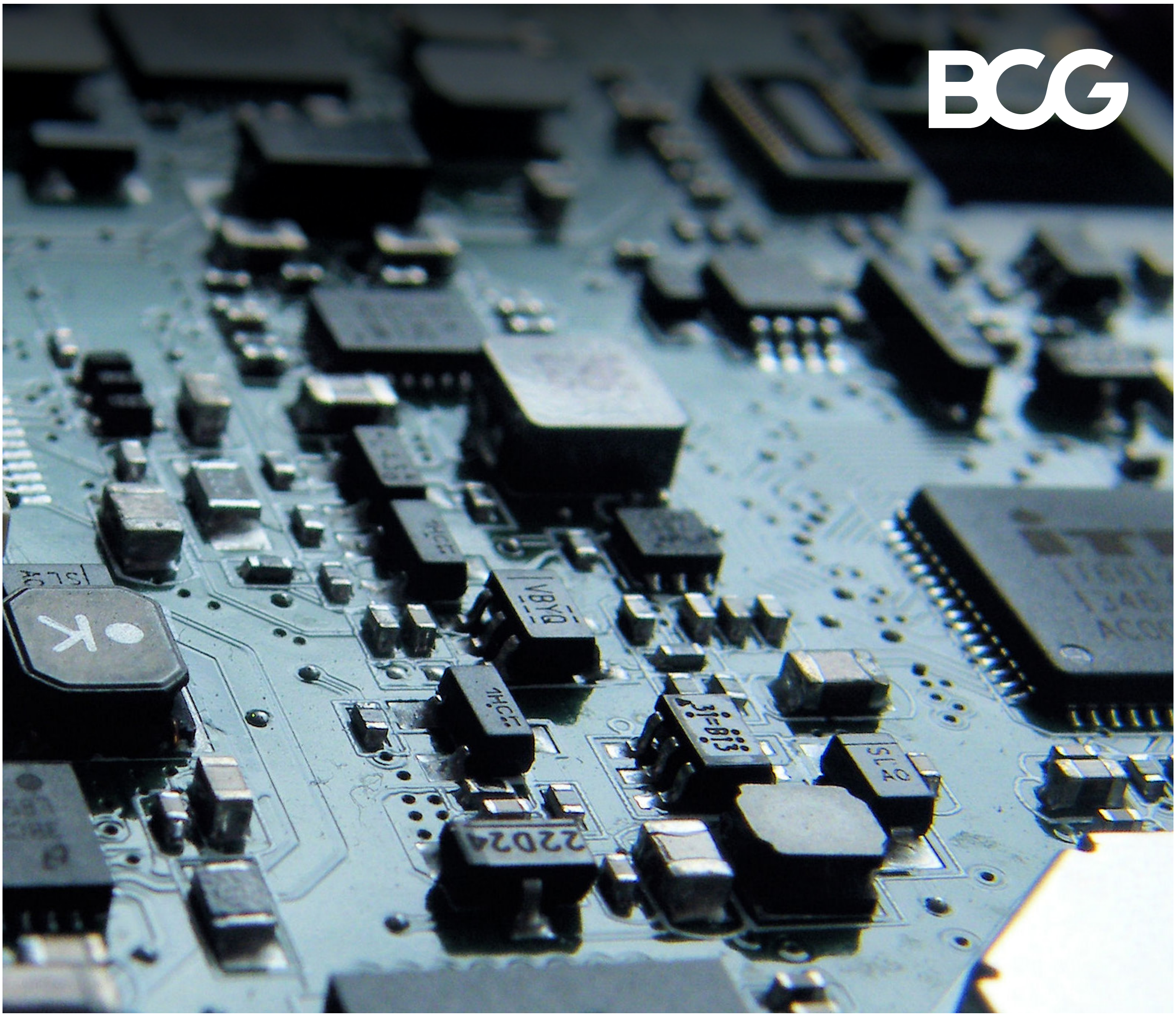


WHITE PAPER

The Future of Automotive Compute

Are Chiplet Systems a promising technology step on the path toward a centralized stack?

