Electronic Components Challenges in AI Power Management

CMSE 2025

European Passive Components Institute

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president

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Table Of Contents

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10 Years !

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DC/DC Converter Handbook POPULAR ARTICLES

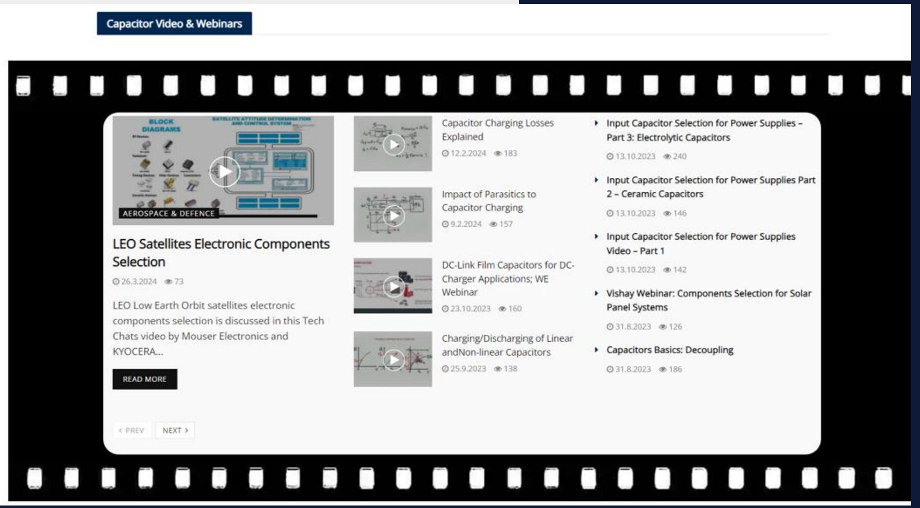
- DC-DC Converter Basic Characteristics and Formulas
- Input filters for DC/DC converters
- Selection of Storage Inductors for DC/DC Converters
- Selection of Capacitors for DC/DC Converters
- Buck Converter Design and Calculation
- SEPIC Converter Design and Calculation
- Boost Converter Design and Calculation
- Flyback Converter Design and Calculation
- Fly-Buck Converter Explained and Comparison to Flyback

Capacitors
Resistors
Inductors
Shielding
Inter-Connect
PCB
Filter
Crystals & Oscillators
Circuit Protection
Applications
Mounting Guidelines
Video Tutorials & Webinars

- Applications EXTENDED
- EMI/EMC Shielding NEW/UNDER CONSTRUCTION
- Capacitors
- Resistors
- Inductors
- Filters
- Crystals and Oscillators
- Circuit Protection
- PCB & Mounting
- Inter-Connect NEW/UNDER CONSTRUCTION
- Sam Video Learning

Capacitor Basics

- What is a Capacitor ?
- Capacitor Symbols
- Capacitance and its Calculation, Dielectric, Dipoles and Dielectric Absorption
- Dielectric Constant and its Effects on the Properties of a Capacitor
- DCL Leakage Current Characteristics of Capacitors
- Insulation Resistance, DCL Leakage Current and Breakdown Voltage
- Capacitor Losses (ESR, IMP, DF, Q), Series or Parallel Eq. Circuit ?
- ESR Characteristics of Capacitors
- Effects of ESL on Capacitor Performance
- Capacitor Energy Content and Force
- Capacitor Energy Density and Power Density
- Capacitors Derating and Category Concepts
- Capacitor Ripple Current, Transient and Surge Power Load Ratings
- Ripple Current and its Effects on the Performance of Capacitors
- Capacitor Technologies Overview
- Electrostatic Capacitors
- MLCC and Ceramic Capacitors
- Film and Foil Organic Dielectric Capacitors
- Silicon and Silicon Wafer Based Integrated Capacitors
- Glass, MICA, Air and Vacuum Capacitors
- Electrolytic Capacitors
- Aluminum Electrolyti
- Tantalum and Niobi
- Supercapacitors
- Variable Capacitors,
- Introduction to Powe
- Selection of Capacito
- Failure Analysis of Ca
- Supercapacitor Balar
- Capacitor Charging L



Global Leading Blog dedicated to Passive Components

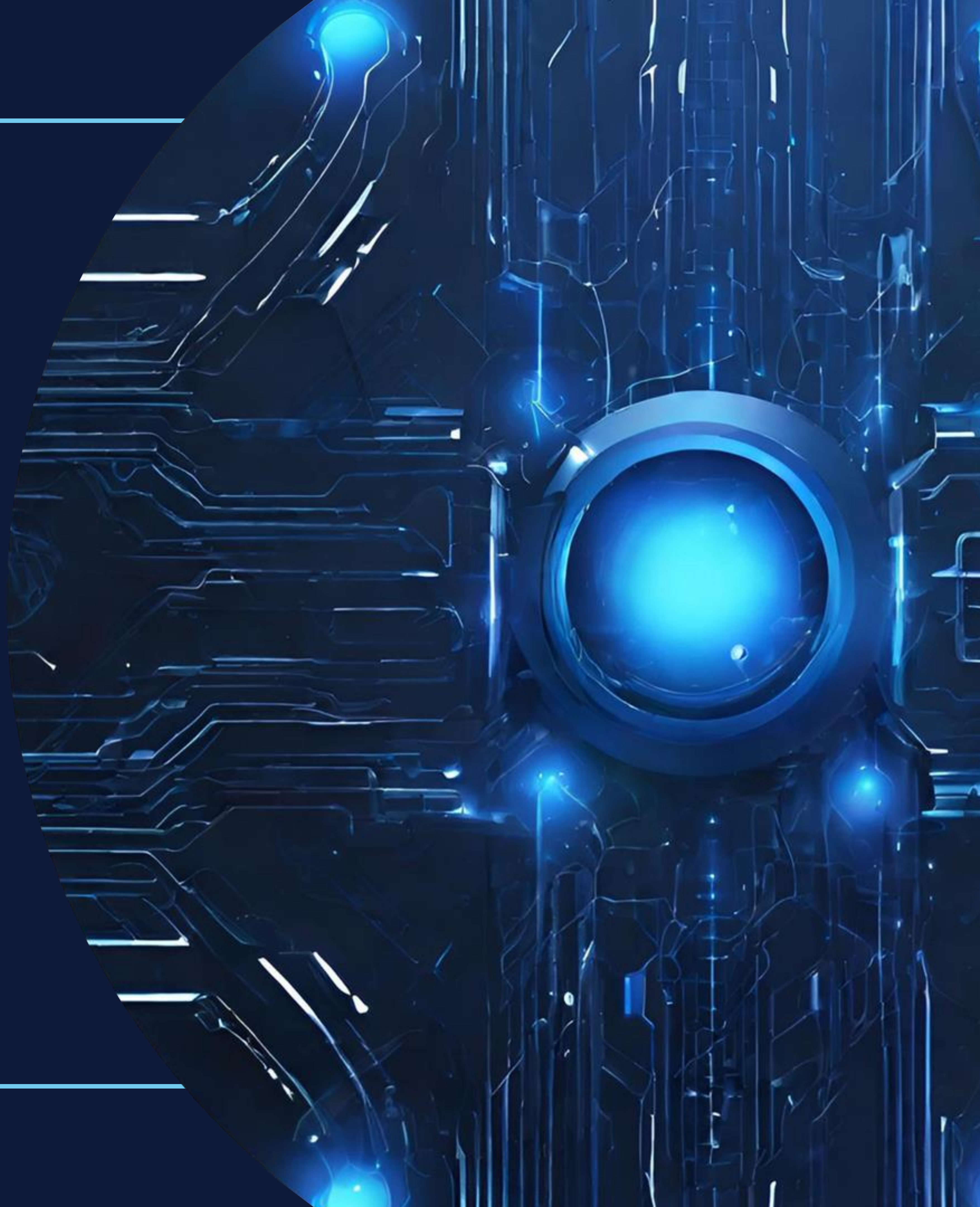
Google Search Phrase Stats 2024 passive-components.eu

Search Formula	Clicks	Views	Position
inductor design	644	3720	1,64
flying capacitor	505	3687	1,84
low esr capacitor	370	10476	5,01
buck converter calculator	290	2697	8,23
temperature coefficient of resistance formula	275	9889	5,16
buck converter design	242	3585	5,24
snubber capacitor	241	8967	4,35
pvc dielectric constant	231	1583	2,39
boost converter design	218	2543	4,32
what is ripple current	202	2334	2,16
ripple current	200	13386	4,06
x8l vs x7r	186	438	1,31
dielectric constant	175	357794	6,54
capacitor equivalent circuit	150	1504	1,5
temperature coefficient of resistance	145	15369	9,63
buck converter design calculation	138	551	3,55
polycarbonate dielectric constant	134	794	2,05
boost converter calculator	128	3127	7,3
flyback converter design	121	1923	7,89
mlcc size	112	475	1,04
buck converter equations	102	964	4,95
filter poles and zeros	101	243	2,06
flying capacitor balancing	84	464	3
x7r vs x8l	84	212	1,32
capacitor symbol	83	84909	2,13
smd inductor	83	7779	6,11
design of inductor	81	244	1,31
inductor selection for buck converter	80	563	3,56
x8l	72	1582	4,85
capacitor datasheet	71	4953	3,02

1

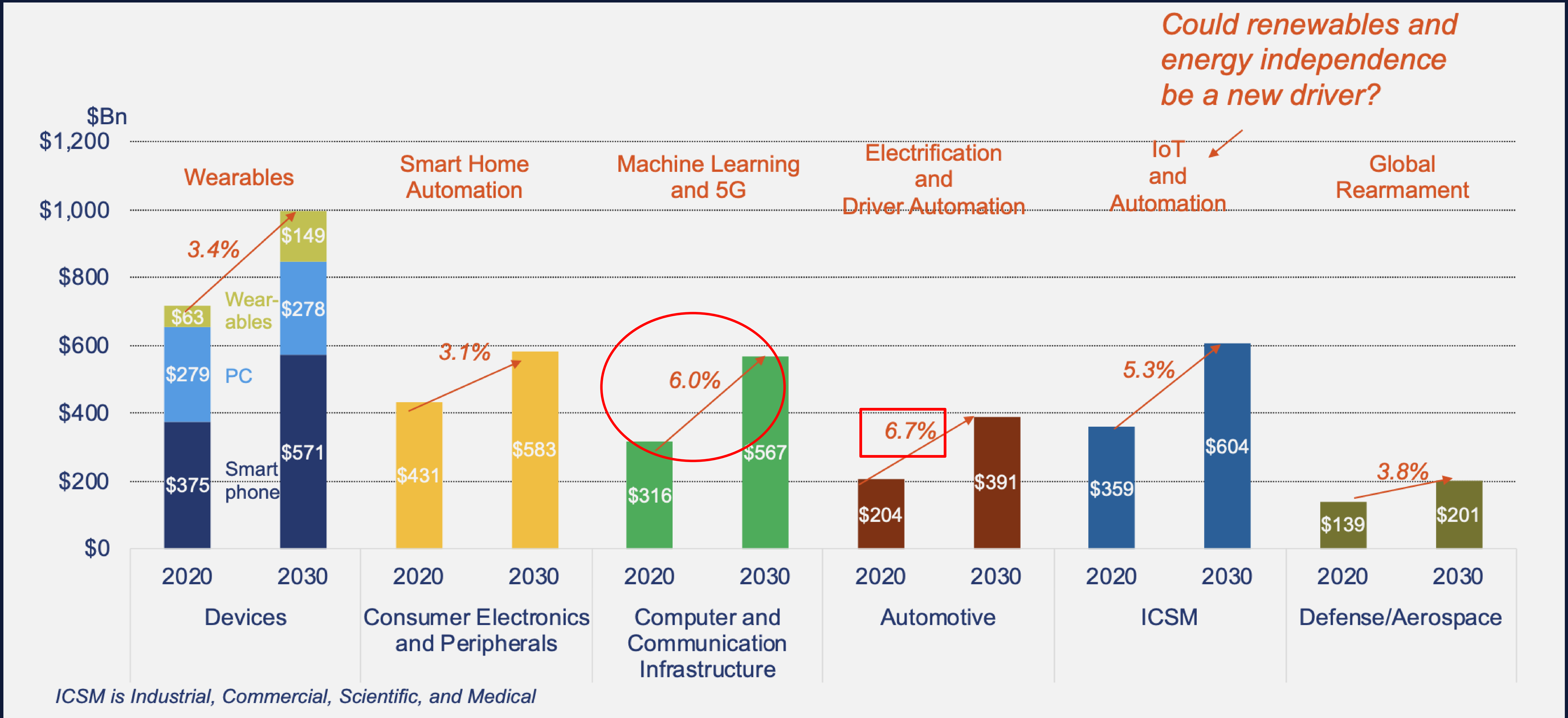
Introduction

Key Growth Areas and
Electronic Components
Drivers



Key Growth Areas

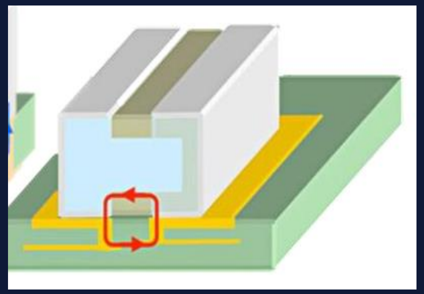
Mega Trends in Electronics for the Rest of the Decade



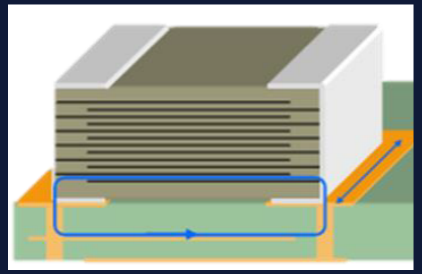
Semiconductor IC Development – Processors

DIE SCALING HAS DROPPED IC SUPPLY VOLTAGE

- *Capacitors job decoupling more critical*
- *Clock & data speeds making Di/Dt drawn larger*

