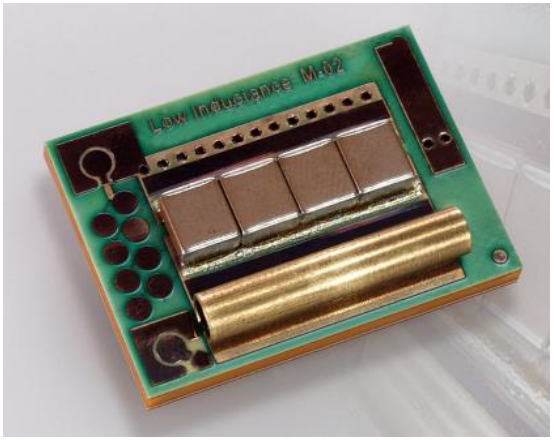
→ **Adv. Packaging of Power Semicond (Chip Scale etc.)**
* Low Power Path Parasitics
* Low Gate Drive Parasitics
* Low Coupling of Power and Gate Drive Path
* Low Thermal Resistance
* 3D Interconnection
* PCB Embedding (incl. Therm. Management)
* Minimizing DM and CM EMI (Integr. Switch. Cell)

DC/DC Converter with Embedded Chip



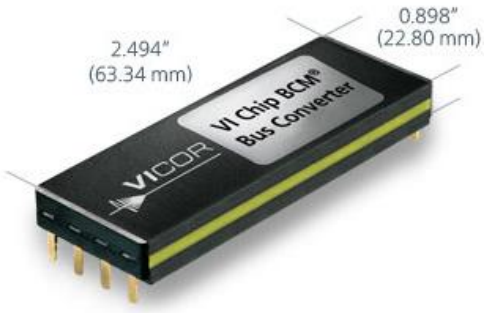


Ultra Low Inductance Package

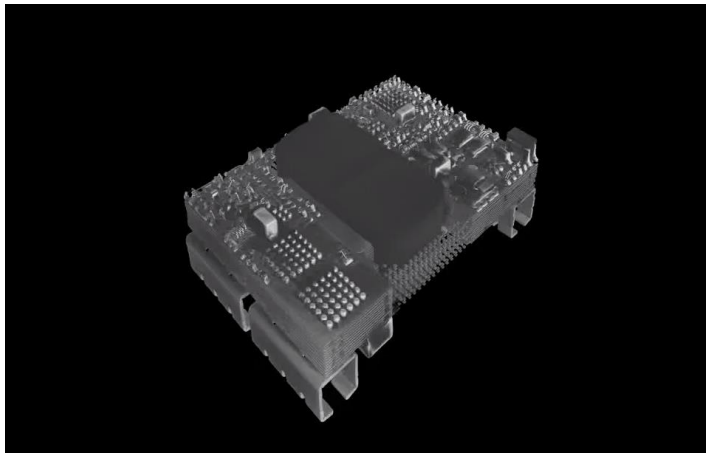


Enabling Technologies (4)

→ **Heterogeneous Integration**
* Switching Cell in a Package
* Drivers with Integrated Power Supply
* DC/DC Converter in a Package



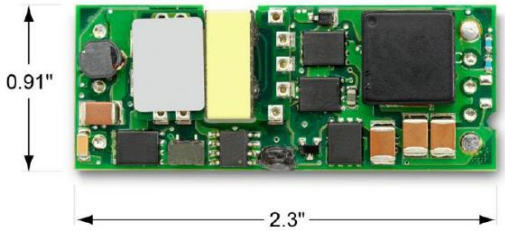
X-Ray Image (Video)



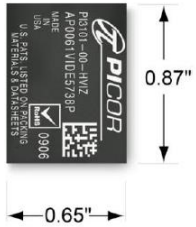
Enabling Technologies (5)

→ **Heterogeneous Integration**

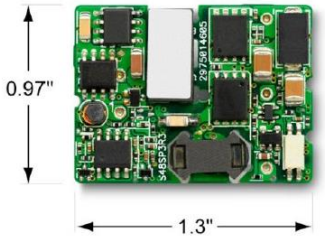
Competitor A
2.1 in² and 34 W/in²
72 Watts



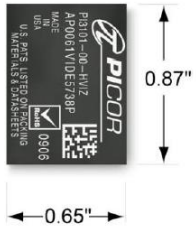
PI3101
0.57 in² and 105 W/in²
60 Watts



Competitor B
1.26 in² and 26 W/in²
33 Watts



PI3101
0.57 in² and 105 W/in²
60 Watts

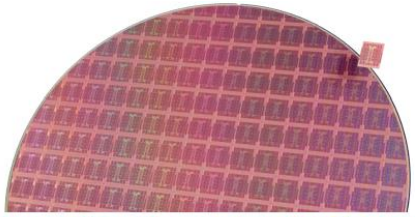


VICOR

System in Package (SiP) Approach

Enabling Technologies (6)

