AI Hardware Development and Its Consequences for Passive Electronic Components

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1. ABSTRACT

The rise of artificial intelligence (AI) has brought about a technological revolution, with its impact felt across various industries. However, this advancement comes with a significant energy cost, particularly within data centers that power AI operations. Power management is a critical concern in data centers that directly impacts thermal management and overall efficiency. One of the key advancements is the development of new power supply topologies. These innovative designs are crucial for enhancing power delivery and reducing waste. The transition from traditional 12V to 48V power distribution allows for a substantial reduction in power losses.

Passive components made a lot of progress towards new technologies for processor coupling, 48V power system, and increasing power rating characteristics. They must further adapt to architecture changes.

The paper will discuss changes and challenges of AI systems and its consequences to the selection of passive components. The progress will be demonstrated especially on the example of the fast development of MLCC ceramic capacitors to meet the fast-evolving requirements.

2. INTRODUCTION

As artificial intelligence (AI) accelerates into a new era of computational intensity and real-time decision making—from hyperscale data centers to edge deployments—the supporting electronic infrastructure faces unprecedented challenges. The rise of AI has brought about a technological revolution, with its impact felt across various industries. However, this advancement comes with a significant energy cost, particularly within data centers that power AI operations. While much attention has focused on AI processors and active accelerators, the passive electronic components (e.g., MLCCs, inductors, resistors) that underpin power delivery, signal integrity, and thermal management are equally crucial.

Our discussion addresses evolving power architectures (e.g., 48V systems), advanced memory interfaces (DDR5, MRDIMM), and next-generation component-level solutions such as U2J-based MLCCs, advanced inductor construction, and precision resistor technologies—all crucial in supporting AI's high density, high-frequency, and high-energy-demand environments.

The rapid evolution of AI is not merely about scaling up processor cores or deploying larger models—it is fundamentally changing power infrastructures. AI data centers now consume energy at rates up to eight times higher than conventional facilities, with future consumption predicted to swell dramatically. Alongside cloud-based AI accelerators, edge devices and on-die integration are placing severe demands on passive components. Capacitors, inductors, and resistors now operate under extreme transient conditions, requiring ultra-low parasitic and exceptional thermal stability.

3. EVOLUTION OF AI HARDWARE ARCHITECTURES

3.1. Specialized AI Compute Engines and Processor Coupling

Recent advances have seen a shift from general-purpose CPUs/GPUs toward specialized accelerators such as Google's TPU, AWS's Trainium, and Microsoft's Athena. These processors utilize domain-specific architectures with advanced coupling mechanisms to maximize instruction-level parallelism and throughput [10]. In parallel, Arm-based designs fabricated on TSMC's 3nm node achieve power reductions of 30–40% compared to legacy x86 systems [10][11]. Such advancements demand passive components capable of coping with high switching frequencies and tighter voltage margins in power delivery networks.

3.2. Performance and Thermal Power Boost

The latest Nvidia AI GPU architecture is Blackwell, and its top-tier models—like the B100, B200, and GB200 Grace-Blackwell Superchip—are pushing the envelope in both performance and power draw. These chips are designed for massive AI workloads and feature dual compute dies with high-bandwidth memory (HBM3e), delivering up to 20 petaflops of compute power.

In terms of thermal design power (TDP):

Blackwell GPUs already exceed 1kW, and future generations like Rubin and Feynman are projected to triple or even quintuple that figure. In addition, it shall be noted that the whole server system consists of more GPUs, so for example, the DGX B200 system (with 8 Blackwell GPUs) has a TDP of around 14.3 kilowatts in total.