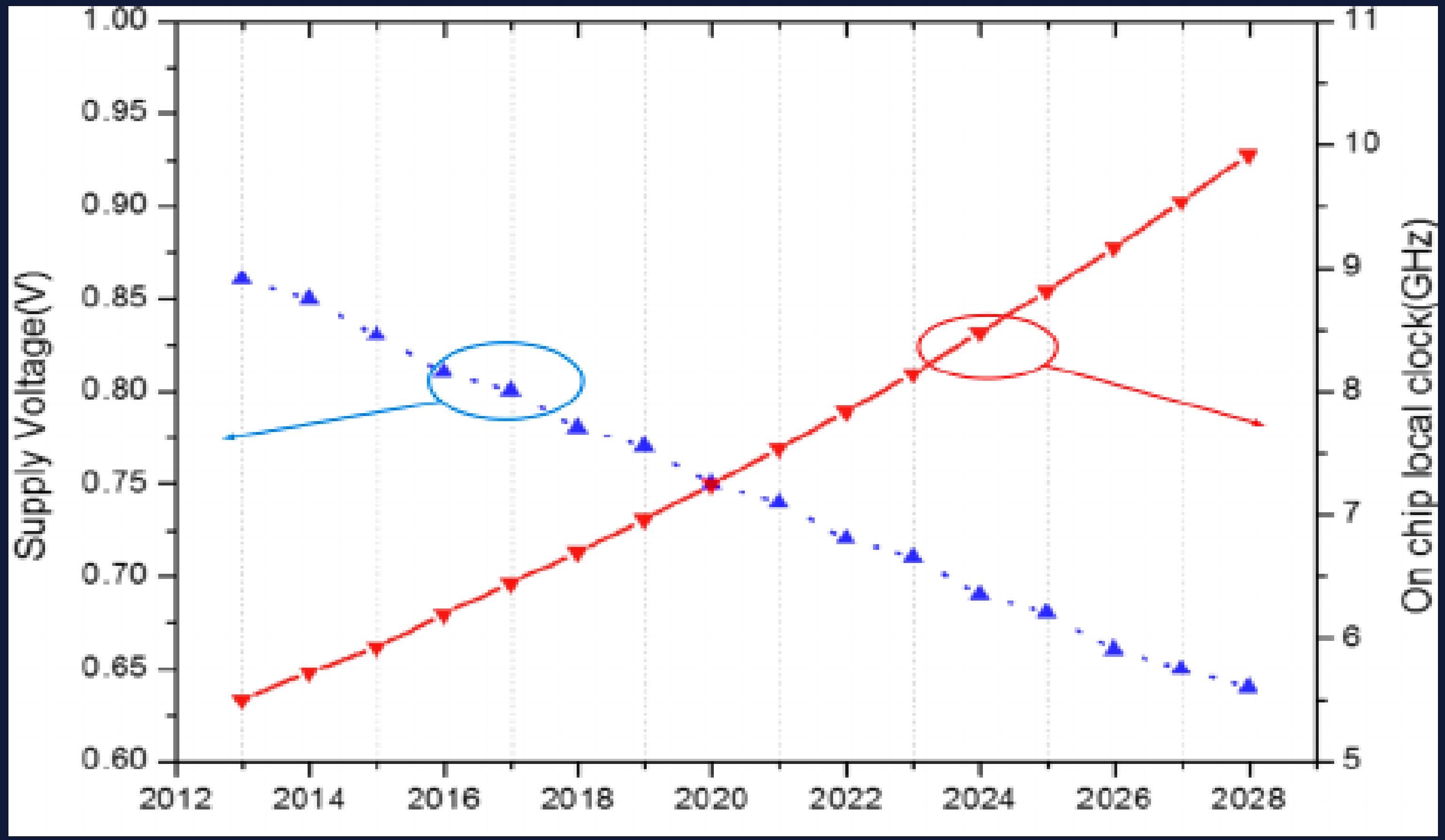


0508 MLCC
ESL ~ 45pH



0805 MLCC
ESL ~ 600pH

Source: ITRS

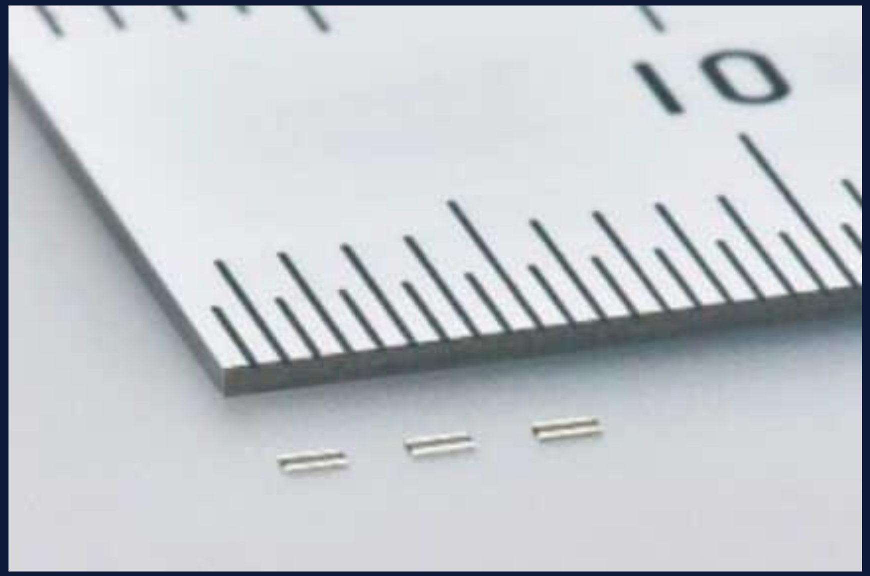


Best Fit Mass Volume Capacitor Technology:

Past: Electrolytics + MLCC
Current: MLCC Ceramic Capacitors
Future: Integrated on Chip

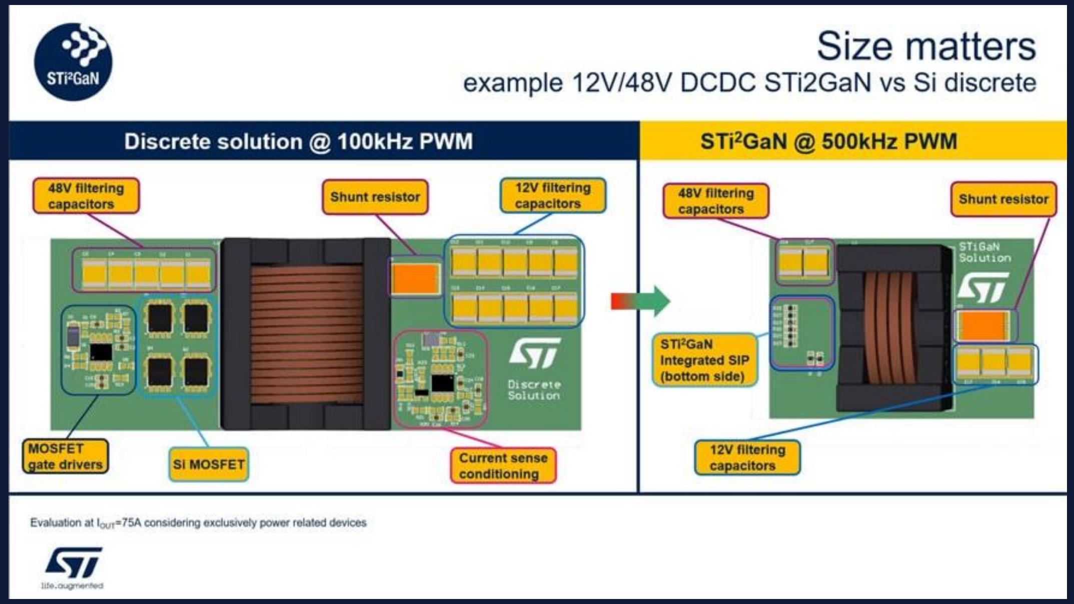
Capacitor Requirements

- Low ESL
- Low ESR
- High power
- Small Size
- Low Profile

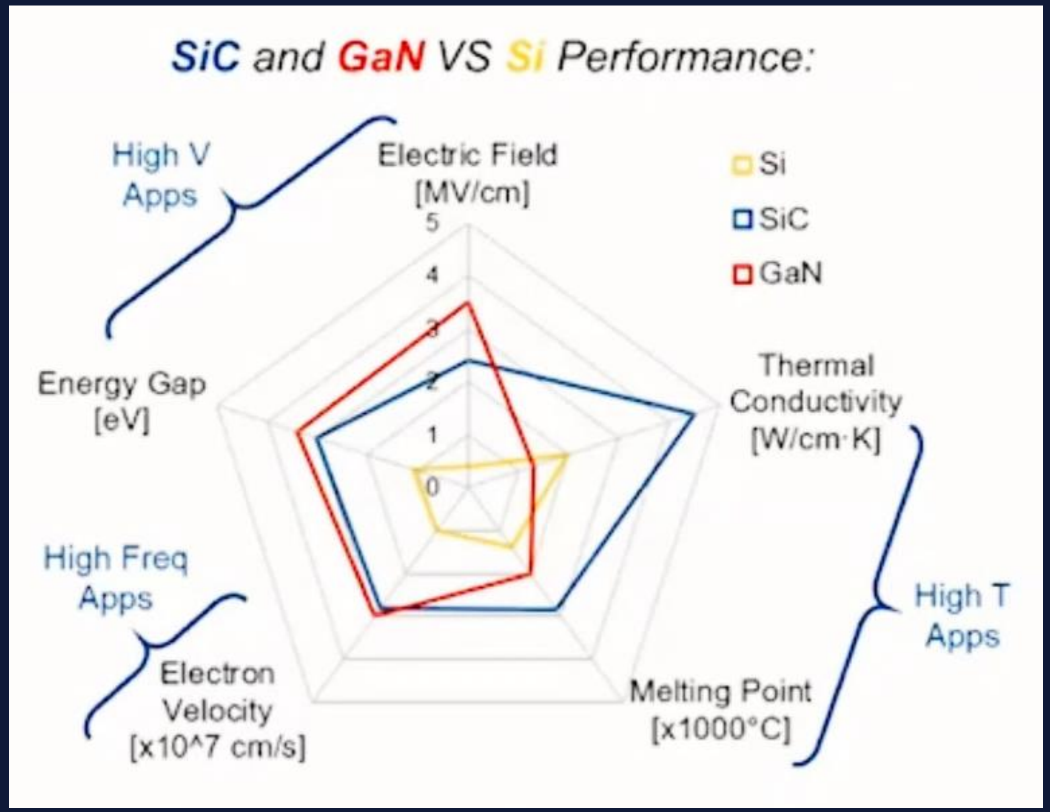


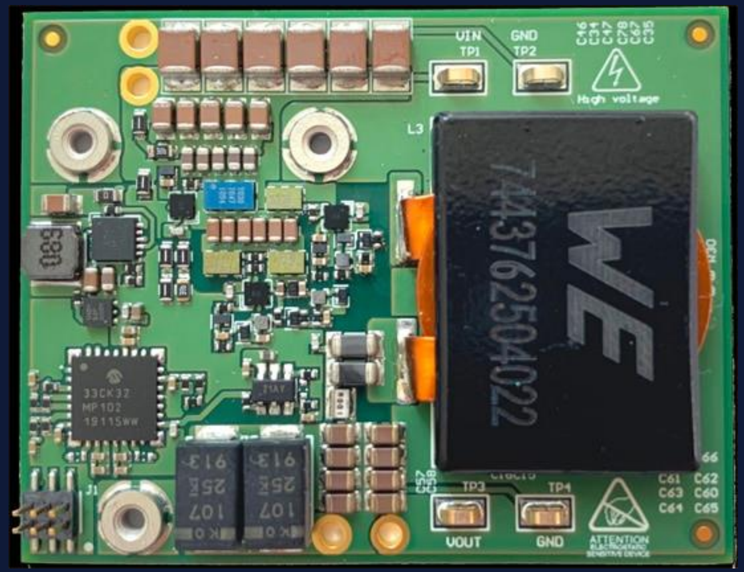
Reverse geometry MLCC 0.47uF 4V size: 0.52 x 1.0 x 0.1 mm

Semiconductor IC Development – Wide Gap GaN/SiC Transistor „Revolution“



Need for Low Loss, High Power Components





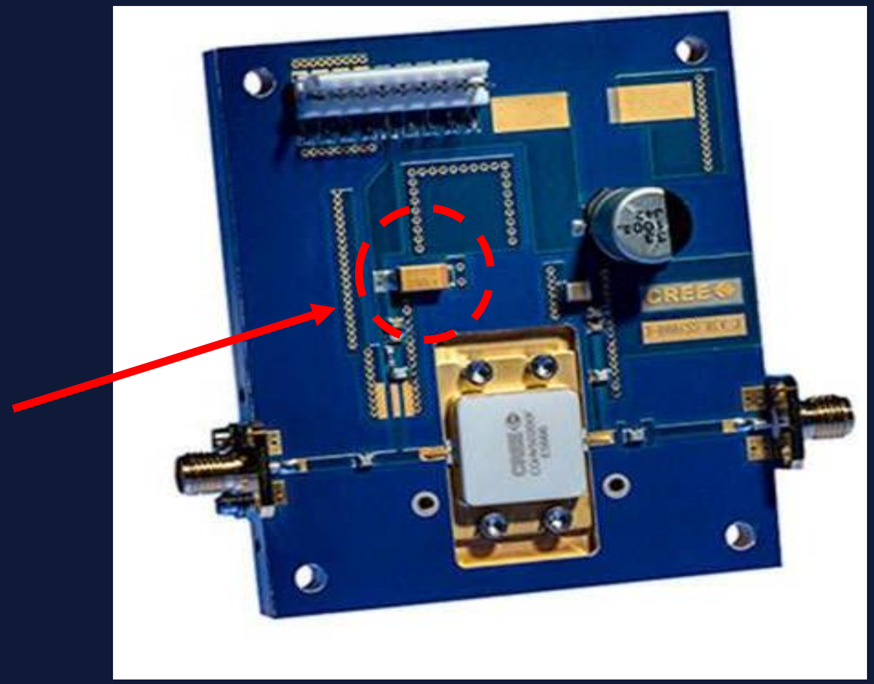
48 V three-stage synchronous buck converter with GaN technology

Output Capacitor Changes:

- Lower ESR, High Ripple Current
- Low ESL, Higher Frequency
- Lower Capacitance Needed
- Small & Thin Profile
- **Move away from electrolytics to MLCC Class II or Class I** output capacitors

New Requirements:

- **Stable Gate Drive Voltage Capacitors** (tantalum)
- Output low loss, high power inductors