→ **Heterogeneous Integration**



Information Processors Are Sawn Out of Scalable Wafers

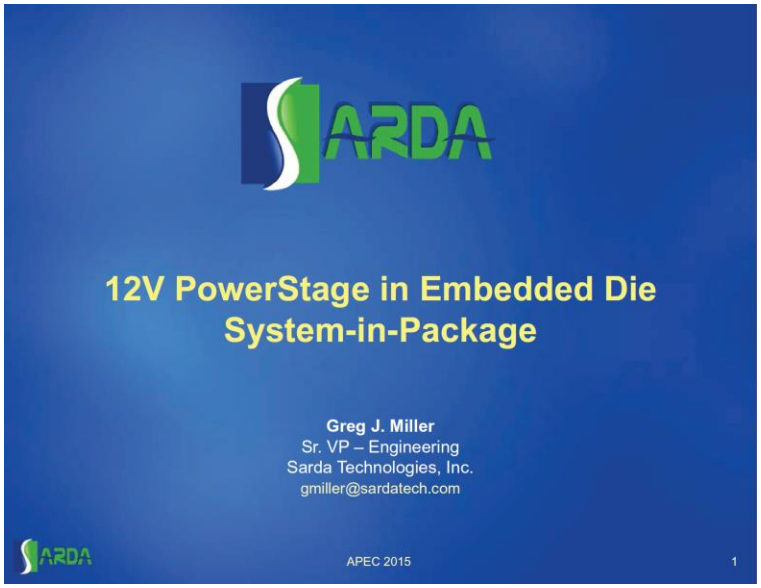
ChiP Power Components Are Sawn Out of Scalable Magnetic Panels

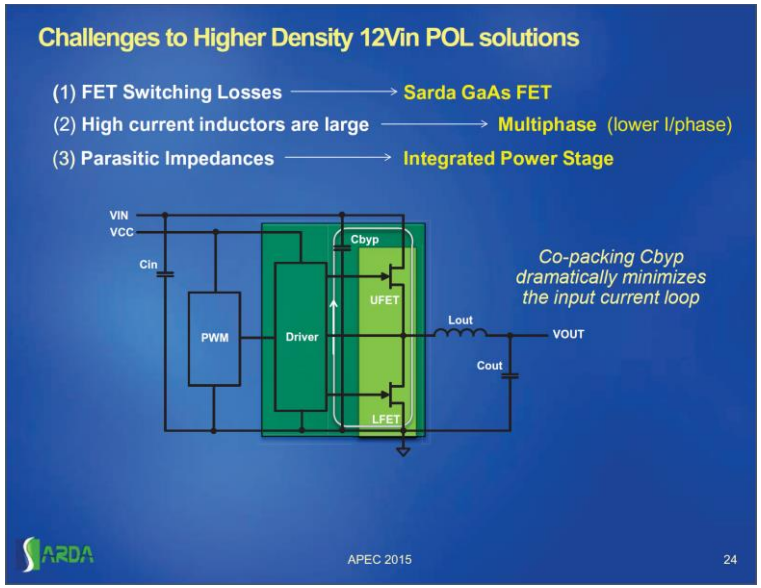
VICOR

- System in Package (SiP) Approach

Enabling Technologies (7)