June 2023

At A Glance

A shift to software-defined cars is driving demand for automotive compute

With software-enabled use cases significantly increasing the demand for automotive compute chips, the auto industry is undergoing a shift in focus from hardware to software. As a result, the industry is evolving toward single centralized compute stacks within the electrical and electronic (E/E) architectures of cars.

Current state-of-the-art solutions come with trade-offs

To fulfill these increasing compute requirements, high performance compute (HPC) chips are needed as, now more than ever, automakers desire a resilient supply chain for tailored and modular System-on-Chips (SoCs), while chip suppliers need high volumes to recoup up-front research and development (R&D) efforts.

Multiple approaches are being considered on the path toward a single compute stack

To address these trade-offs on the path toward a single compute stack, the industry has multiple options to consider. These include a gradual migration toward a centralized E/E architecture with strong domain controllers, customized SoCs, and Chiplet Systems, among others.

Chiplet Systems are one approach being used to customize hardware designs for specific requirements

Disaggregating SoCs into functional Chiplets to form Chiplet Systems allows for both customization—for specific segments or models via higher modularity and scale—and a higher degree of integration by combining different node sizes on one chip, which is usable as bridging tech or even in future centralized compute stacks.

A new value chain dynamic can be enabled by an open ecosystem of Chiplet Systems

A Chiplet System's value chain contains new value pools with sizeable opportunities, as the Chiplet System leads to a disaggregation of value chain steps within the automotive compute market—which is expected to grow to ~$20 billion to $22 billion in 2030. If the value chain is covered in an open ecosystem, multiple new plays are enabled, including combining Chiplets from different suppliers.

Overall, the automotive compute industry may profit from new dynamics

Automakers, Tier-1 suppliers, and smaller chip suppliers without compute presence may profit from open Chiplet Systems, enabling them to be involved in chip development—potentially customizing automotive compute chips in an open ecosystem for increased supply chain resilience and a reduced risk of lock-in effects.

The Future of Automotive Compute

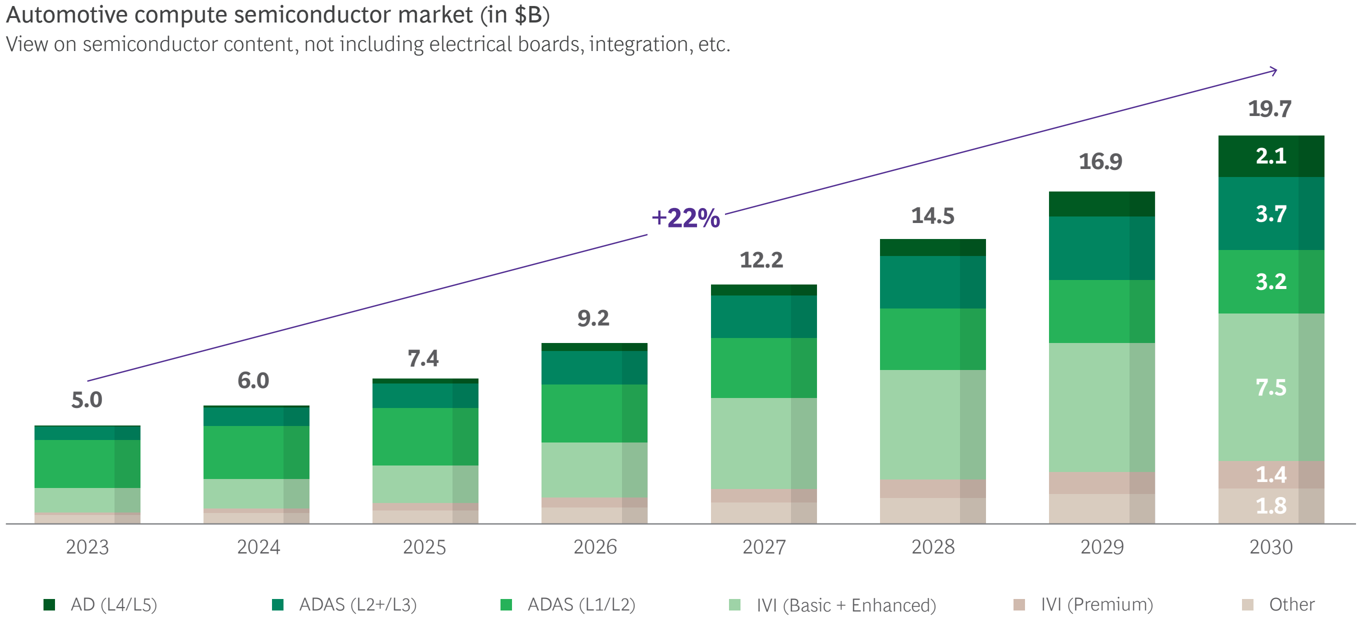
Shift to Software-Defined Cars Drives Demand for Automotive Compute