2

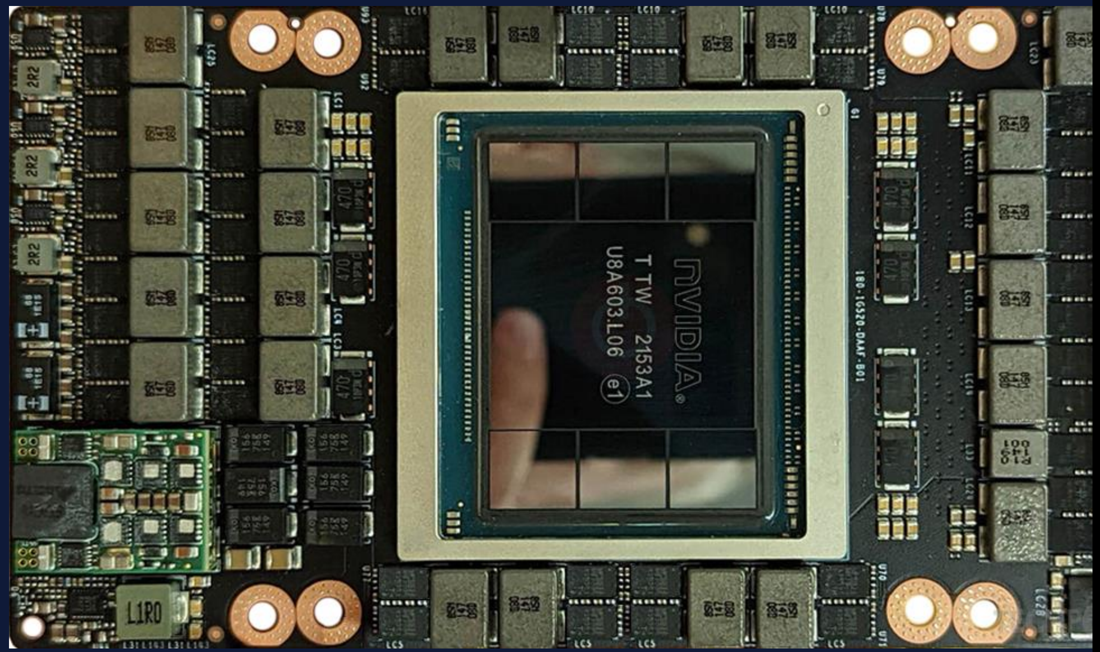
AI Power

AI Energy & Power
Management Challenges

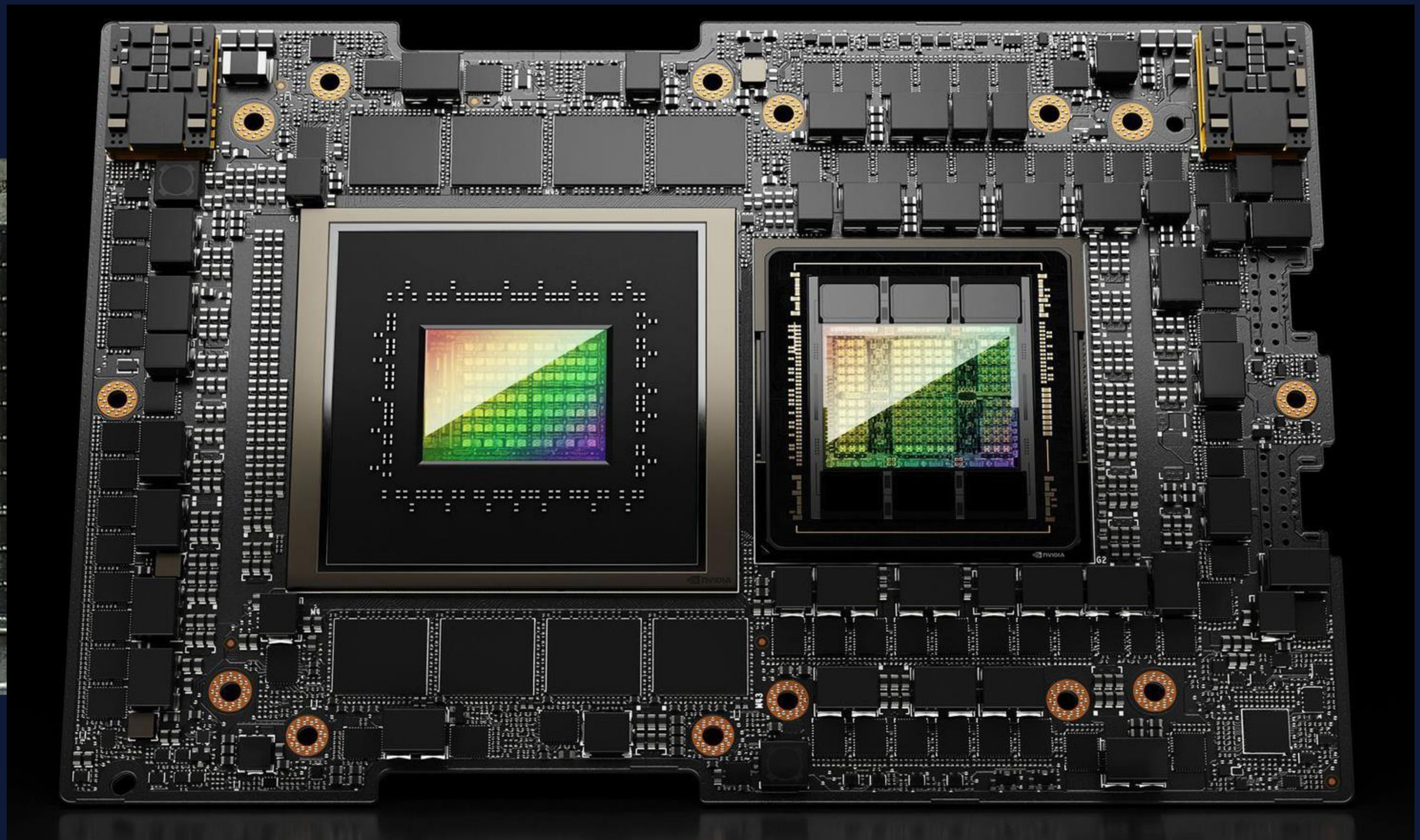
AI Demand

- **AI demand noted as remaining robust in CY24-CY25**
- Supply chain optimistic on Nvidia's new AI H200 Blackwell chip demand into U.S. hyperscalers with supply started in C3Q24. Major customers potentially exceeding $1B in CY24 could include **Microsoft** and **Tesla**/xAI
- Nvidia Blackwell is supply constrained (3/25), there are a lot of different configurations and suppliers need to coordinate; working to ramp capacity but it doesn't always align perfectly across all suppliers, In C2H25 Nvidia will have Blackwell Ultra ramping, then Rubin in CY26.
- **Power is becoming a datacenter bottleneck;** the constraints have changed from GPUs to physical space and availability of power.
- The next gen solutions are consuming **too much power and generating too much heat, so they need to figure out alternative means for cooling first.**
- Cloud demand for AI systems has been on fire, challenge is how much AI will be in the cloud vs. on-personal PC/NB.

AI GPU Cloud Servers



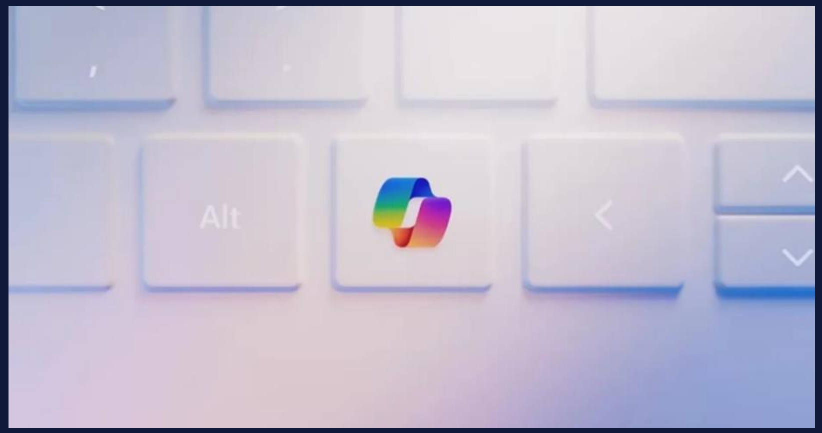
Nvidia AI Cloud GPU H100 (first gen)



Nvidia H200 Blackwell (current gen from 4Q24)

AI Personal PC/NB

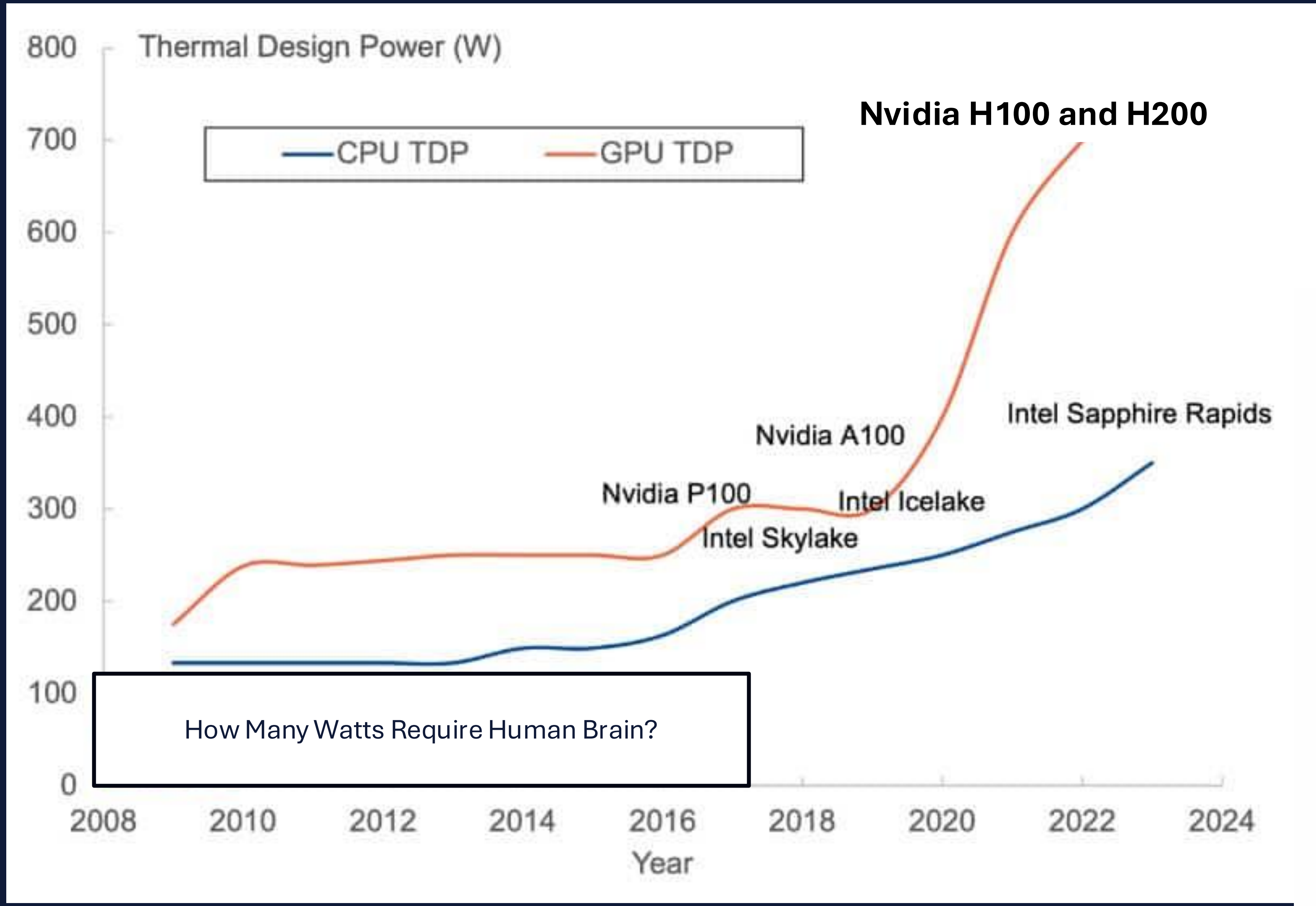
offline AI PC/NB from CY25



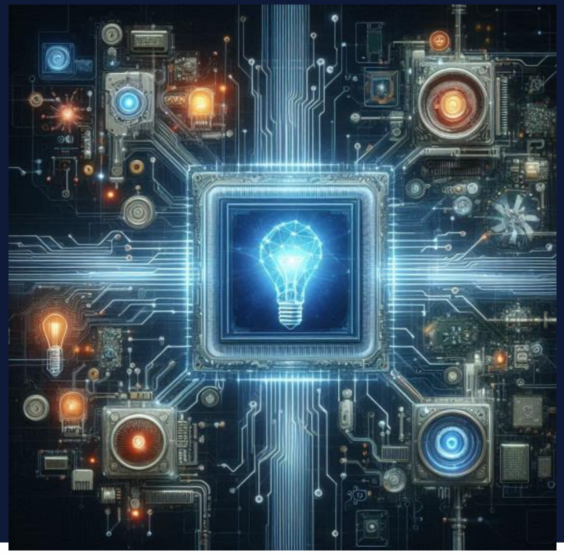
AI Energy Supply Challenge

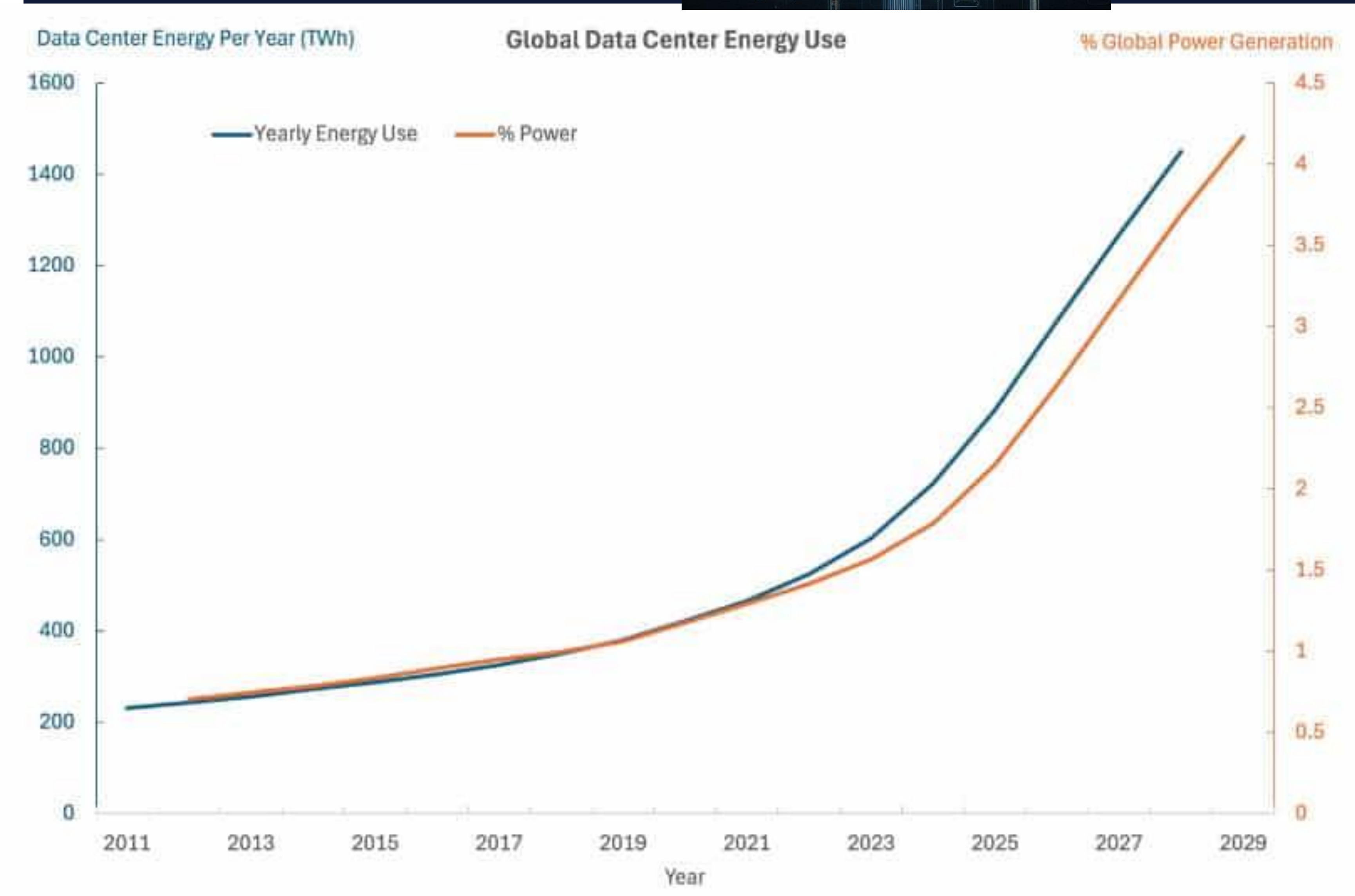
AI Server Technology Market

The Energy Challenge of AI in Data Centers



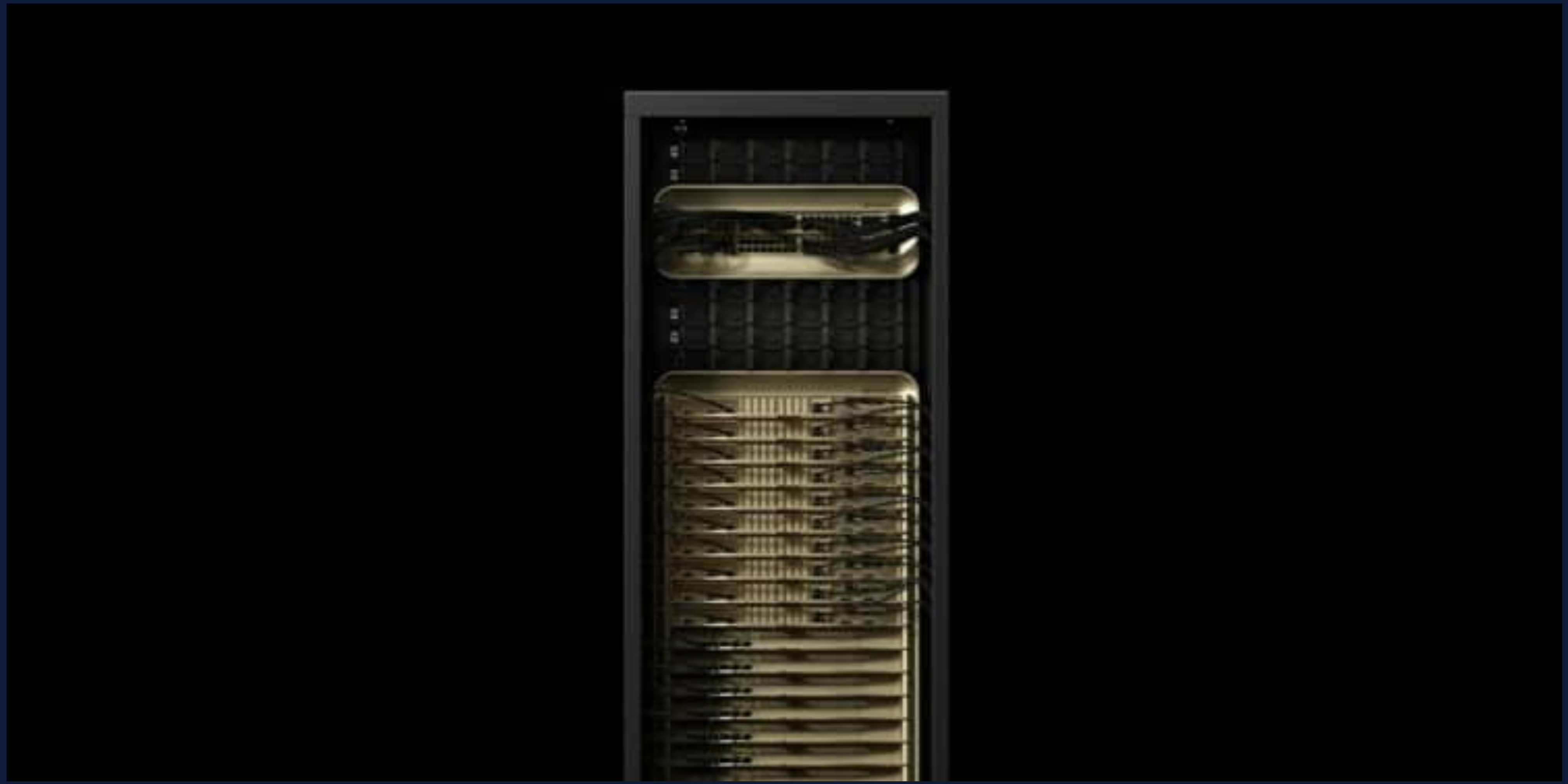
How Many Watts Require Human Brain?