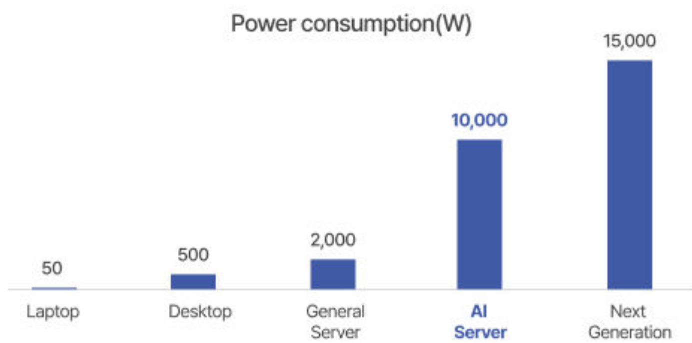

Figure.1. Power consumption comparison of PCs, servers and AI servers; source: Samsung Electro-Mechanics

Blackwell Ultra represents a significant improvement over its predecessor. A single 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 has also increased by 50% to 288 GB, thanks to a 12-layer HBM3e stack rather than eight layers. Additionally, the system employs advanced water cooling, and ConnectX 8 network cards enhance interconnectivity. The optical modules have been upgraded from 800G to 1.6T networking. For power management, the NVL72 rack configuration features a standard capacitor tray, optional Battery Backup Units (BBU), and more than 300 supercapacitors per rack. Furthermore, the GB300 combines a Grace CPU with the Blackwell Ultra GPU, marking the first server implementation of LPCAMM memory.

3.3. Memory Systems: DDR5 and MRDIMM

Memory performance is a key bottleneck in AI systems. Transitioning from DDR4 to DDR5 yields up to a 163% increase in speed and 300% higher density, compressing voltage tolerances and raising current transients [8][13]. Moreover, emerging MRDIMM (Multiplexed-Rank DIMM) technologies target high-core-count processors by delivering as much as 39% increased bandwidth and 40% lower latency compared to traditional RDIMMs [15][17]. These advances necessitate robust decoupling networks using high-performance MLCCs and other capacitors to curb voltage droops and noise under rapid current changes.

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. This changes the rail from input on the DDR memory from below 1.2V to 12V and in consequence selection of the DDR input capacitors. Typically 10uF/6.3V MLCC / Tantalum capacitors in DDR4 – migrate to 25V capacitors – such as 22uF MLCC (10uF effective) / 25V now available in 0805 MLCC case size – See Figure 2.

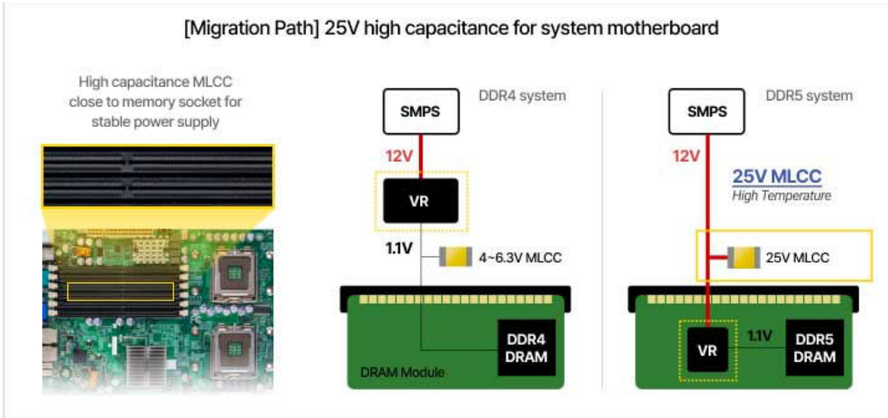

Figure 2. DDR4 to DDR5 regulator integration and input voltage / capacitor changes; source: Samsung Electro-Mechanics

4. AI SYSTEM-LEVEL POWER MANAGEMENT STRATEGIES

Adaptive Voltage Scaling (AVS) and Dynamic Voltage and Frequency Scaling (DVFS) have become pivotal in optimizing power efficiency in AI systems. AVS algorithms utilize in-chip monitoring to track timing margins and adjust supply voltages in real time, achieving power savings of up to 14% with minimal performance impact. This approach is complemented by highly responsive decoupling networks that maintain voltage stability despite rapid load fluctuations.