Currently, the automotive industry is undergoing tremendous change. Along with electrification efforts by all automakers globally, the automation of driving functions—which will eventually lead to fully autonomous vehicles—is one of the key global trends. We expect the share of light vehicle sales with Advanced Driver Assistance Systems (ADAS) functions of Level 2 or higher to reach about 50% by 2030, meaning that share is likely to double relative to 2022. Further advancements focus primarily on the cockpit, with the introduction of more virtual and digital use cases such as augmented reality and gaming.

The key to this trend is software. As outlined in Chasing the Software Defined Dream Car, software will continue to play a central role in automobiles, as it enables not only innovation but also differentiation among Original Equipment Manufacturers (OEMs)—and also has an outsized influence on customers' purchase decisions.

To enable these complex software features, more and more powerful chips are required, which will lead to a strong growth—with an expected Compound Annual Growth Rate (CAGR) of 22% between 2023 and 2030—in the automotive compute semiconductor market, as shown in Exhibit 1.

Exhibit 1 - Automotive Compute Semiconductor Market Growing to ~$20 Billion in 2030[1]



Source: IHS Light Vehicle Forecast, BCG analysis
Note: Includes SoC, CPU, GPU, Chiplet-integrable memory, MCUs, etc.

1. Based on IHS automotive semiconductor market tracker 2022-11 filtered for automotive compute, which includes mainly SoCs but also GPUs, memory, etc.

The increased need for automotive compute power driven by a focus on software is also leading to an evolution toward more centralized E/E architectures. Coming from a network of 50–100 distributed Electrical Control Units (ECUs), the next step is architectures with domain controllers for each functional cluster (e.g., autonomous driving, in-vehicle infotainment). Hybrid architectures are combining this domain-based approach with zone hubs clustering information locally and sending it to a vehicle server. In purely centralized architectures, only zone hubs are used to collect edge-device data and send it to a central vehicle server.[2] In the long run, we expect the industry to shift toward a single compute stack in a centralized E/E architecture—including a mixed-criticality safety stack to account for automotive specific requirements—and will likely apply a horizontal layered approach in order to reach sufficient sales volumes.

Current State-of-the-Art Solutions Come with Trade-Offs

Since the automotive industry is, at any given time, evolving toward a centralized E/E architecture at different speeds, the requirements from automakers regarding automotive compute semiconductors—in particular, chips for vehicle computers—are diverse. Requirements may include a low time to market to adapt architecture and feature innovations quickly. Or automakers might prefer a broad offering of chip suppliers with ample choices to avoid lock-in effects and enforce a resilient supply chain. Further, updatability, exchangeability, and the availability of a software stack can reduce adaption and development efforts. Plus, automakers might express a wish for customization and envision having chips tailored according to their architecture choices and compute power needs. Thus, a modular and scalable solution is desired in order to realize different implementations (e.g., for different platforms or regions). In this way, only the necessary amount of compute power is integrated, possibly improving the cost per (necessary) performance. Also, customized compute chips may allow automakers to better differentiate themselves from their peers.