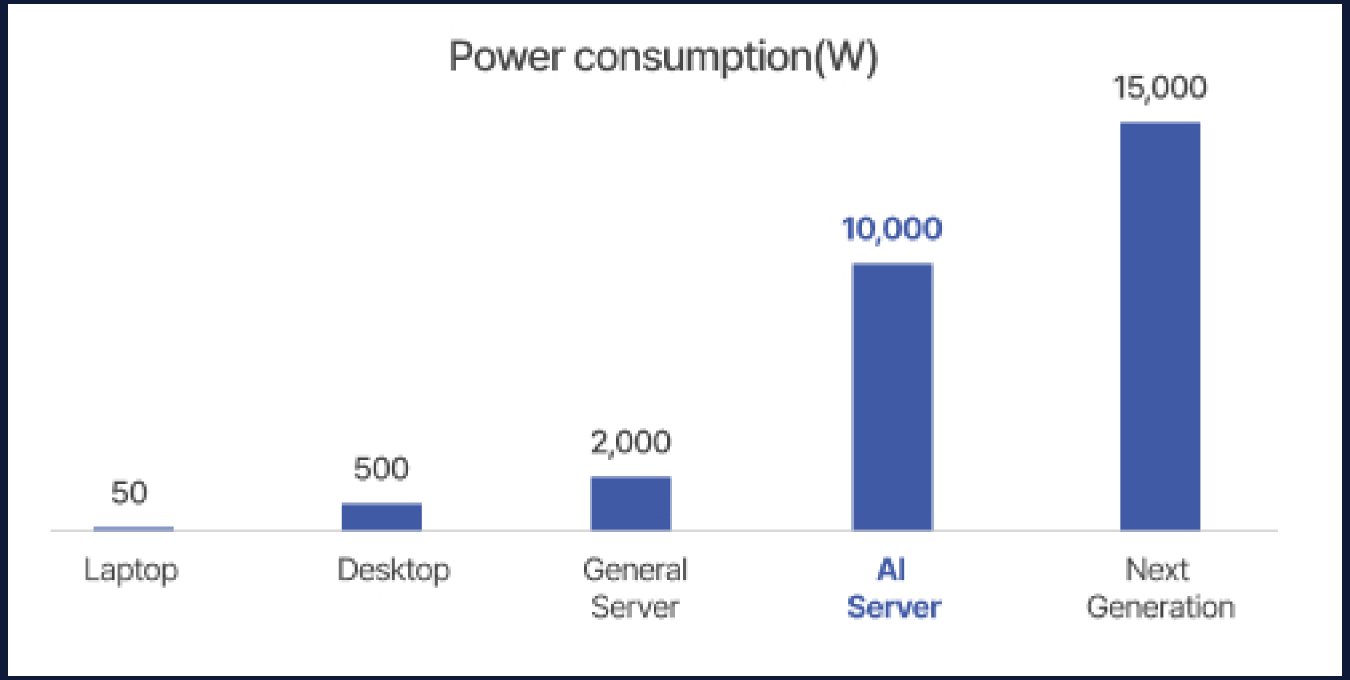
AI Energy Supply Challenge

- Blackwell Ultra B300 GPU delivers 1.5 times faster FP4 performance, though it requires 1,400 watts instead of 1,200 watts to do so.
- Memory per GPU increased by 50% to 288 GB
- For power management, the NVL72 rack configuration features **and more than 300 supercapacitors per rack**.



Demand for capacitors in servers to quadruple by 2029

AI Server Power Consumption



source: Samsung Electro-Mechanics

AI Energy Supply Challenge

1 Data Centers are Focused on Reducing Energy Consumption

- 2% of global electricity use today; equivalent to total electricity usage of Spain or Italy
- US data centers alone are forecasted to consume 140B kilowatt-hours by 2020
- Powering IT equipment is one of the largest operating expenses for data centers

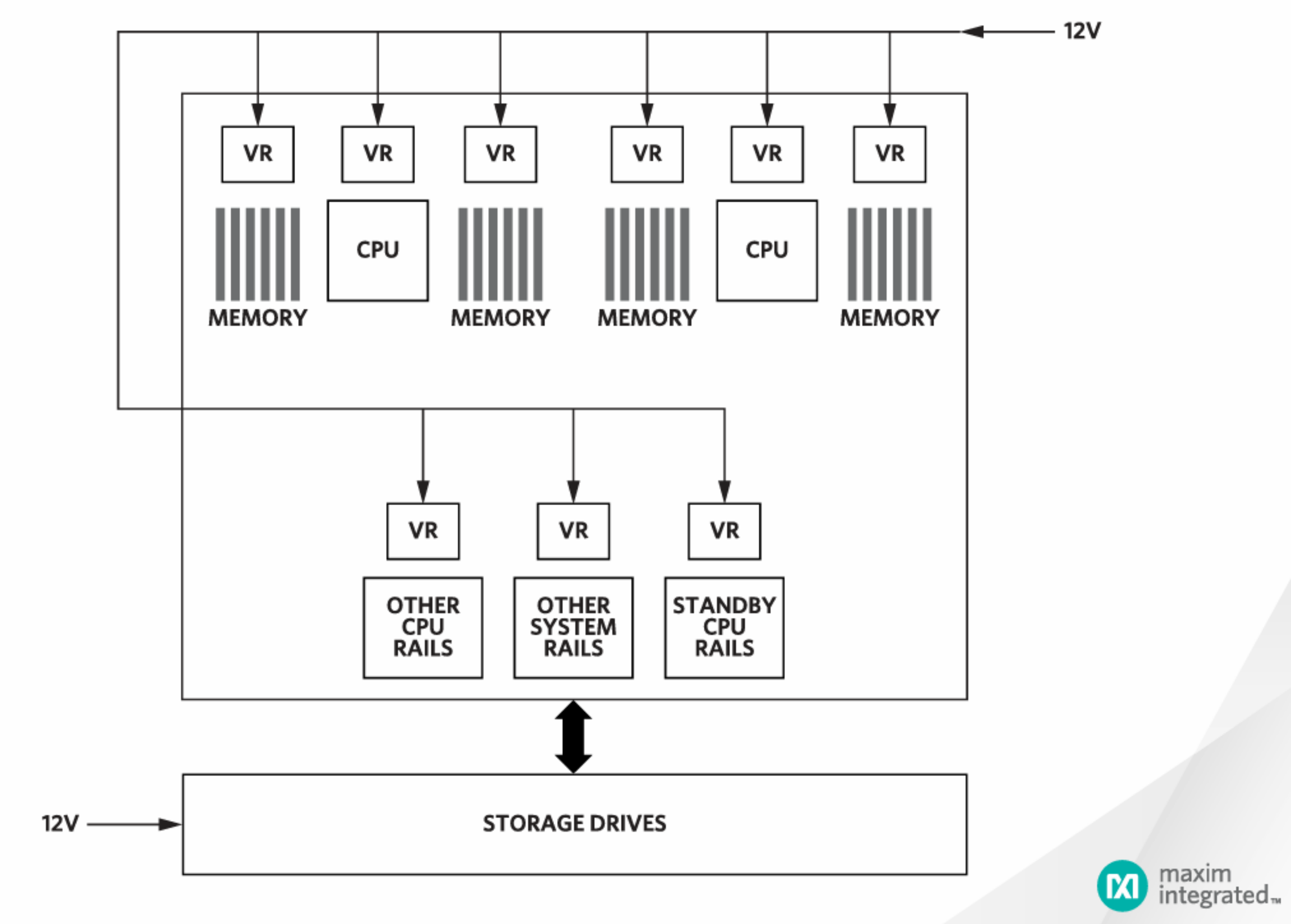
2 CPU & Memory Consume Most Power in Rack

- CPU & Memory represent ~80% of total server power
- CPU power & dynamic requirements continue to increase

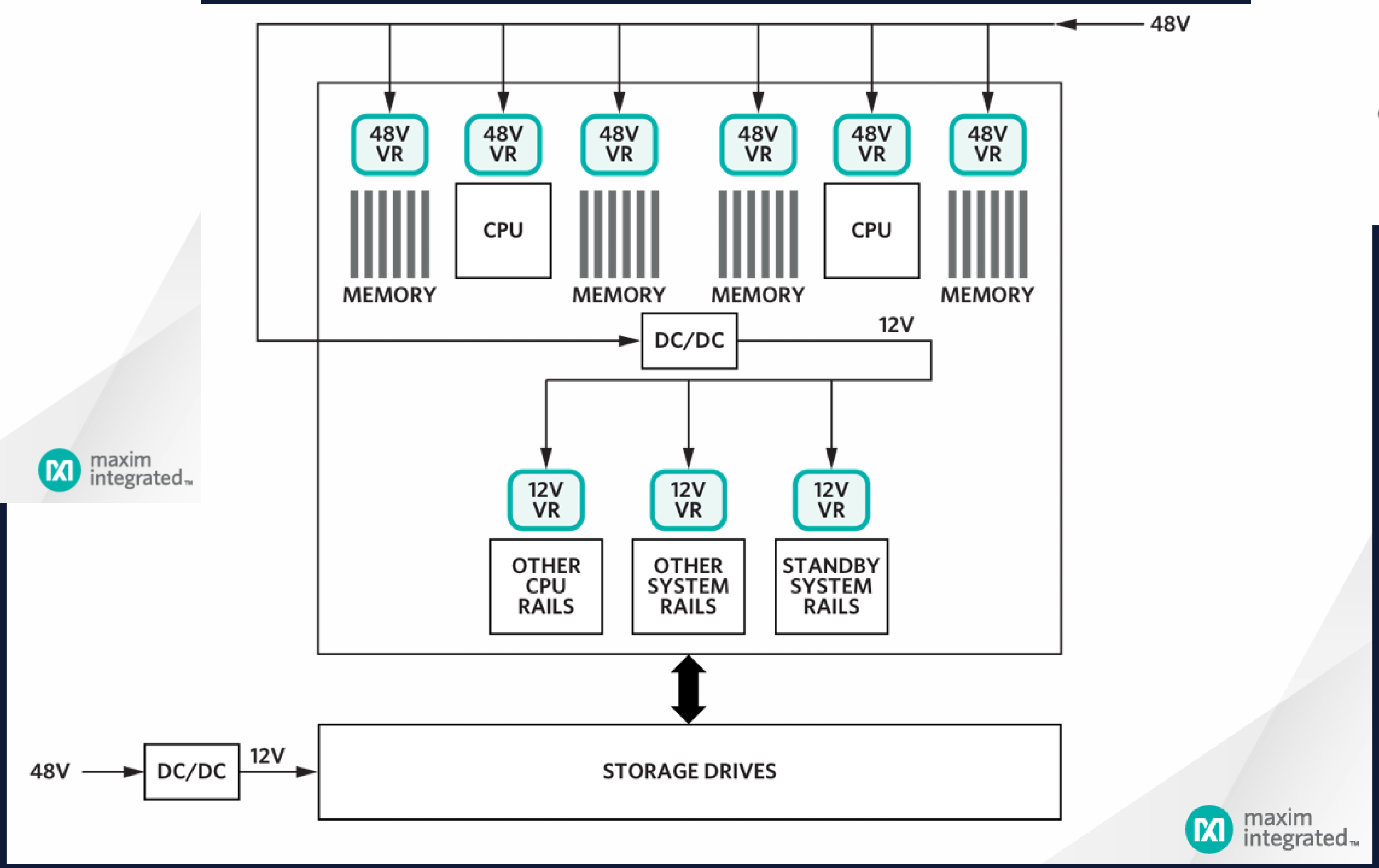
3 New 48V Rack Power Architecture

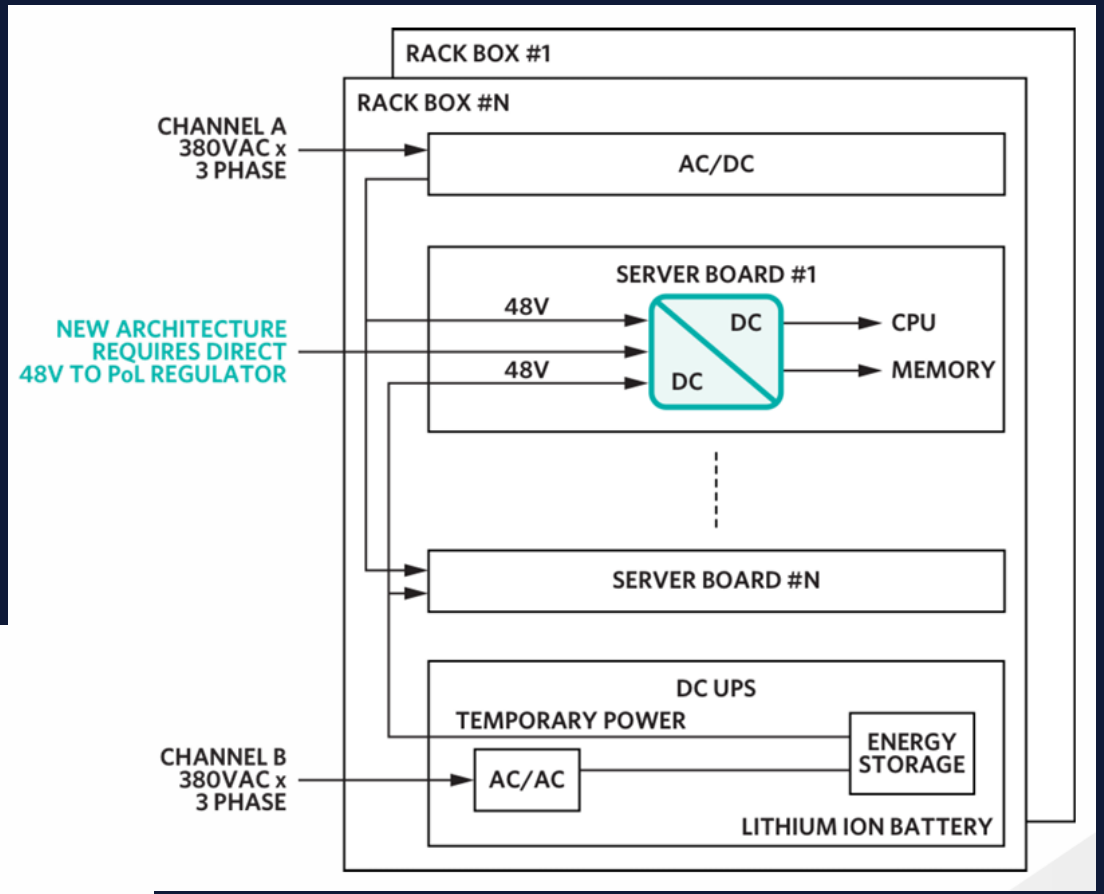
- Google introduced a 48V rack power architecture at 2016 OCP Summit to replace 12V
- Using 48V provides a 16x reduction in power distribution and up to 30% lower conversion losses
- Requires new high efficiency 48V to PoL regulator