DVFS dynamically modulates operating frequencies and voltages based on workload demands, offering a critical strategy for reducing energy consumption without compromising throughput. For example, experiments training BERT models have demonstrated energy savings of 12–15% with negligible effects on training duration.

Grid-level energy stabilization is another crucial aspect of AI power management. Supercapacitor arrays and passive energy storage systems play a vital role in stabilizing power delivery during transient load spikes, particularly in data centers integrating renewable energy sources. These systems ensure overall grid stability, reducing the risk of voltage excursions even as AI workloads fluctuate.

4.1. Thermal Design, Cooling Innovations, and Material Challenges

As AI chips approach power densities exceeding 1 kW per chip, traditional air-cooling methods have become inadequate. Advanced cooling solutions, such as Direct Liquid Cooling (DLC) and immersion cooling, have emerged as effective alternatives. DLC systems circulate coolant directly to the hottest components, while immersion cooling submerges entire systems in thermally conductive liquids. These methods not only enhance component performance but also influence the design parameters for nearby passive components, ensuring reliable operation at elevated temperatures.

Predictive thermal management has also gained traction, leveraging machine-learning-based models to forecast on-chip temperature variations with remarkable accuracy. These models enable preemptive adjustments in cooling strategies and power distribution, mitigating thermal stress and prolonging component lifespan. The integration of predictive thermal management with passive component design is essential for maintaining system reliability in high-performance AI environments.

4.2. 48V Power Supply Topology

One of the key advancements is the development of new power supply topologies, including the increase of the main power rack voltage. These innovative designs are crucial for enhancing power delivery and reducing waste. The transition from traditional 12V to 48V power distribution allows for a substantial reduction in power losses. 48V power rack architecture energy savings can reach above 30% in less conversion losses and 16x less power distribution losses.

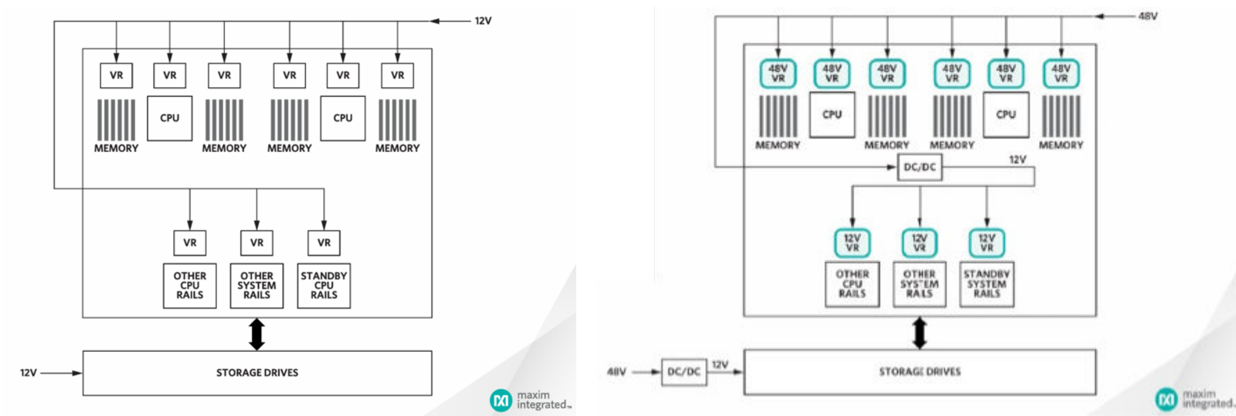

Figure 3. Comparison of 12V AI power power architecture (left) with 48V (right); source: Maxim Integrated

4.3. 800V Power Supply Topology

The rapid expansion of AI workloads is increasing the power demands of data centers. Traditional 48-54 V in-rack power distribution, which was designed for kilowatt (KW)-scale racks, is inadequate to support the megawatt (MW) - scale racks that are expected to be introduced in modern AI factories. NVIDIA is spearheading the transition to 800 VDC data center power infrastructure to accommodate 1 MW IT racks and beyond, with the implementation starting in 2027. To expedite this transition, NVIDIA is collaborating with key industry partners across the data center electrical ecosystem, including silicon providers, power system components and data center power system suppliers.