Chip suppliers, on the other hand, need to look at the automotive market from another point of view. The design of new chips comes with large R&D efforts in the range of several tens to hundreds of millions of US dollars. Since the prices of chips are limited by automakers' willingness to pay, in order to reach sufficient margins to recoup the up-front R&D efforts, large sales volumes are needed. Automotive sales, especially when looking at specific car models, have much smaller volumes than do other markets, such as consumer electronics. For example, in 2022, smartphone sales were more than 10 times higher than car sales, amounting to roughly 66 million units. Therefore, chip suppliers aim to maximize their sales volumes in the automotive industry to make this an attractive business case.

Multiple Approaches Are Being Considered on the Path Toward a Single Compute Stack

At this point, the industry has the opportunity to shape the path for automotive compute. Eventually, this decision will also be influenced by the E/E architecture implemented by the respective automakers, as certain architectures are better suited to specific compute solutions. In order to address the trade-off between cost, customization, scalability, modularity, availability of software stack, resilient supply chains, and time to market considerations, there are multiple approaches automakers and chip suppliers might consider, including:

2. The vehicle server does not have to be a single (physical) device and can be split up into several compute units.

1. Gradual migration with strong domain controllers

Some automakers are choosing to implement a gradual migration toward a centralized compute stack with strong domain controllers. Compute-intensive functional clusters are formed in such a manner, meaning that, for example, all ADAS functions are executed on one domain controller with a dedicated SoC. Different update times and cycles (per domain controller) can be acknowledged like this, and the adaption effort from a traditional E/E architecture with distributed ECU is lower than for the following options.

Taking this path, automakers may prefer a standardized compute solution that is in line with chip suppliers driving toward an industry setup of horizontal platforms and standardized SoCs. These chip suppliers also offer parts of a software stack (in the form of Software Development Kits (SDKs), etc.) to simplify development for automakers by reducing their R&D efforts.

2. Customized SoC

In a centralized E/E architecture (hybrid or purely centralized), automakers may prefer a more customized compute solution and therefore involve themselves in the design of SoCs for automotive compute. Even though these SoCs are typically based on existing designs, there is a significant effect on the value chain, since SoC design is a high-margin business (in the range of ~25%–35%). One example of this approach is Tesla taking an existing chip from Samsung and using it as a basis to replace an SoC from NVIDIA in its Autopilot hardware for the Tesla Model 3. In this way, Tesla can not only customize the design for strategic purposes, but also act as a fabless player and directly interact with a foundry, which cuts out the margin of the original chip supplier.

Despite this sizeable opportunity, chip design is a complex endeavor that requires large investments in R&D. To some degree, this can be mitigated by “simply” modifying existing designs, but many OEMs still hesitate to involve themselves in chip design due to the lack of capabilities and resulting business risk.

3. Chiplet Systems

Another approach to designing customized chips is disaggregating SoCs into single Chiplets and packaging them with advanced technologies. At first glance, this may appear to be a technological method for chip design, which can be leveraged by the traditional suppliers. However, this disaggregation may change the value chain, as the individual Chiplets could be developed and supplied by different players—thereby bringing in new plays and opportunities, especially when an open Chiplet ecosystem evolves. While in the long run this may come with many benefits for automakers, such as higher modularity and scale, there are also significant shortcomings regarding this technology if no solution is found (e.g., the potentially high costs of (advanced) packaging, the need for a Chiplet architecture, and common agreed-upon standards across the industry).