12V Server Motherboard Power Architecture



48V Server Motherboard Power Architecture



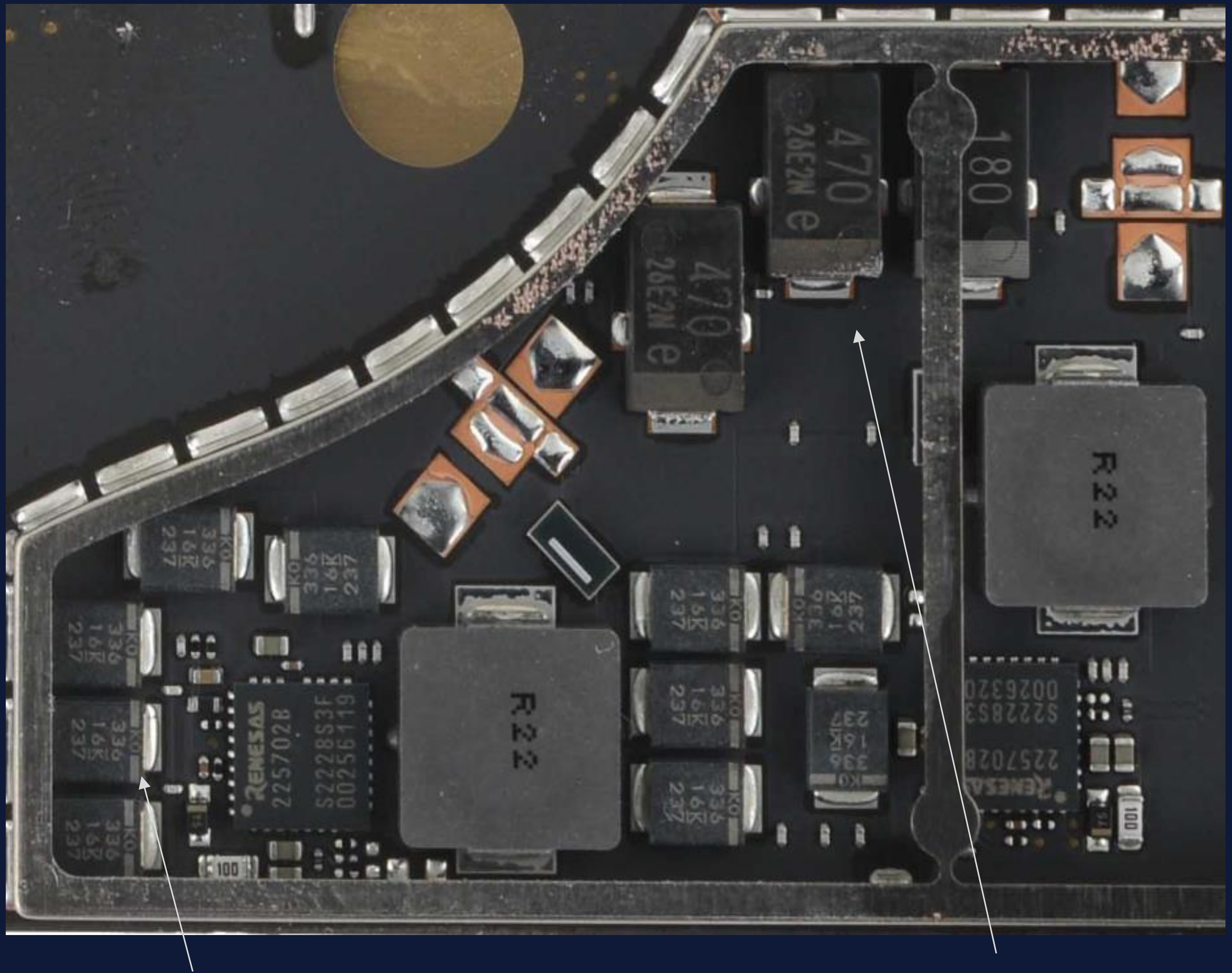


Energy Savings

- > Up to 30% less conversion losses
- > 16x less power distribution losses

Source: Maxim Integrated: New 48V Rack Power Architecture For Hyperscale Data Centers

The Evolution of AI Power Management



33uF 16V low ESR tantalum polymer chip capacitors on 12V line and 2.5V aluminum polymer chip capacitors on processor line of Apple Macbook Pro M2 board

- **new power supply topologies** for enhancing power delivery and reducing waste
- transition from traditional **12V to 48V power distribution systems** (reduction of power losses by a factor of 16). Note: 48V voltage move trend is also valid for automotive
- integration of **wide band gap power switches** GaN and SiC - higher temperatures, voltages, and frequencies = reduced cooling requirements and the potential for smaller passive components, which can be positioned closer to the processor, thereby cutting down on losses in circuit board wiring
- **addressing 'parasitic losses'** the power dissipated as heat due to the ESR of capacitors, and losses in inductors' windings and magnetic cores is essential. By focusing on reducing these losses, data centers can conserve energy and lower cooling demands.

3

Consequences

Passive Electronic

Components Requirements

Processor Power Management & Coupling

MLCC

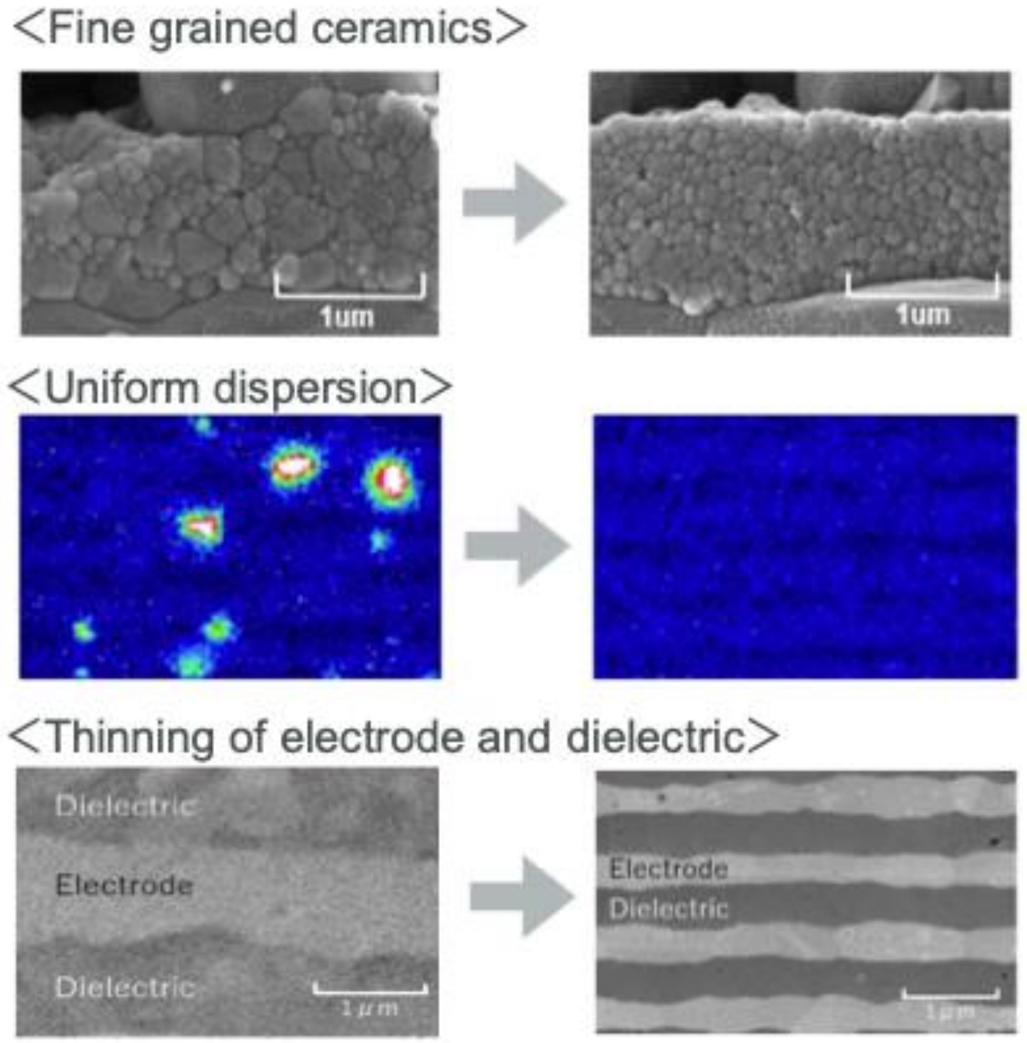
	Opportunity	Rec
Edge devices	Future enhancements to on-device AI capabilities will lead to renewed growth of edge devices	● ●
Mobility	Growth of automotive ADAS and xEV will increase the number of parts required for high-performance MLCCs	● ●
IT infrastructure	Demand for AI servers and other IT infrastructure applications will grow as cloud AI becomes more prevalent	● High reliability ● Increased capacity

Smartphones	**1,000–1,400**

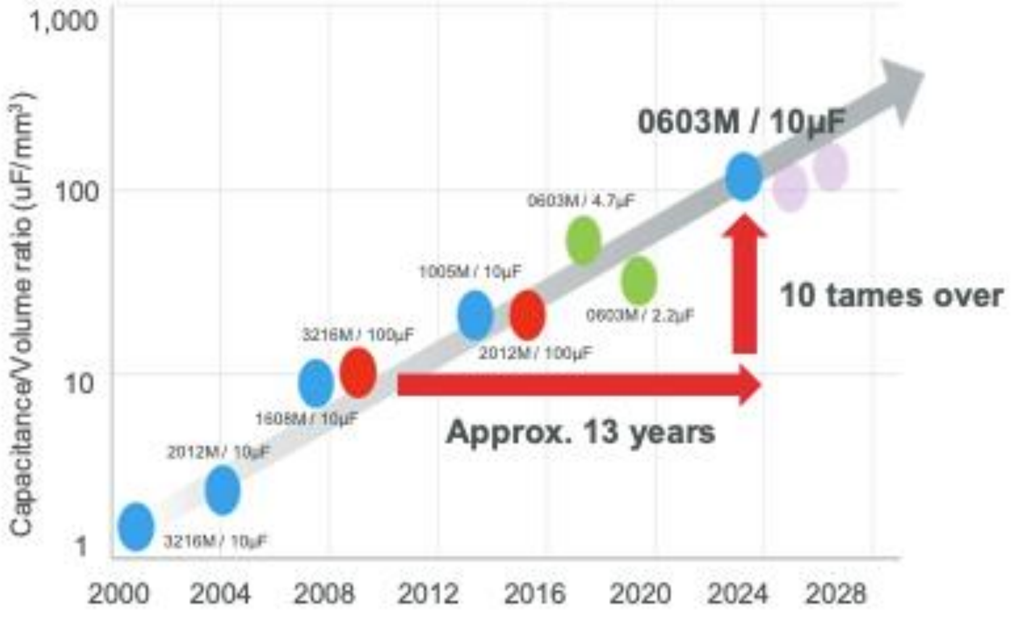
	ICE	BEV	PHEV
Powertrain	300–500	**2,000–2,500**	**2,500–3,000**
ADAS (Lv 2/3)	**1,500–3,000**		
ADAS (Lv 4/5)	**3,000–5,000**		

Servers (Baseboard)*	1,800–2,500
AI servers (Baseboard + AI accelerators × 8)*	**10,000–20,000**

miniaturization and higher capacity technologies



High capacitance MLCC roadmap (6.3V rated or less)



Growth potential in the AI【Edge devices】

Because of the high computational power requirements, the power needed for semiconductors is expected to increase, leading to a further rise in demand for miniaturization and high-capacity solutions due to space constraints on edge devices.

Processor Power Management & Coupling

MLCC

MLCCs for AI Servers

	General Server	AI Server
MLCC Usage	2,000pcs	**25,000pcs** (12.5x)
MLCC Capacitance	20,000μF	**200,000μF** (10x)

	10uF	22uF	47uF	100uF	220uF	330uF
0402	4V X6S	4V X6S	General Server			AI Server
0603		4V X6S	4V X6S			
0805			4V X6S	4V X6S		
1206				4V X6S	4V X6S	
1210						2.5V X6S

Processor Coupling (low voltage 2.5/4V)

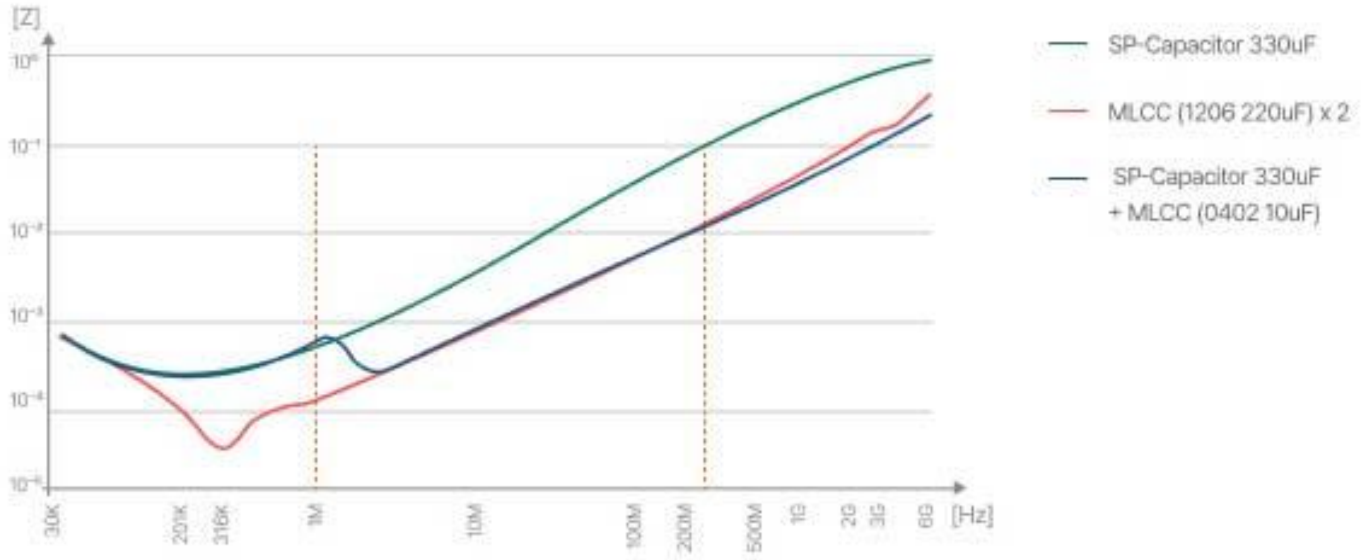
Benefit of Space Saving

2x high capacitance value is available in smaller size

2x MLCC effective capacitance value (360uF) is higher than 1 SP-Capacitor (330uF)