This initiative aims to drive innovations that will establish high-efficiency, scalable power delivery for next-generation AI workloads, thereby ensuring greater reliability and reducing the complexity of the infrastructure.

Key efficiency gains of 800V power infrastructure

- Up to 5% improvement in end-to-end power efficiency
- Maintenance costs reduced by up to 70% due to fewer PSU failures and lower labor costs for component upkeep
- Lower cooling expenses from eliminating AC/DC PSUs inside IT racks
- Cost reductions in copper usage and thermal losses across the data center backbone.

Figure 4. NVIDIA 800 VDC architecture minimizes energy conversions; source: NVIDIA [21]

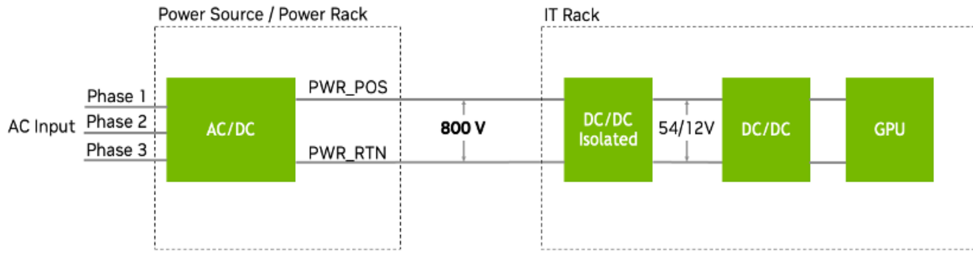

Figure 5. 800 VDC distribution to IT racks and DC/DC conversion to 12 V for GPUs; ; source: NVIDIA [21]

4.4. Signal Integrity in High-Speed AI Infrastructures

Maintaining signal integrity in high-speed AI infrastructures is a significant challenge, particularly with the adoption of multi-chip modules and chiplet architectures. PAM4 signaling, which doubles data rates compared to NRZ, reduces voltage margins and increases the risk of crosstalk. Precision passive components, such as controlled ESR resistors and tuned capacitor-resistor networks, are deployed to address these challenges.

Advanced validation and testing methodologies are critical for ensuring the performance of passive networks in high-speed systems. Techniques such as jitter decomposition and eye diagram analysis, performed using digitizing oscilloscopes and integrated logic analyzers, help meet the stringent requirements of modern AI infrastructures.

5. PASSIVE COMPONENT ENGINEERING IN AI SYSTEMS

As AI systems evolve, advanced passive component technologies have emerged as a cornerstone of this transformation.

5.1. Capacitor Technologies

Multilayer Ceramic Capacitors (MLCCs) are now engineered to meet the extreme demands of modern AI processors. These capacitors exhibit ultra-low equivalent series resistance (ESR) and inductance (ESL), ensuring voltage stability during rapid current transients.

Leading manufacturers Murata and Samsung Electro-Mechanics (SEMCO) have been promoting its MLCC innovation, developing high-capacitance models tailored for AI server applications. For instance, high capacitance 0402-inch, 47µF and 0603-inch, 100µF MLCCs are designed to support high-current transients and maintain low ESR/ESL performance. These components are particularly effective for near-die decoupling in high-density AI processors, such as those utilizing Nvidia’s Blackwell GPUs.

The transition to 48V power rack voltage in AI servers has further driven the need for advanced MLCCs. 100V-rated MLCCs today offer high capacitance and thermal stability, reducing conversion losses in power delivery networks and supporting point-of-load (PoL) converters near AI chips. Additionally, automotive-grade MLCCs, originally designed for high-temperature 48V environments, are now being adopted in ruggedized AI systems and edge devices.