→ Heterogeneous Integration

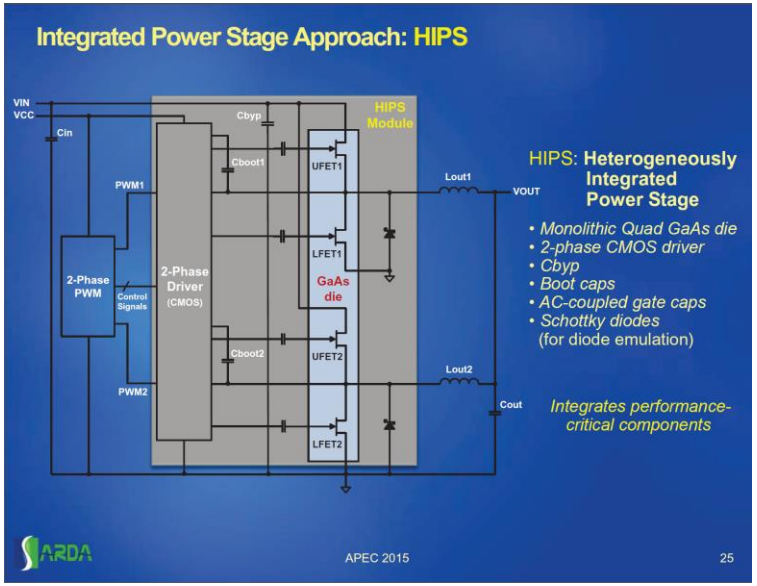


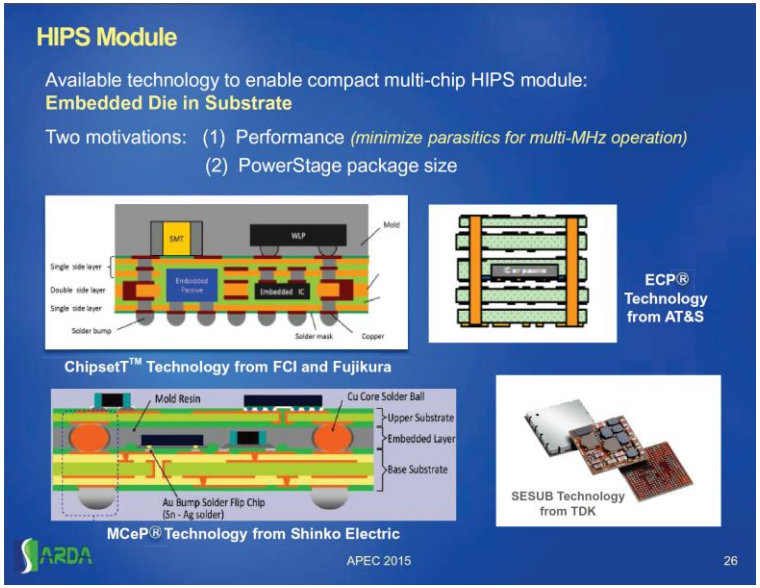


► Presented @ APEC 2015

Enabling Technologies (8)

→ Heterogeneous Integration

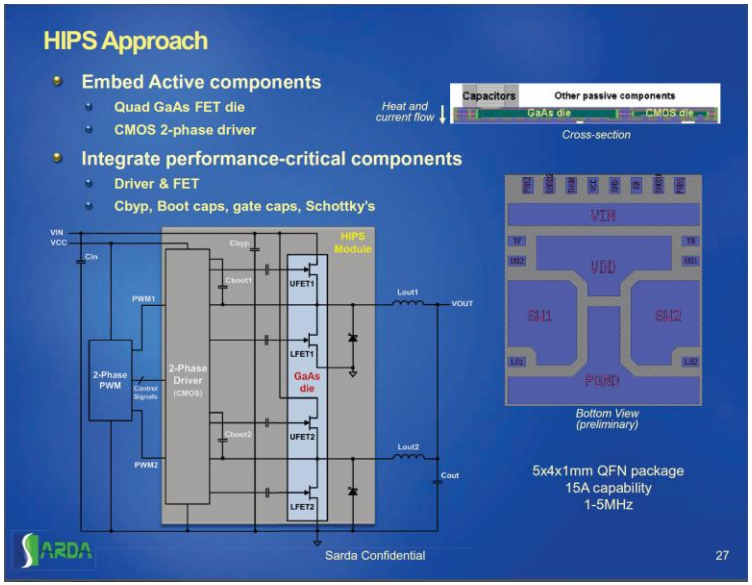


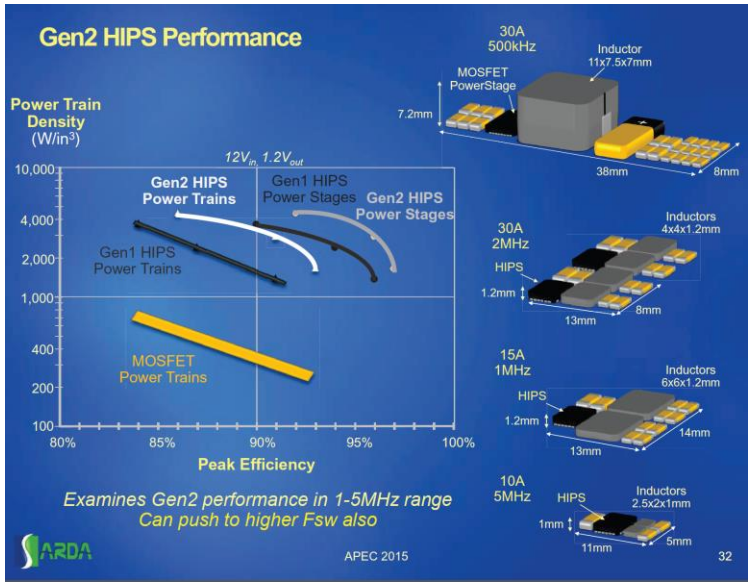


► Presented @ APEC 2015

Enabling Technologies (9)