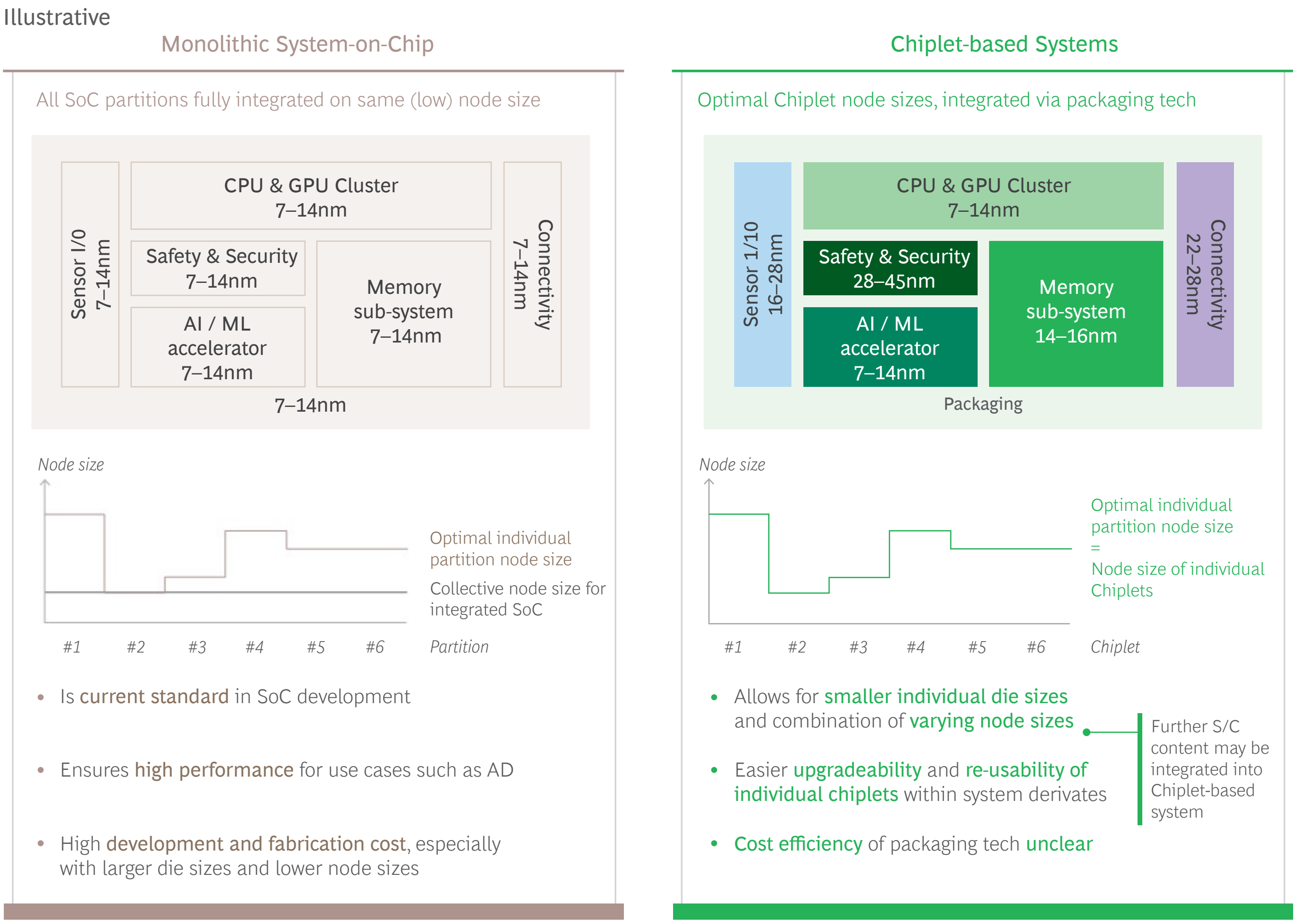
While none of these three approaches has yet emerged as the clearest path forward, this study takes a deeper look into the third approach, as Chiplet Systems are an option that has gained increased traction in the automotive industry of late.