Robust 800V working voltage passive components must be prepared or enhanced to assist data center infrastructure in managing load spikes and subsecond-scale GPU power fluctuations, as part of the upcoming 800V DC main power supply architecture. The 800V operational voltage is an optimal operating point for the application of wide-gap semiconductors like SiC or GaN ICs. These wide-gap semiconductors operate at higher frequencies, lower resistance, and higher current capabilities, which presents challenges for the robustness and precise transient/EMI suppression passive components.

Snubber capacitors are a typical example of components in the 800V architecture that must contend with such SiC/GaN-induced transients. Figure 6 illustrates the increase in transient spikes as we move from conventional Si IGBTs to SiC MOSFET ICs, making the job of snubber capacitors more difficult and challenging.

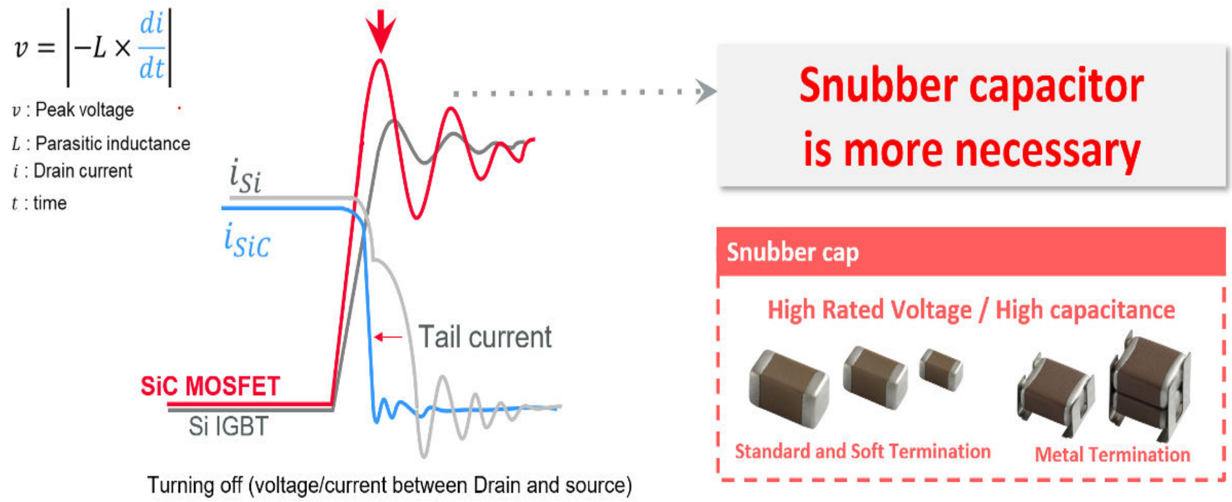

Figure 6. SiC MOSFET induced high surge transient vs Si IGBT; source: Murata

Overcurrent protection components and safety capacitors, as passive components, must be capable of addressing the challenges posed by the 800V AI main power systems.

High-Performance Decoupling Capacitors

Decoupling capacitors are crucial in AI hardware, acting as local power reservoirs that instantly store and release current to stabilize power supply voltage and minimize noise during rapidly fluctuating loads. As AI chips demand more power, traditional capacitor placement strategies face growing challenges.

Emerging technologies, such as **Silicon Capacitors**, address these demands effectively. Silicon capacitors with ultra-low equivalent series inductance (ESL) of just 1 picohenry and equivalent series resistance (ESR) below 3 milliohms have emerged as critical solutions for achieving the precise voltage regulation that AI chips require. For instance, Empower Semiconductor's EC1005P offers ultra-low impedance up to 1 GHz, ideal for high-performance computing and AI applications. These capacitors possess near-ideal parasitic parameters, enhancing power delivery efficiency to AI processors.

Innovative designs also integrate capacitors directly into processor package substrates. Startups like Saras Micro Devices develop embedded capacitor tiles within the organic substrate of processors, minimizing parasitic inductance and resistance, thereby improving performance.