→ Heterogeneous Integration





► Presented @ APEC 2015

Enabling Technologies (10)

→ **Adv. Inductor Concepts**
* Magnetic Integration (CM/DM)
* Multi-Gapped Magnetic Cores
* Constant Flux Density Magnetic Cores
* Integrated Cooling
* Parasitic Capacitance Cancellation
* 3D Interconnection

→ **Adv. Capacitor Concepts**
* Low Parasitic Ind. 3D Interconnection
* Integrated Cooling / High Current Concepts

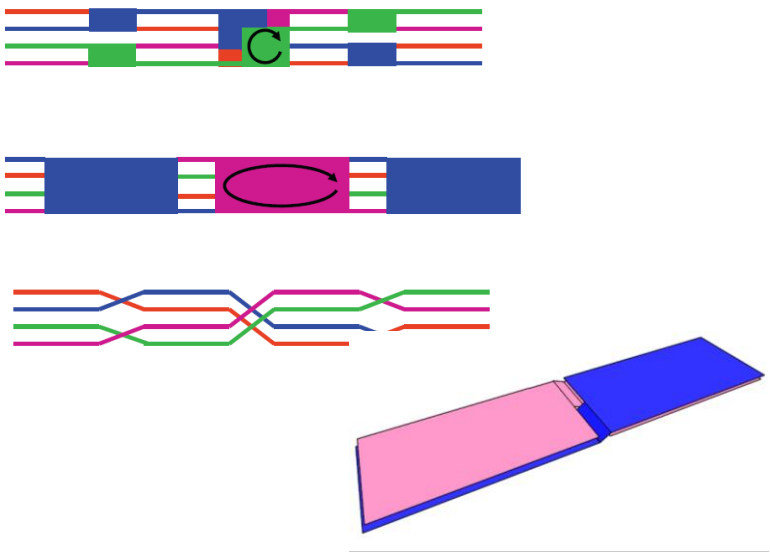
→ **Adv. Component Interconnection Concepts**
* Low DC and HF Loss Interconnection
* Integrated Concepts (Cooling, Sensing)

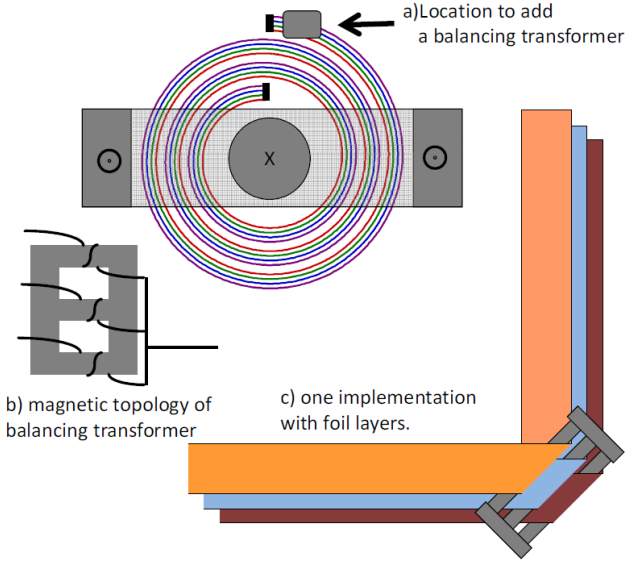
→ **Adv. Cooling Concepts**
* Heat Spreading Concepts
* Two-Side Cooling
* Two Phase Cooling
* Integr. Concepts (El. and Thermal Interconn.)

→ **Adv. Low Frequency Energy Buffer Concepts**
* Replace Electrolytic Cap. by Conv. And High Δv Cap.

Enabling Technologies (11)

→ Advanced Inductor Concepts

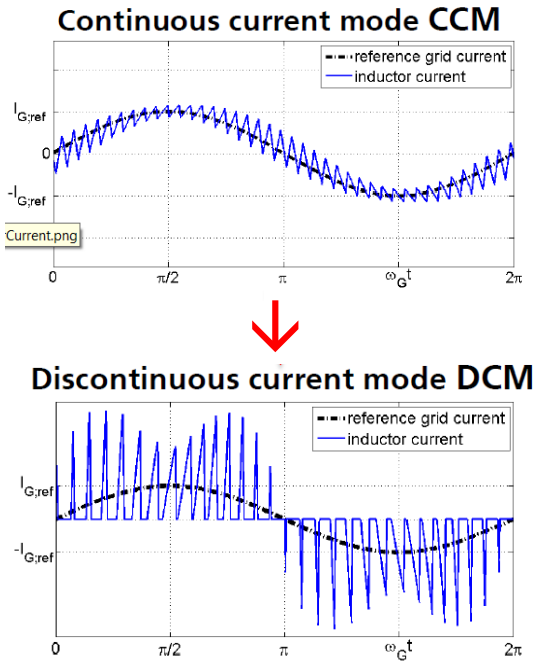




- Layered Foils as Alternative to Litz Wire
- New Winding Geometries
- Quasi-Distributed Airgap
- etc.