35% smaller but 218% higher effective capacitance

Benefit of Performance



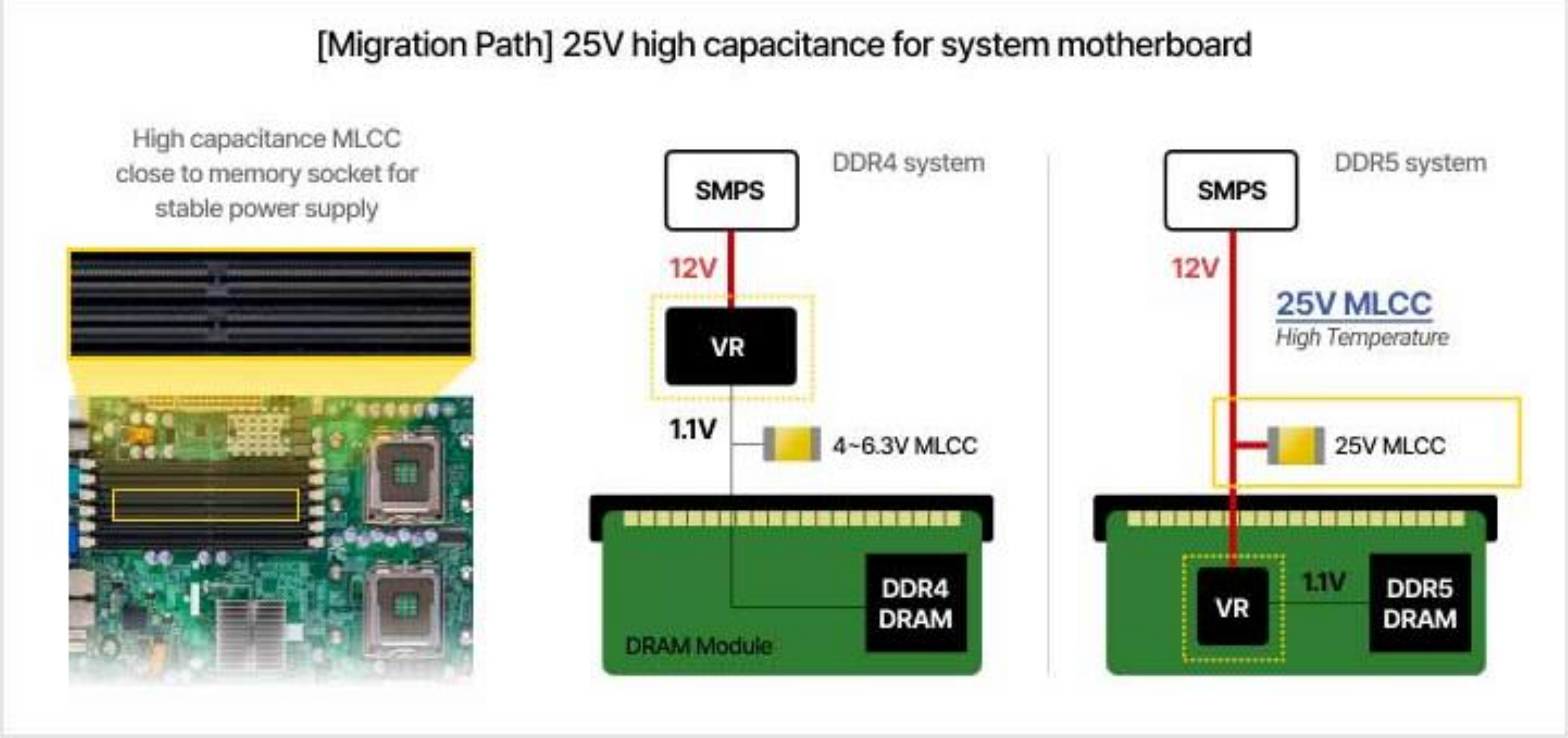
source: Samsung Electro-Mechanics

MLCCs for AI Servers

Memory Applications

DDR4 to DDR5 Architecture Migration

The shift from DDR4 to DDR5 has brought significant changes to power architecture. DDR5 offers higher bandwidth and improved power efficiency compared to its predecessor, featuring a redesign that **moves the voltage regulator (VR) to the inner part of the mainboard.**



10uF/6.3V MLCC / Tantalum capacitors in DDR4 – migrate to 25V capacitors – 22uF (10uF effective) / 25V now available in 0805 MLCC case size

source: Samsung Electro-Mechanics

Capacitors

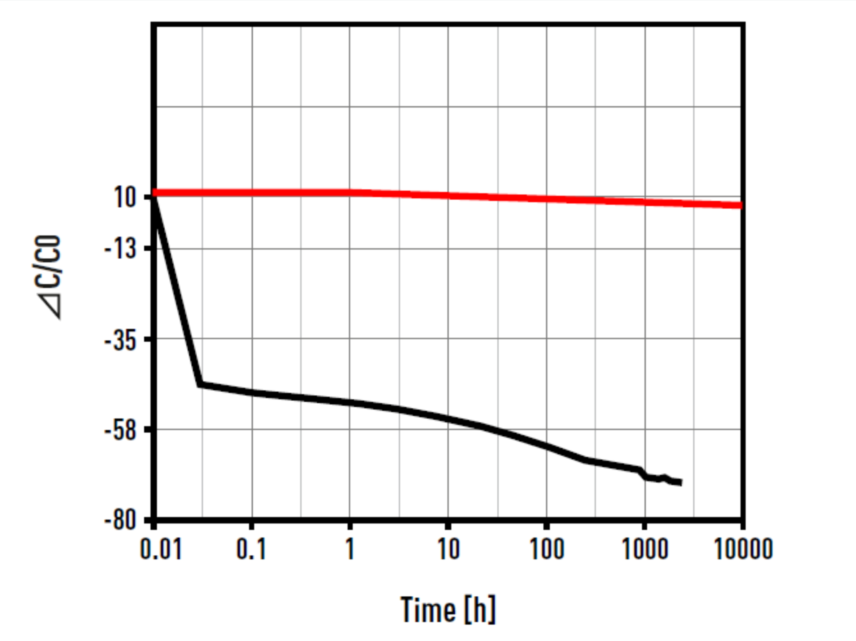
48V Power Rail Challenge

- Tantalum and Aluminum Polymer capacitors new low ESR, high capacitance 63V and 75V ratings
- MLCC drive the downsizing and ESR reduction BUT class II (ferroelectric) high CV temp/volt/age behaviour is an issue

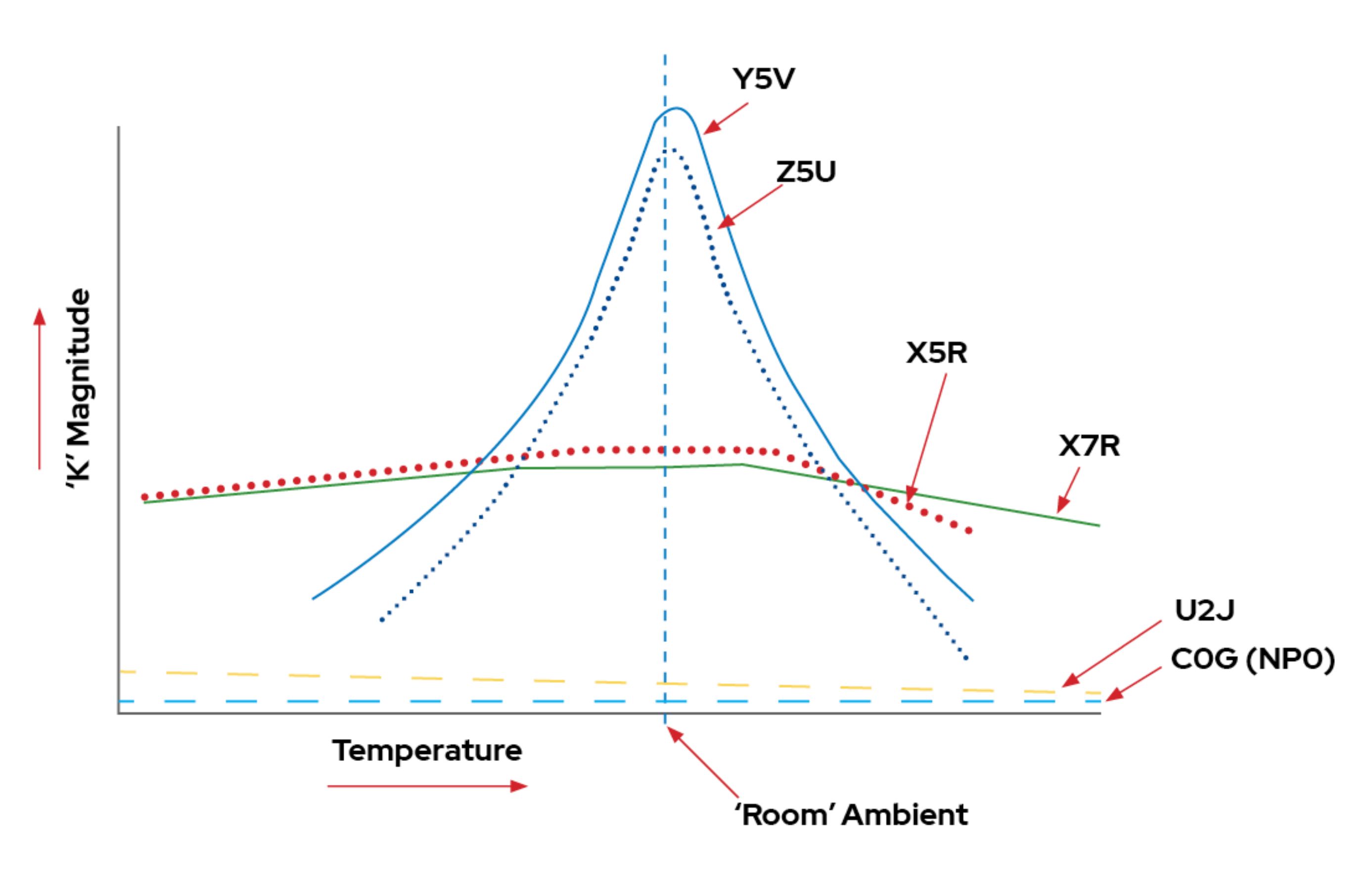
Material	Class	Dielectric constant	% Cap Change / Oper. temp. (°C)	Dissipation factor at 1kHz at RT
UP porcelain	I.	4.5-6.7	30ppm (-55..+125C)	0.05%
NPO	I.	15-100	<0.4% (-55...+125C)	0.10%
X5R	II.	1000 - 4000	± 15% (-55..+85C)	3.50%
X7R	II.	2000 - 4000	± 15% (-55..+125C)	3.50%
Y5V	II.	> 16 000	up to 82% (-30..+85C)	9%

MLCC class I and class II basic behaviour comparison

- New MLCC class I dielectrics (paraelectric) development (U2J) is offering approx 2.5 times the capacitance of C0G/NP0
- Electronic components must be designed for long operational lifetimes, withstanding up to 125°C, along with enhanced humidity resistance



Capacitance ageing of MLCC class II (black) vs tantalum capacitors comparison; source: Panasonic

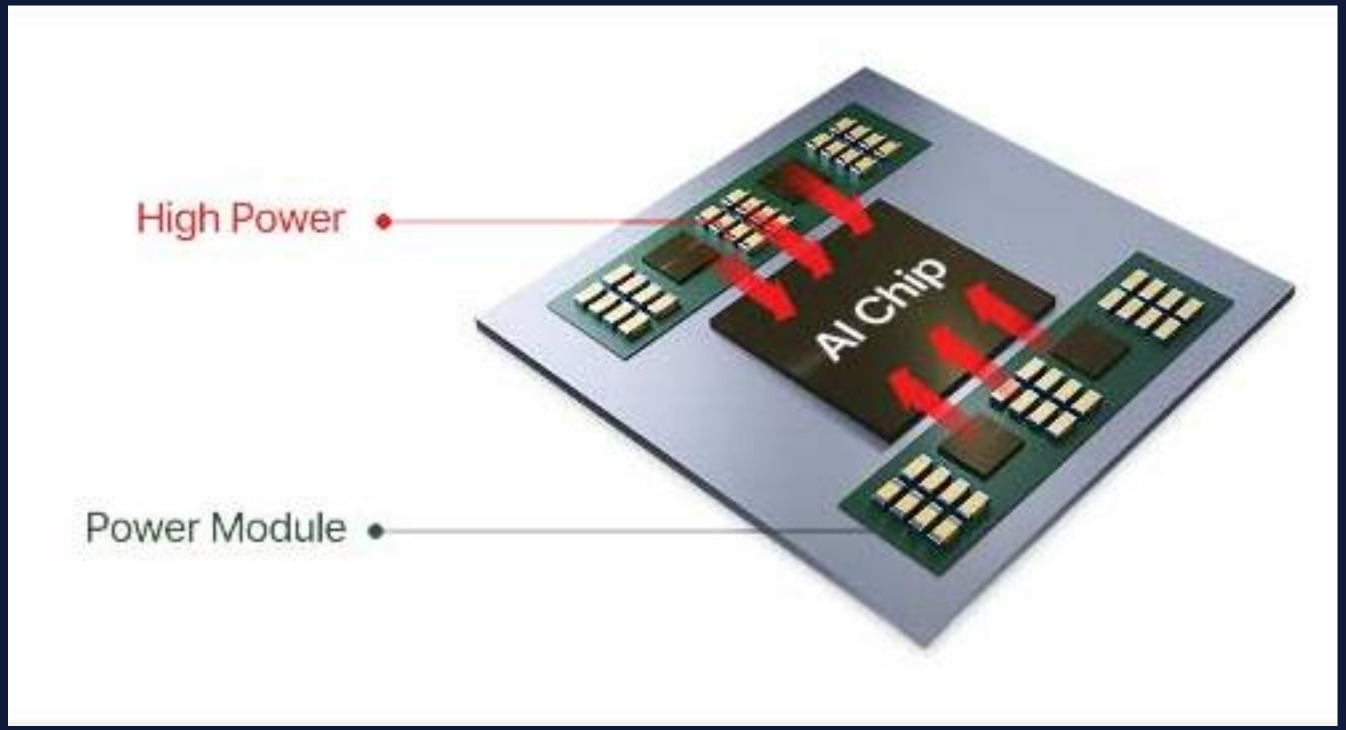


Dielectric constant temperature dependency of various ceramic materials; source: KEMET YAGEO

Passive Components Consequences

MLCCs for AI Servers

48V Power

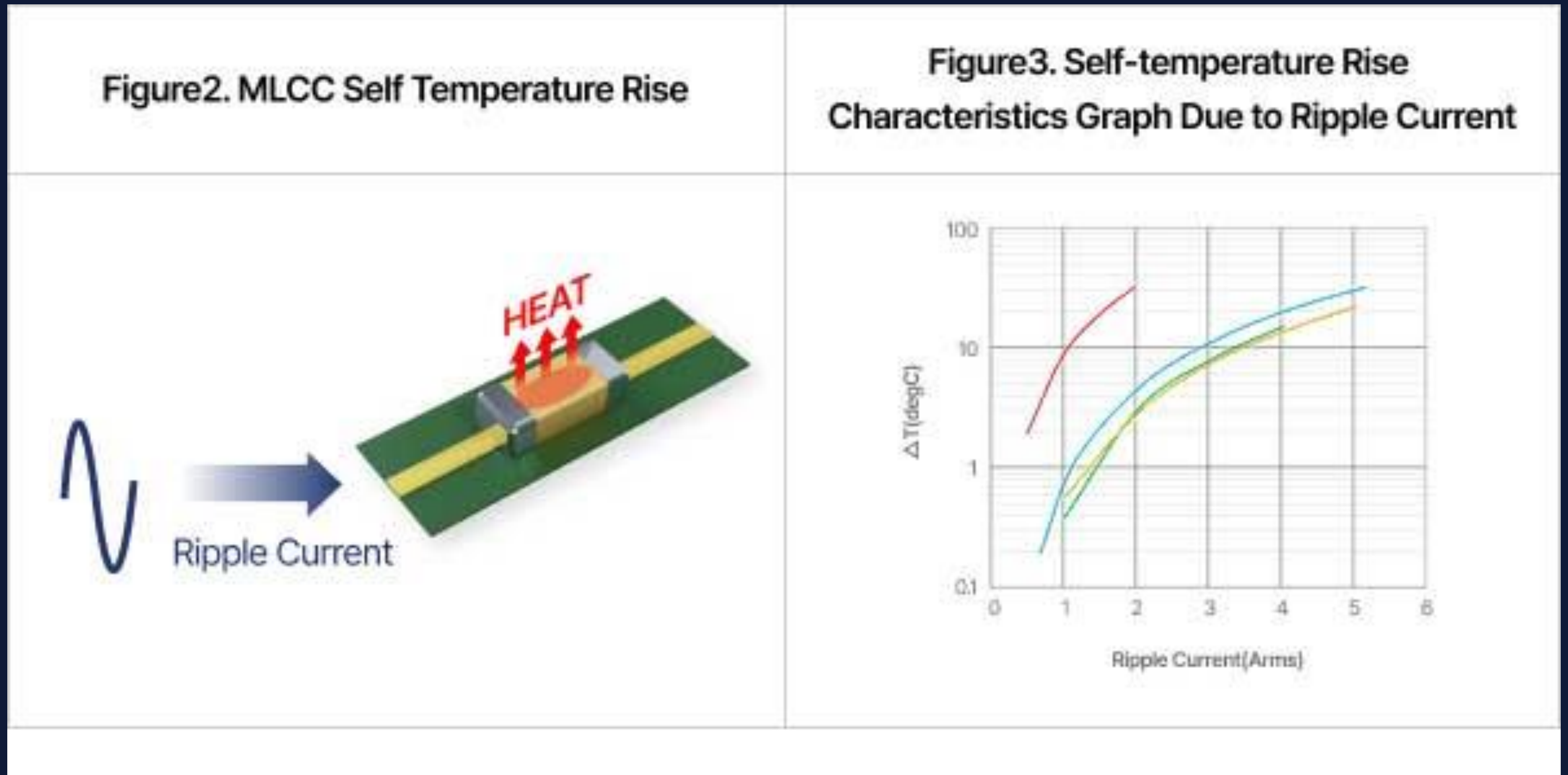


Released in April 2025:

4.7uF 100V in 1206 INCH size X7S dielectric

High-capacitance 100V MLCC to AI 48V input/output voltage circuits - consider

- usage of Soft Termination to reduce mechanical stress
- evaluation of the Self-temperature Rise of the MLCC caused by high ripple currents

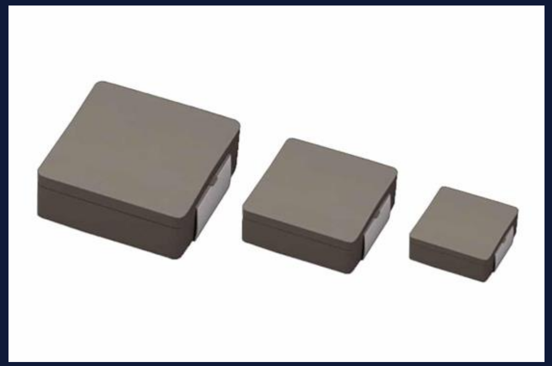


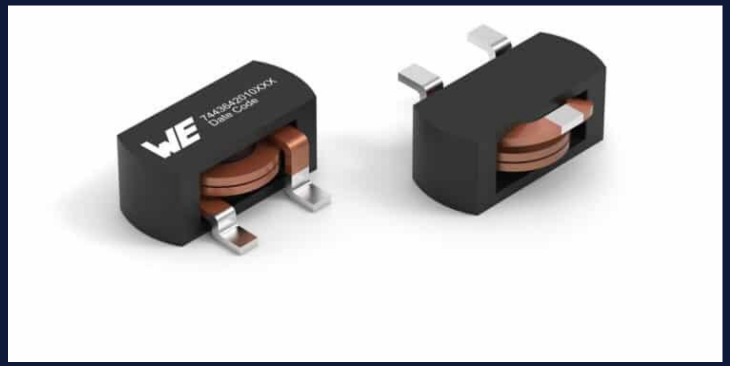
source: Samsung Electro-Mechanics

Passive Components Consequences

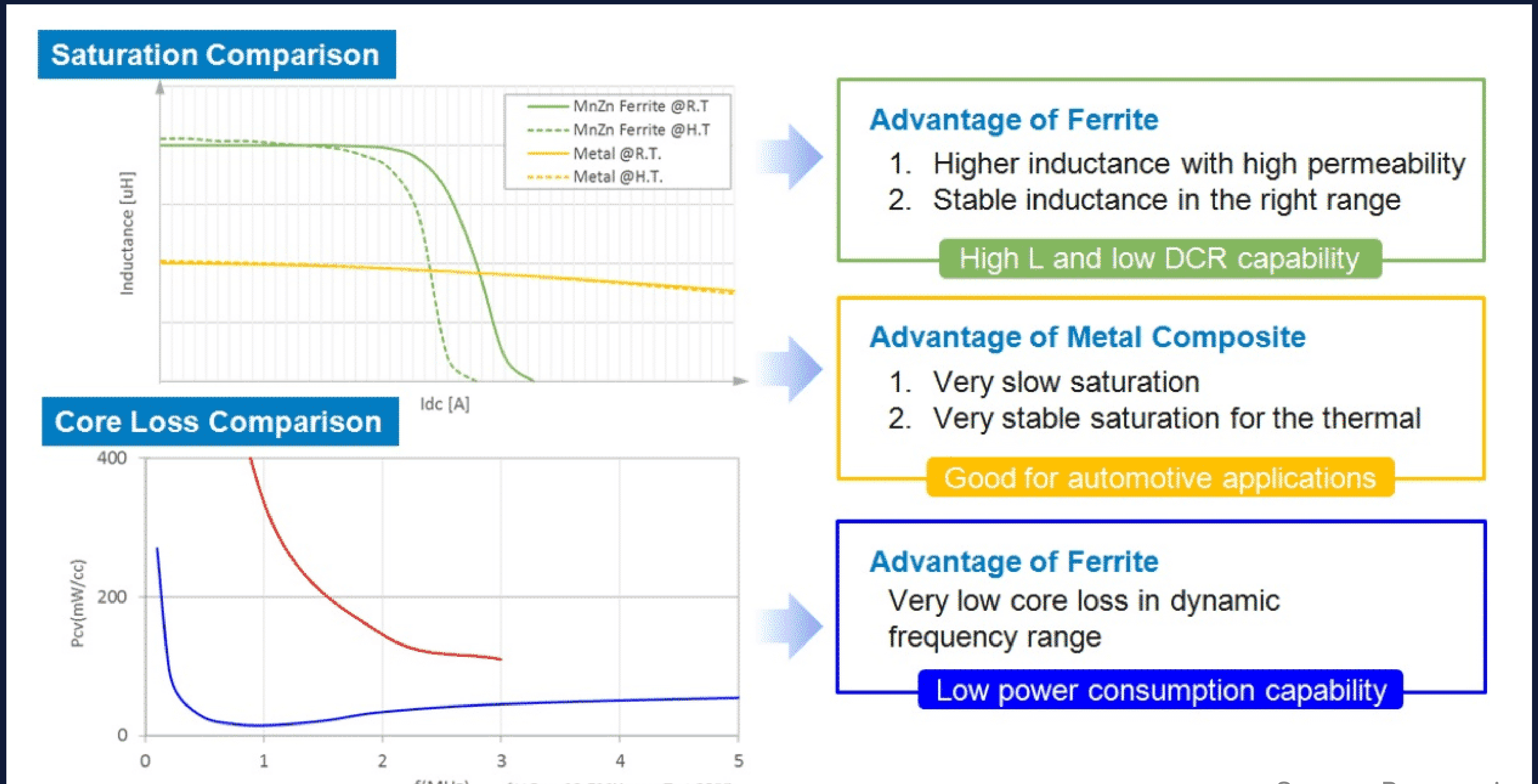
Inductors

New nano-crystal metal composite magnetic materials featuring high saturation, temp stability





Flat wire MnZn ferrite core construction increases saturation currents up to 25% at low core losses



Source: Panasonic

Inductor Technology	Inductance	Magnetic Saturation	Thermal TC	Efficiency	DCR	Insulation Resistance to Core
Metal Composite	Low	Very Good (Soft)	Verry Good	Good	Low to Medium	Good
Ferrite (Mn-Zn)	High	Not as Good (Hard)	Not as Good	Very Good	Low	Not as Good
Ferrite (Ni-Zn)	Medium	Good (Hard)	Good	Good	Lot to High	Very Good

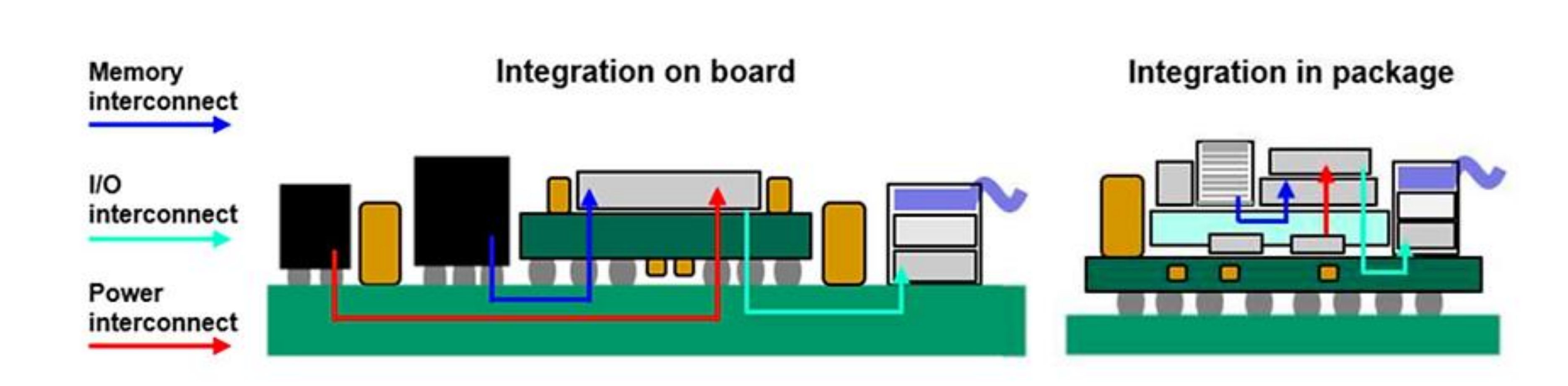
Source: KEMET YAGEO

4

Future of AI Power Delivery

Key Enabling Technologies
and Developments

Integration in package



Integration in package to reduces interconnect parasitics and losses, lower cooling force requirements.

MLCC capacitors drives the minaturization, but also novel silicon and wafer based integrated solutions are stepping-in.

Murata Expands Silicon Capacitor Production Line in France

7.10.2024 93

Murata Manufacturing Ltd has opened a new production line at its site in Caen, France, expanding the scope of its

Smoltek's New Zapping Method Accelerates CNF-MIM Capacitors Development

11.10.2024 45

Smoltek innovative "zapping" method drastically reduces development time and costs, enabling us to advance CNF-MIM silicon wafer based capacitor technology faster and making Smoltek Semi's technology even more attractive to

Murata Boosts Silicon Capacitance Density Beyond 1.3 µF/mm²

17.6.2021 37

Murata has extended its product offering for the mobile

Improving High Voltage Power Modules with new Silicon Snubber Capacitor Technology

10.10.2023 280

Full paper download Murata's new Silicon Snubber Capacitor technology offers solutions for high voltage power modules, enabling them to fully harness the benefits of wide band gap technologies by overcoming the issues ...

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Smoltek Boosts its CNF-MIM Capacitance Density by 230 percent

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Smoltek Nanotech Holding AB reports significant advances in wafer-based carbon nano-fiber CNF-MIM capacitor technology with a 230% boost in capacitance density through a new dielectric stack based on zirconium oxide. Smoltek Semi, ...

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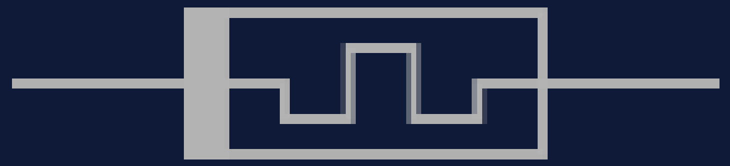
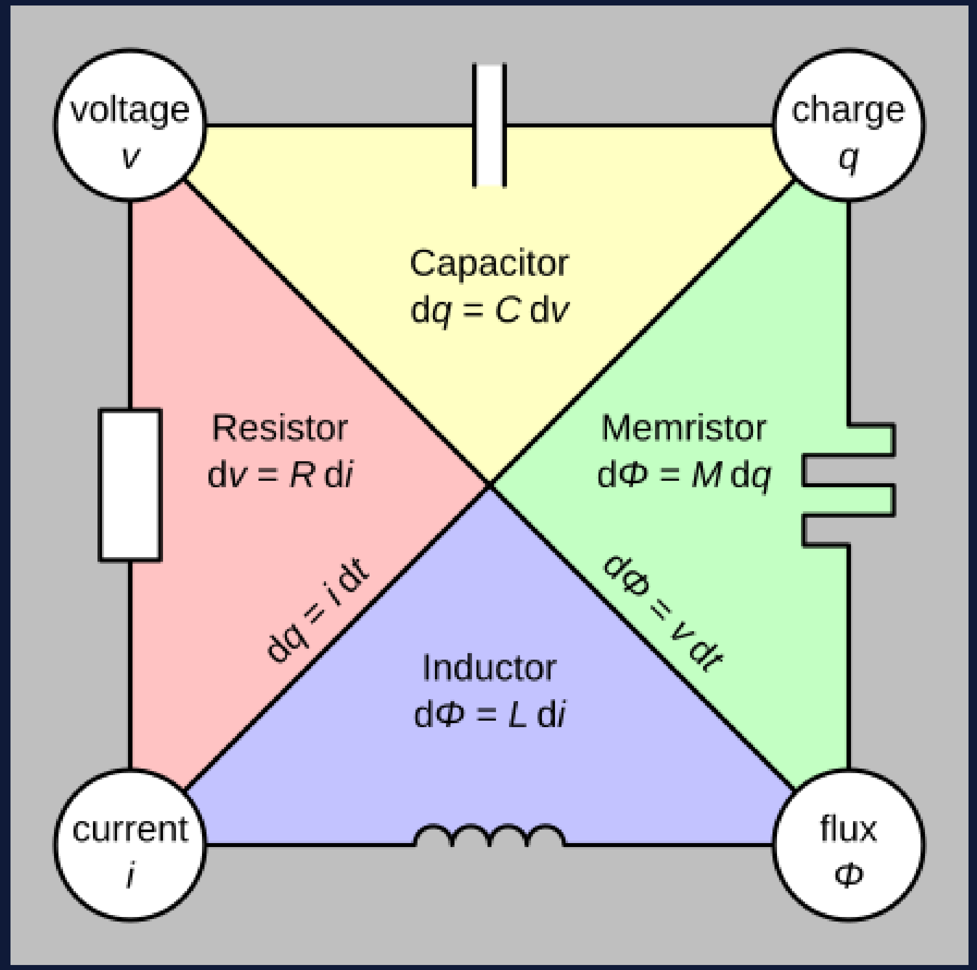
Memristor

“memory resistor,” is a two-terminal electrical component that regulates the flow of electrical current in a circuit and retains memory of the amount of charge that has passed through it.

When current flows in one direction, the resistance increases; when it flows in the opposite direction, the resistance decreases. This change in resistance is retained even after the current is turned off, hence the term "memory resistor"





It was described and named in 1971 by Leon Chua, completing a theoretical quartet of fundamental electrical components which comprises also the resistor, capacitor, and inductor

Typically, a memristor consists of a thin film of a material (like titanium dioxide) sandwiched between two metal electrodes. The resistance of this material changes based on the movement of ions or defects within it.

Data shuttling of conventional processors from memory to logic and back again takes a lot of energy and slows the speed of computing and requires a lot of space. If the computation and memory storage could be located in the same space, this bottleneck could be eliminated.

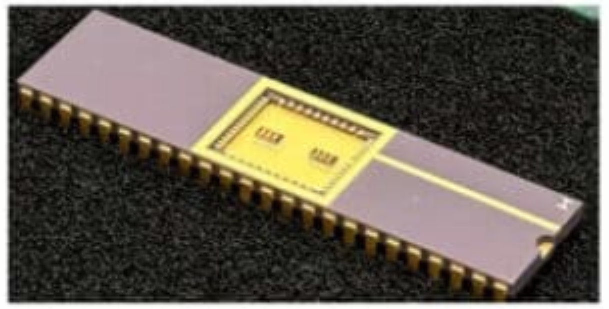
Memristors are proposed as memory elements in nanometre-scale logic for future brain-like networks.

Future of AI Power Delivery

- AI semiconductor development program, which fuses memristor and spintronics technology
- Spintronics: A technology that utilizes both the charge and spin of electrons or the spin element alone
- Novel “spin-memristor” can solve the reliability issues experienced with conventional memristors

TDK Develops Spin-Memristor for Neuromorphic Devices to Reduce AI Power Consumption to 1/100

3.10.2024 31



TDK develops "spin-memristor" for neuromorphic devices, and collaborates with CEA and Tohoku University to achieve practical application of neuromorphic devices able to reduce power consumption of AI down to 1/100. TDK Corporation ...