Low ESR vs. Controlled ESR Applications

While low equivalent series resistance (ESR) is often preferred in capacitors, controlled ESR values can be advantageous in specific AI applications. In switching power source output decoupling, extremely low ESR may cause phase lag in feedback circuits, leading to poor load responsiveness or oscillation.

This may be an ideal position for **Polymer Tantalum and Aluminum Electrolytic Capacitors.**

The latest advancements in polymer tantalum capacitor technology have led to the extension of operating voltages up to 63V, 75V, and above. These capacitors provide remarkable high capacitance and superior stability with high energy density, all within a compact design. This makes them ideally suited for emerging 48V power rack systems, ensuring efficient performance and space optimization in modern power applications.

For CPU decoupling circuits operating at low voltage and high current, low ESR might negatively impact system stability. Carefully controlled ESR values help prevent parasitic oscillations, ensuring stable operation. AI hardware typically employs a combination of capacitors: large bulk capacitors mitigate noise at lower frequencies, while small, high-frequency capacitors handle rapid current fluctuations.

Energy Management

Supercapacitors have gained prominence in AI infrastructure for their ability to handle rapid energy bursts and provide grid stability during dynamic AI workloads. Modern supercapacitors demonstrate charge/discharge efficiencies exceeding 95% and unlike batteries they can endure millions of cycles with minimal degradation.

The integration of supercapacitors into AI data center infrastructure addresses the synchronized energy spikes created by thousands of GPUs operating simultaneously. Advanced supercapacitor systems can handle up to 75 megawatts per unit with lifespans of 12 to 20 years, providing millisecond-scale power support at the data center level.

5.2. Inductor Technologies

Inductors in AI data centers must carry high currents while maintaining low DC resistance and core losses. Innovations like single-turn, flat wire ferrite inductors support up to 53 A with minimal DC resistance (as low as 0.32 mOhms). Composite core inductors exemplify modern inductor technology for AI, featuring low core loss and efficient, flat-wire designs suitable for high switching frequencies. To meet escalating demands for power density, inductor technologies evolve through advanced core materials, novel winding techniques, and improved thermal management, enabling higher currents, faster transient responses, and better thermal performance.

Single-turn inductors are gaining traction in AI hardware design because they offer exceptional current handling, low losses, and compact integration —all critical for the high-density, high-efficiency power delivery networks that AI systems demand. Here's why they're a smart fit:

- Ultra-High Current Capability: A single-turn inductor, often made from a thick copper trace or bar, can carry hundreds of amps with minimal resistive loss. This is ideal for AI accelerators like Nvidia's GB200 or AMD's MI300X, which require massive transient currents during peak compute loads.
- Low DC Resistance (DCR): With only one turn and a large conductor cross-section, these inductors exhibit extremely low DCR, minimizing I^2R losses and improving overall power efficiency—especially important in 48V-to-PoL (point-of-load) conversion stages.
- Minimal Core Loss: Many single-turn inductors are "coreless" or use low-loss magnetic materials, which reduces core hysteresis and eddy current losses at high switching frequencies. This is crucial for AI systems operating at MHz-range switching speeds.
- Thermal Simplicity: Their simple geometry and low resistance make them easier to cool. In high-power AI servers, this translates to "better thermal management" and reduced risk of hot spots near critical components.
- Compact and Customizable: single-turn inductors can be integrated directly into PCB layers or mounted as planar copper shapes, saving board space and enabling tight coupling with power stages. This is especially useful in AI accelerator cards where every millimeter counts.
- Mechanical Robustness: Their solid construction makes them resilient to vibration and thermal cycling, which is valuable in ruggedized AI edge systems or automotive AI modules.