Source: Ch. Sullivan / Dartmouth

Enabling Technologies (12)



→ **Digital Control (Moores Law)**
  * High Calc. Capability / Monitoring / Adv. Control
  * High Clock Rates / High Sampling Frequ.

→ **Change from CCM to DCM Operation**
  * DCM Inductors Store Less Energy / Lower Vol.
  * Facilitates ZVS / Res. Transition Operation
  * Workaround for Slow Passives Improvement
  * i=0 Instead of Cont. Current Sensor

→ **Advanced Modulation**
  * Noise Shaping Variable Switching Freuqnecy

→ **Active ZVS / Resonant Operation**
  * Low Switching Losses
  * Low EMI / No Free Ringing

→ **Interleaving / Multi-Cell / Multi-Level Converters**
  * Increase of Effective Switching Frequency
  * Cancellation (DM-CM Transfer) instead of Filtering

→ **Advanced Control**
  * Trajectory-Based Control
  * Predictive Control

Enabling Technologies (13)

→ Bringing Together Advanced Circuit Concepts / Semiconductors / Packaging

zolt

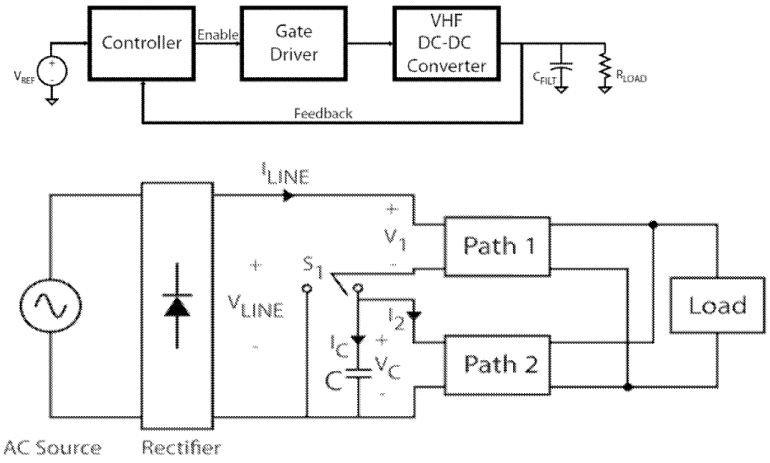
* World Smartest Laptop Charger

FINSiX

* World Smallest Laptop Charger

Enabling Technologies (14)