AI circuit board equipped with four spin-memristor ceramic packages

The human brain requires around 20 W of power, which enables it to make more complex decisions than current digital AI processors, but with far lower power consumption. Therefore, TDK set itself a goal to develop a device that electrically simulates the synapses of the human brain: the memristor.

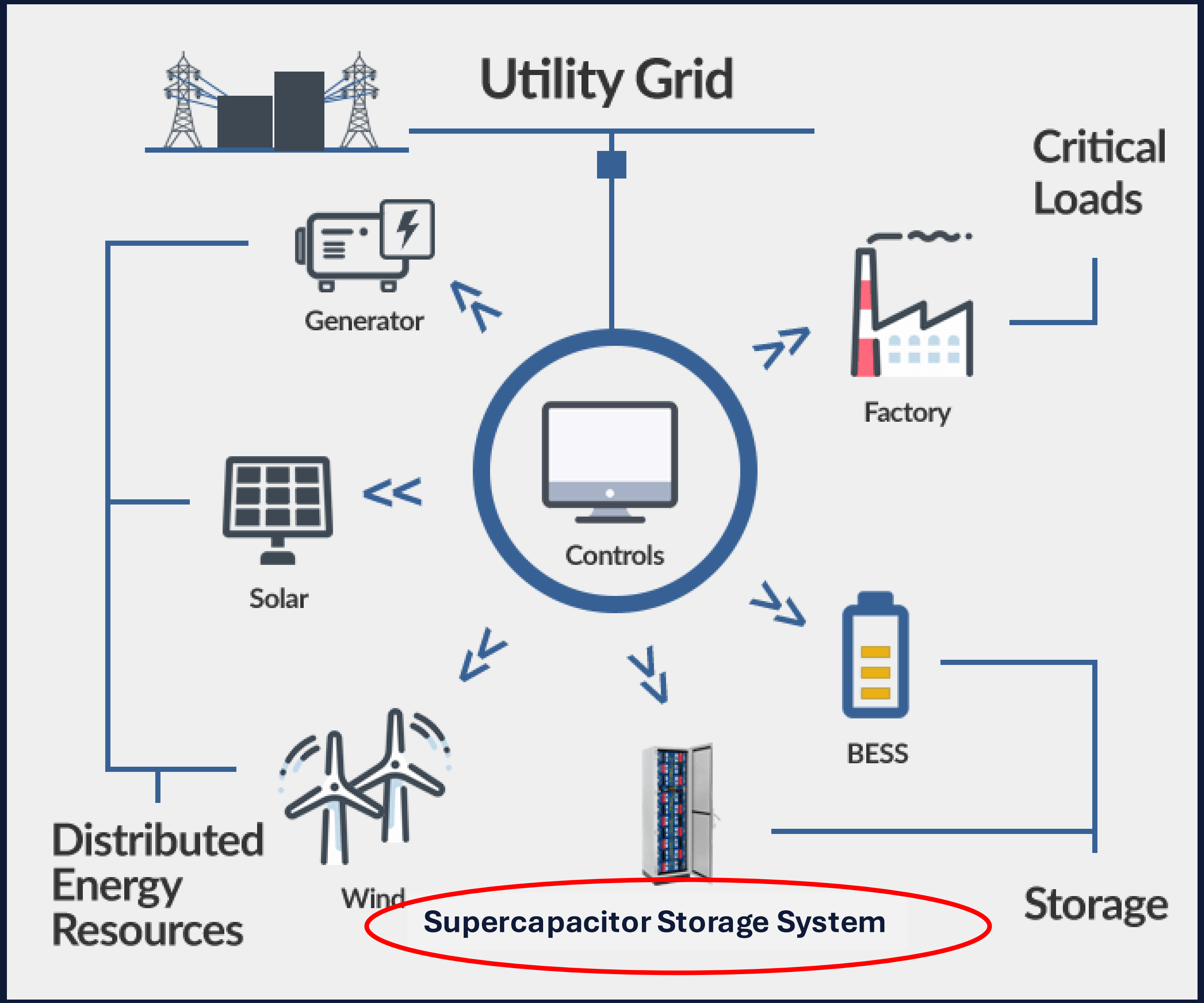
https://passive-components.eu/tdk-develops-spin-memristor-for-neuromorphic-devices-to-reduce-ai-power-consumption-to-1-100/

Future of AI Power Delivery

Power Grid Stability

AI Induces Fast Transient Dynamics Challenges: The power grid must manage peak loads effectively. Sudden spikes in energy consumption due to AI operations can strain the grid, potentially leading to instability or the need for additional infrastructure.

Supercapacitor Based Power Grid Stability System



[Submitted on 9 Sep 2024]

The Unseen AI Disruptions for Power Grids: LLM-Induced Transients

Yuzhuo Li, Mariam Mughees, Yize Chen, Yunwei Ryan Li

Recent breakthroughs of large language models (LLMs) have exhibited superior capability across major industries and stimulated multi-hundred-billion-dollar investment in AI-centric data centers in the next 3-5 years. This, in turn, bring the increasing concerns on sustainability and AI-related energy usage. However, there is a largely overlooked issue as challenging and critical as AI model and infrastructure efficiency: the disruptive dynamic power consumption behaviour. With fast, transient dynamics, AI infrastructure features ultra-low inertia, sharp power surge and dip, and a significant peak-idle power ratio. The power scale covers from several hundred watts to megawatts, even to gigawatts. These never-seen-before characteristics make AI a very unique load and pose threats to the power grid reliability and resilience. To reveal this hidden problem, this paper examines the scale of AI power consumption, analyzes AI transient behaviour in various scenarios, develops high-level mathematical models to depict AI workload behaviour and discusses the multifaceted challenges and opportunities they potentially bring to existing power grids. Observing the rapidly evolving machine learning (ML) and AI technologies, this work emphasizes the critical need for interdisciplinary approaches to ensure reliable and sustainable AI infrastructure development, and provides a starting point for researchers and practitioners to tackle such challenges.

- With fast, transient dynamics, AI infrastructure features ultra-low inertia, sharp power surge and dip, and a significant peak-idle power ratio. The power scale covers from several hundred watts to megawatts, even to gigawatts. These never-seen-before characteristics make AI a very unique load and pose threats to the power grid reliability and resilience
- Shortage of motion generator devices resulting in power disruptions and increased risk of blackouts
- Battery energy storage systems are being implemented, however, faster / quicker stabilization may be needed
- Supercapacitor storage systems are needed to assist with fast voltage / current peak and frequency fluctuations

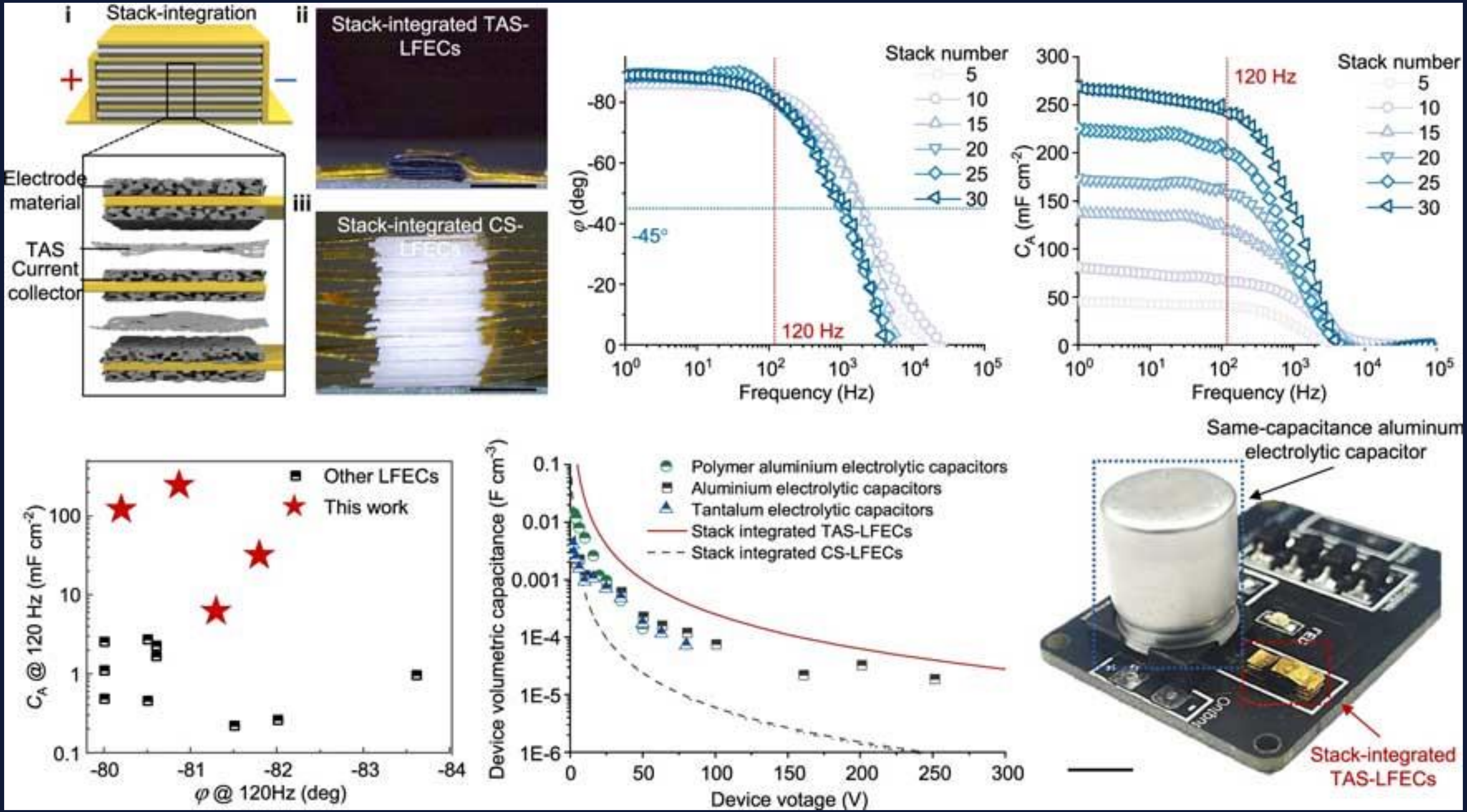
Supercapacitor Based Power Grid Stability System

•Skeleton Sustainable AI goals:

- Reduce the power connection required for AI data centres by 40% by handling fluctuating peak loads
- Reduce total electricity consumption in data centres by 1/3 by storing excess energy in supercapacitors, instead of overheating
- Increase computing power by up to 40%.

https://passive-components.eu/skeleton-supercapacitors-contribute-to-sustainable-ai/

Can Supercapacitors Replace Aluminum Electrolytics in Line Filters (~120Hz) ?



https://passive-components.eu/supercapacitor-separator-with-high-ionic-conductivity-enables-line-filter-applications-at-high-power/

Summary

AI is Driving Current Electronic Market

AI GPU Power Requirements > 700W

Challenging AI Power Management

Power Loss Suppression

48V power rack

Low loss components

Wide gap semiconductors

New Electronic Components

High performance @48V

Low loss, low ESR

Temperature and Life Stability

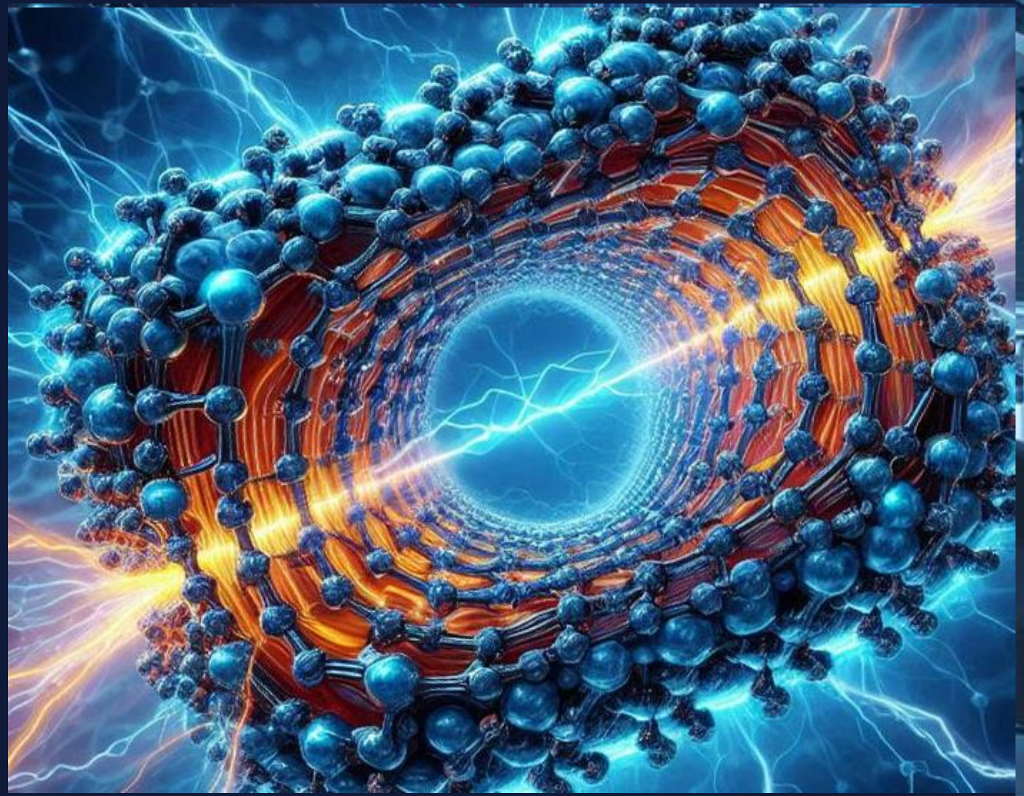
Future Developments

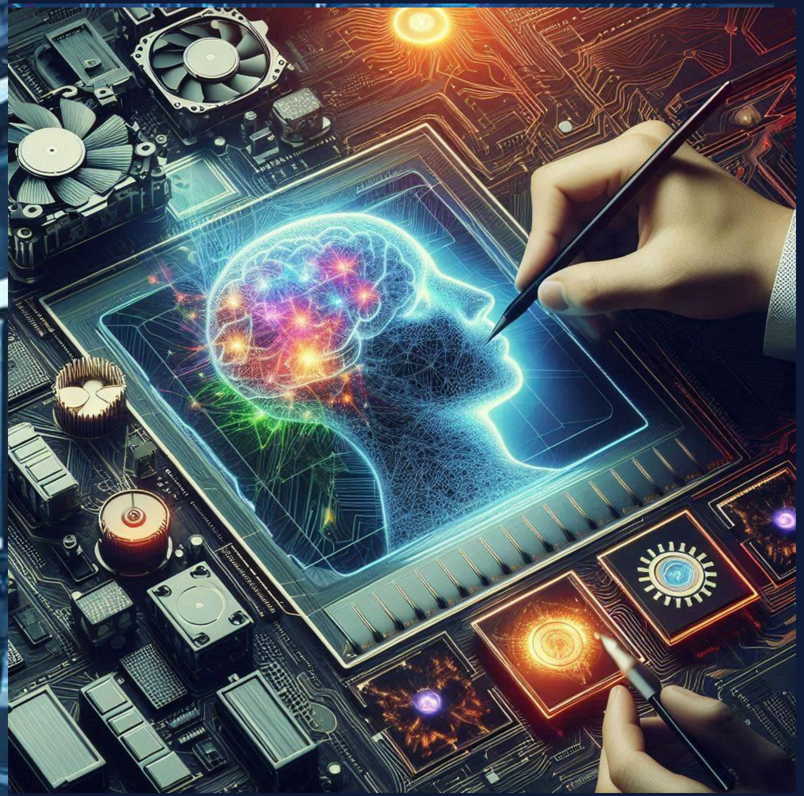
Ongoing miniaturization

On chip integrated solutions

New neuromorphic architecture

Power quality challenges





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