Composite inductors are particularly well-suited for AI hardware due to their exceptional combination of high current handling, low core losses, and compact form factors—all crucial for the demanding nature of modern AI systems. Here's why they excel in this domain:

- High Saturation Current:AI processors like Nvidia's Blackwell or AMD's MI300X draw substantial transient currents. Composite inductors, particularly those utilizing metal powder cores, can handle higher saturation currents without magnetic saturation, ensuring stable power delivery during peak loads.
- Low Core Loss at High Frequencies: AI workloads often rely on high-frequency switching regulators to enhance power efficiency. Composite materials, such as iron-based or amorphous metal powders, exhibit lower core losses at these frequencies compared to traditional ferrite cores, thereby reducing heat generation and improving overall efficiency.
- Thermal Stability: AI servers operate in thermally demanding environments. Composite inductors maintain stable inductance and low DCR (DC resistance) even at elevated temperatures, which is vital for maintaining voltage regulation and minimizing power loss.
- Compact Size and Integration: With AI systems pushing for higher density, composite inductors can be manufactured in smaller footprints while still delivering high performance. This enables closer placement to power-hungry chips, reducing parasitic losses and enhancing transient response.
- EMI Suppression: Composite materials naturally dampen high-frequency noise, making these inductors effective at electromagnetic interference (EMI) suppression—a growing concern in densely packed AI boards with high-speed signaling.
- Design Flexibility: Suppliers like Vishay, Murata, TDK, Wuerth Elektronik or YAGEO offer composite inductors in a wide range of shapes, sizes, and electrical characteristics, allowing engineers to fine-tune power delivery networks for specific AI workloads and thermal envelopes.

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

Table 1. Inductor technology features comparison; source: YAGEO Group

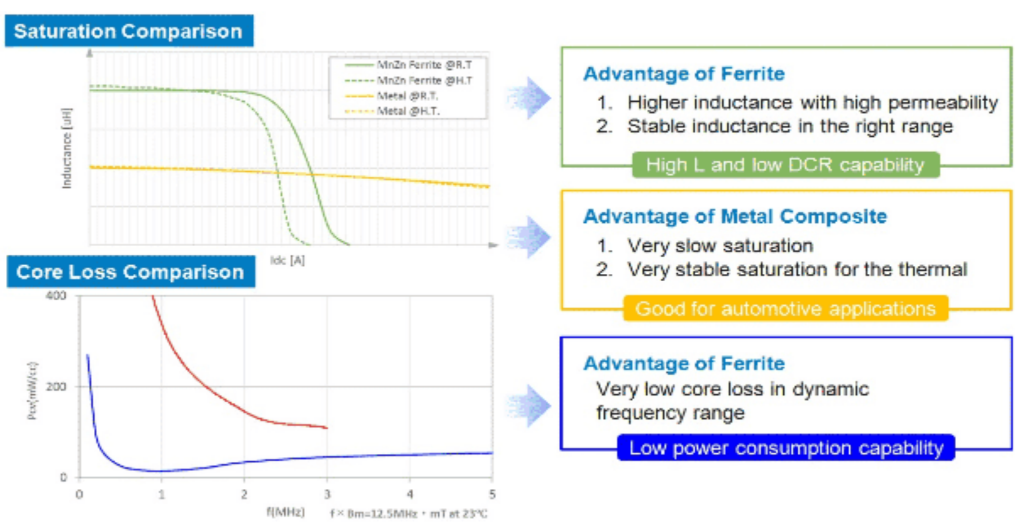

Figure 7. Saturation and Core Loss comparison of ferrite and composite inductor core materials; source: Panasonic

5.3. Resistor Technologies

Precision and Tolerance Specifications

Modern AI hardware systems demand unprecedented precision from resistor components, with tolerance requirements becoming increasingly stringent. Precision **thin-film resistors** with tolerances of 0.1% or tighter and Temperature Coefficient of Resistance (TCR) values of 25 ppm or better have become standard in AI applications. These tight specifications are essential for maintaining computational accuracy in analog deep learning systems where small variations can significantly impact neural network performance.

The evolution toward higher precision has been driven by the need for consistent performance across multiple processing cores and the requirement for reliable analog-to-digital conversions in AI accelerators. Metal film resistors have emerged as the preferred technology for AI applications due to their superior stability, low noise characteristics, and ability to maintain accuracy across varying environmental conditions.