→ **Bringing Together Advanced Circuit Concepts / Semiconductors / Packaging**

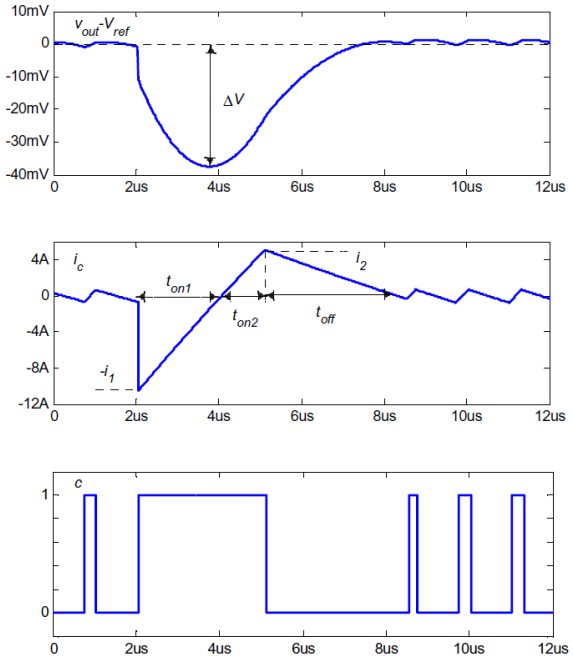


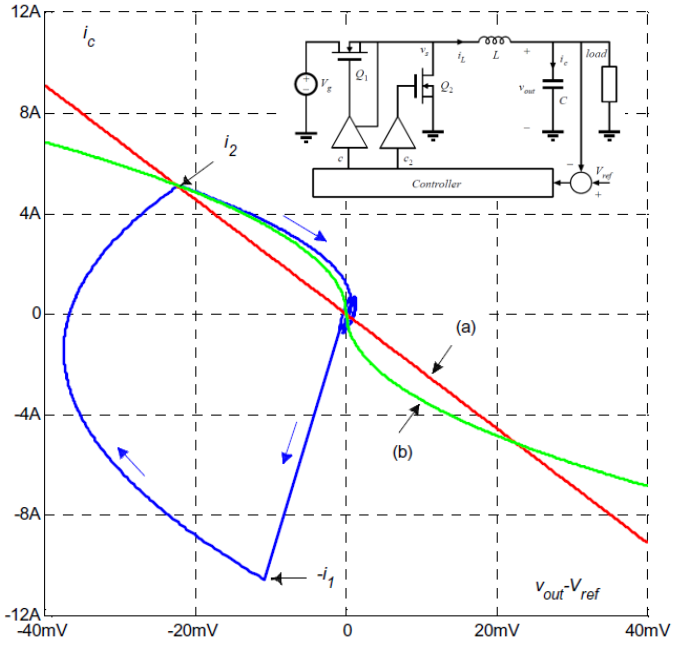
* **World Smallest Laptop Charger**

Enabling Technologies (15)

→ Predictive Control and Optimal Trajectory Control

Source: TI / Yousefzadeh





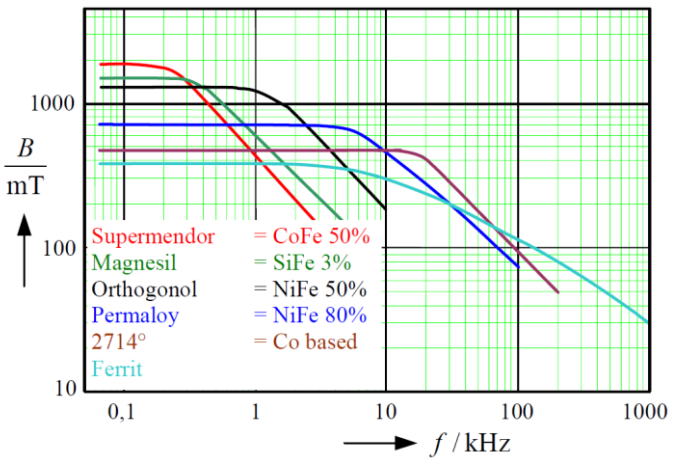
► Consider Individual Switching Instants vs. Average over Numerous Swiching Cycles

Examples of Technology Barriers

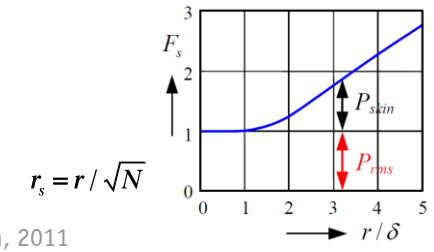
Technology Barriers

► Example: Serious Limitation of Operating Frequency by HF Losses

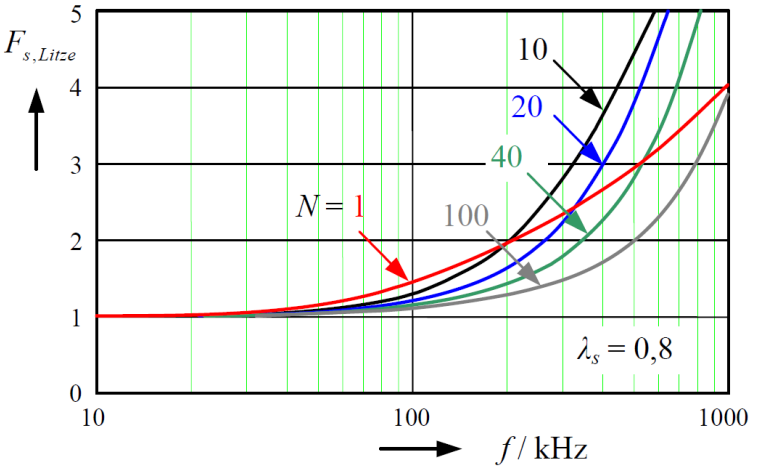
- Core Losses (incr. @ High Frequ. & High Operating Temp.)
- Temp. Dependent Lifetime of the Core
- Skin-Effect Losses
- Proximity Effect Losses