Chiplet Systems as an Approach to Customizing Hardware Designs for Specific Requirements

The basis for Chiplet Systems is a technology trend from the semiconductor industry that is now slowly entering the automotive domain. Mercedes-Benz CTO Markus Schäfer, for example, recently announced that "the industry urgently needs high-performance, energy-efficiency, and cost-effective automotive-grade Chiplets."[3] Robert Bosch CEO Stefan Hartung recently also introduced adaptive chiplet systems for automotive at the ITF 2023.[4]

Instead of having all partitions of an SoC on a single die, in Chiplet Systems, the SoC is split into smaller units—called Chiplets—and combined with emerging high-performance packaging technologies such as 2.5D packaging (see Exhibit 2). This practice is already being used in applications such as for high-performance server chips and in consumer electronics (e.g., in AMD's Epyc 7002 ("Rome") or Apple's M1 Ultra).

Exhibit 2 - Chiplet Systems as an Alternative Alongside Monolithic SoC



Source: BCG analysis

Note: Node sizes are illustrative, architecture design may differ depending on application.

3. LinkedIn post by Markus Schäfer: https://www.linkedin.com/posts/markus-sch%C3%A4fer_chiplets-futureofmobility-leadincarsoftware-activity-7011253968311865346-0wlw/
4. https://www.imecitf.com/2023/world/program/itf-world-day-1/program-part-3/stefan-hartung

There are five key reasons why this technology trend might be an interesting opportunity alongside monolithic designs in the automotive industry:

1. Possibility to mitigate yield limitations by combining several node sizes

In recent years, after decades of successful development toward smaller node sizes, semiconductor players appear to have reached physical limitations, especially in ensuring economic yields. Since monolithic SoCs are designed as fully integrated chips, all parts need to be on the same small node size. For chip designers, this leads to a trade-off, as small node sizes are beneficial for HPC but not ideal for certain other parts, such as analog functions. By disaggregating the monolithic chip into Chiplets, this need for one node size is removed, as each Chiplet's node size can be chosen individually. From a yield perspective, this is very interesting: One small defect on a large fully integrated monolithic SoC leads to the waste of the entire chip. Whereas in Chiplet Systems, the defect will only impact the single Chiplet where the defect is located, while other Chiplets are not wasted. Overall, Chiplet Systems come with yield and cost benefits due to the disaggregation into different node sizes.

2. High scalability and modularity

For monolithic SoCs, changes to parts of a chip lead to a re-design (at least partly) of the whole SoC, which results in high R&D costs. In Chiplet Systems, single Chiplets can be interchanged and replaced. This step is possible without a re-design of the architecture as long as the architecture was designed correctly and the modifications/changes stay within certain limits. The development effort for modular solutions addressing scalability or customization requests from OEMs might be significantly reduced in this way. Chiplet Systems can therefore serve as bridging technology in hybrid E/E architectures and also as an alternative alongside monolithic SoCs in future centralized compute architectures.

3. Chance to increase supply chain resilience and lower risks for lock-in effects

By disaggregating SoCs into single Chiplets, the value chain could be opened up by new players being able to engage, as is discussed in more detail in the following chapter. This could lead to a broader offering on the automotive compute market enriching OEMs' choices. With more alternatives, the risk for lock-in effects can be mitigated and supply chain resilience increased.

4. Long term: Lower R&D effort and accelerated time to market

Chiplet Systems will need a certain time to develop their full potential, as the initial architectures and die-to-die interfaces will first need to be developed. When (and if) these and a sufficient offering of Chiplets are available on the market for automotive compute, new Chiplet Systems can be designed more easily based on existing modules. Then, the modularity will help to reduce R&D efforts and lower the expected time to market.

5. Long term: Vision of open Chiplet ecosystem

Should Chiplet Systems evolve in the long run with open architecture designs and enough players are willing to participate in an open system to cover the whole value chain, Chiplet Systems may lead to an open Chiplet ecosystem. This would allow automakers to mix and match Chiplets from different suppliers, thereby increasing scalability, modularity, and customization (contributing to key reason #2) as well as their supply chain options (contributing to key reason #3).