Power Handling and Thermal Management

AI chips present unique thermal challenges, with power densities reaching extreme levels that require specialized resistor technologies. Modern AI systems can approach power consumption levels of 900A (~700W), creating significant thermal stress on all electronic components. This has driven the development of high-power thin film chip resistors that can withstand harsh environments while maintaining precision specifications.

The thermal management requirements have led to innovations in resistor construction, including improved heat dissipation mechanisms and materials that maintain stable performance across wide temperature ranges from -40°C to 80°C. Temperature compensation circuits have become essential to maintain computational accuracy as AI systems operate under varying thermal conditions.

Noise Characteristics and Signal Integrity

Noise performance has become a critical specification for resistors in AI hardware systems, particularly in high-gain amplifiers and low-level signal processing applications. Thermal noise, represents the primary source of noise in resistors and directly impacts AI system performance.

Thin film, metal foil, and wirewound resistors demonstrate superior noise characteristics compared to thick film alternatives, making them preferred choices for AI applications where signal integrity is paramount. The selection of low-noise resistors becomes especially critical in the input stages of AI processing systems where any noise will be amplified throughout the signal chain.

As AI systems adopt advanced modulation schemes like PAM4 to boost data rates, requirements for resistor precision and stability intensify. PAM4 doubles data rates compared to NRZ but reduces voltage margins, increasing susceptibility to noise and signal degradation, thereby demanding even stricter resistor specifications.

Miniaturization and Integration Challenges

The push toward miniaturization in AI hardware has created new challenges for resistor manufacturing. Modern chip resistors are being designed for sizes ranging from 0402inch (0.04inch × 0.02inch) to larger form factors, with **improved power ratings and TCR characteristics** achieved through optimized internal structures and new materials.

Process and temperature compensation circuits have become necessary to maintain accuracy in miniaturized **resistor arrays**. These compensation systems can provide temperature coefficients between 10 and 1938 ppm/°C across wide operating ranges, reducing output current variations by up to 84% in resistive in-memory computing arrays.

Programmable Resistors and Analog Computing

The most significant evolution in resistor technology for AI applications has been the development of programmable resistors that serve as the foundation for analog deep learning systems.

The integration of **memristor technology** with traditional resistor functions has created new paradigms for AI hardware acceleration. Memristive devices combine memory and computing functions, enabling in-memory processing that dramatically reduces power consumption and increases computational throughput.

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". 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.

Memristors are proposed as memory elements in nanometer-scale logic for future brain-like networks, nevertheless despite decades of research and significant advancements, memristors have yet to achieve maturity for mass production. A combination of persistent technical hurdles, material science complexities, and economic realities continue to relegate this potentially revolutionary technology to research labs and niche applications.

The impact of neuro-like architecture to reduction of AI power consumption can be significant. TDK in co-operation with Tohoku university recently announced [20] achievement of neuromorphic AI device with just 1/100 of typical AI power consumption using "spintronic memristor effect".

6. CONCLUSION

In conclusion, the rapid evolution of artificial intelligence (AI) has significantly transformed the technological landscape, bringing both remarkable advancements and substantial challenges. The increasing computational demands and energy consumption in AI data centers have necessitated the development of advanced power management strategies, including the transition to 48V rack power supply and 800V main power supply topologies and innovative cooling solutions. The role of passive components such as MLCCs, inductors, and resistors has become more critical, with continuous advancements required to meet the stringent demands of high-performance AI systems.

The integration of adaptive voltage scaling, dynamic frequency adjustments, and predictive thermal management has proven crucial in improving system efficiency and reliability. Moreover, the development of new materials and technologies for passive components, including high-capacitance MLCCs, transient, high-current surge and pulse robust components, advanced inductor designs, and precision resistors, highlights the necessity for continuous research and innovation.

Ultimately, as AI systems continue to evolve, a multidisciplinary approach involving power architecture optimization, thermal management, and passive component engineering will be essential. This synergy will support the sustainable growth of AI technologies, ensuring enhanced performance, energy efficiency, and system resilience for future applications.

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