■ Adm. Flux Density for given Loss Density



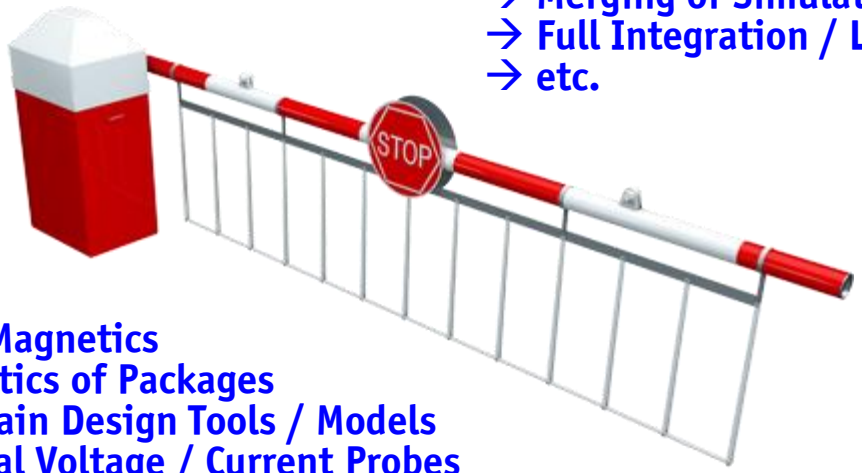
Source: Prof. Albach, 2011



■ Skin-Factor F_s for Litz Wires with N Strands

Technology Barriers

→ >50 MHz Switches
→ Multi-Domain/Objective Design / Models
→ Design for (3D)Manufacturing
→ Manufact. of 3D-Integrated Planar Structures
→ Built-In Measurement Devices
→ Merging of Simulation & Measurement
→ Full Integration / Limited Flexibility
→ etc.

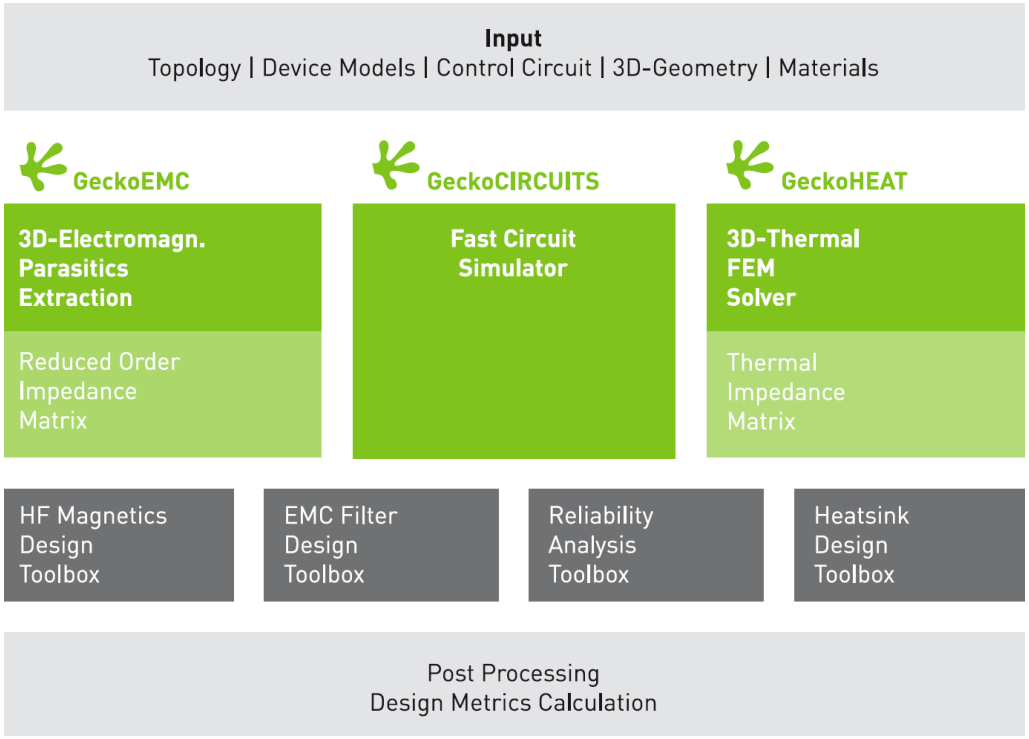


→ < 500 kHz Magnetics
→ High Parasitics of Packages
→ Single Domain Design Tools / Models
→ Conventional Voltage / Current Probes
→ Discrete Components / Max. Flexibility
→ Technological Limits of Universities
→ etc.

► Chicken & Egg Problem of New Technologies / Identification of Killer Applications

▶ Example of Advanced Power Electronics Design Platform

Source: GECKO SIMULATIONS



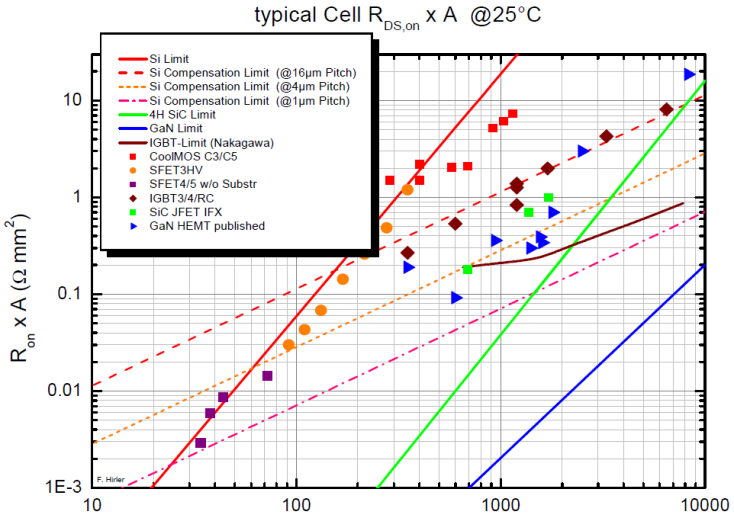
- **Modeling & Design**

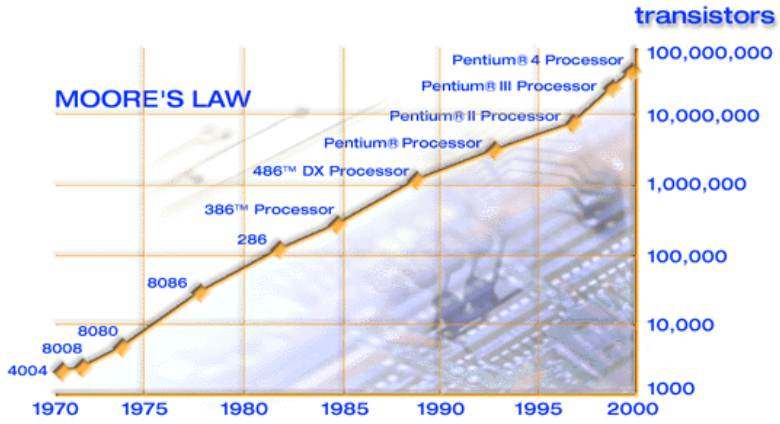
- Circuit Simulation
- Thermal Simulation
- EM Simulation

Summary

Summary (1)

- WBG Semiconductor Technology
- Microelectronics (Moore´s Law)
- Adv. Design / Adv. Packaging (Manufacturing) / Adv. Measurement



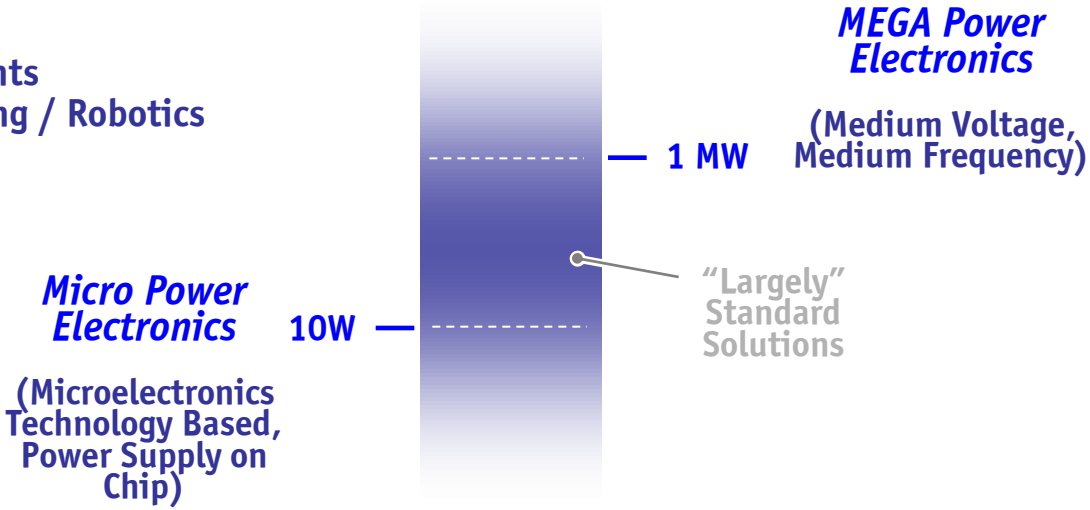


→ Enabling an up to Factor of 10 Performance Improvement

Summary (2)

- Considerable Future Extension of Power Electronics Application Area

* Smart Homes / DC Distribution
* Zero Energy Buildings
* Wireless Power Transfer
* Personal Digital Assistants
* Automated Manufacturing / Robotics
* EV Charging
* etc.



- Bridge to Power Systems
- Establish (Closer) University / Industry (Technology) Partnerships
- Establish Cost Models, Consider Reliability as Performance

Thank you!