At this point in its development, there are also five key shortcomings and challenges to this technology:

1. Special architecture design necessary

Chiplet Systems require system architecture to be compatible with several Chiplets, possibly from different suppliers. This creates an additional R&D effort whose payoff may be unclear, depending on the application.

2. Need end-to-end Chiplet value chain coverage

In order to produce Chiplet Systems, the entire Chiplet value chain needs to be covered end-to-end. Since the Chiplet System value chain contains entirely new steps (e.g., the integration of individual Chiplets to Chiplet Systems), players for these steps need to be identified to reach the mentioned complete value chain coverage.

3. High cost of advanced packaging

Chiplet Systems are enabled by innovative packaging methods, which ensure high-speed low-latency communication between the single Chiplets. Typically, advanced packaging methods such as 2.5D or 3D packaging are used. Compared with traditional packaging, the manufacturing costs of these is significantly higher (by a factor in the range of 10 or greater) which could lead to non-competitive prices compared with monolithic SoCs (as packaging costs would then account for a major share of the chip costs).

4. Need for standardization to reach open ecosystem

To combine Chiplets from different suppliers, the standardization of interfaces is necessary. Chiplet suppliers need to agree on standards for the die-to-die interconnects, including the physical layer and the communication protocol. Since the interests/incentives of different players in the industry may not be aligned, it is possible that no common standard or several competing standards evolve, which would reduce mix-and-match options. The process of standardization also slows down development, increasing both costs and time to market.

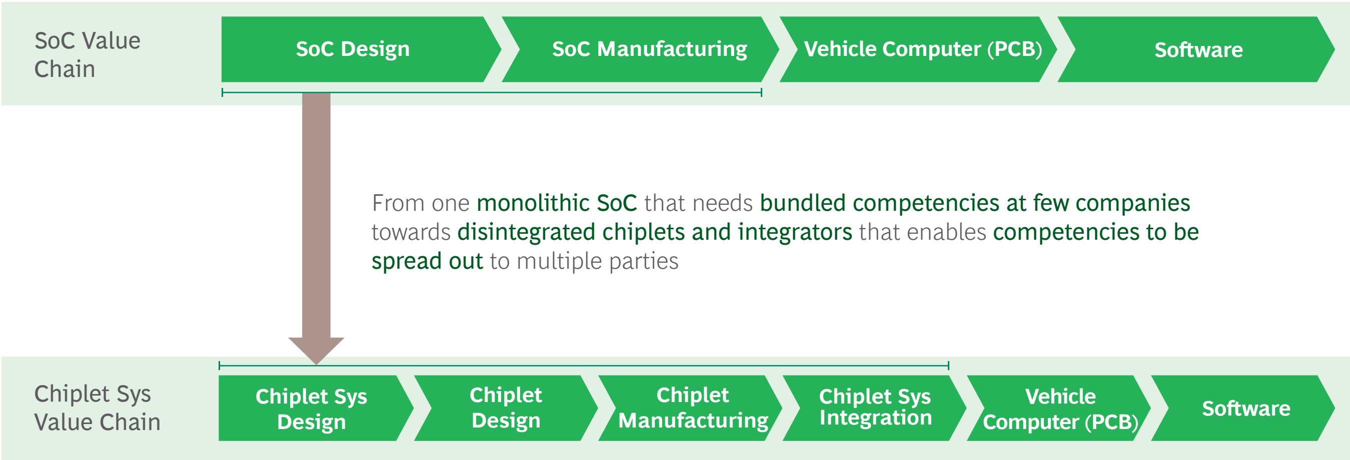
5. Long term: Need for responsible orchestrator in open ecosystem

In an ideal open ecosystem of Chiplets, automakers can design chips by mixing and matching. As a prerequisite, an orchestrating player is needed to both be responsible for the whole Chiplet System and ensure the fulfilment of its requirements. This includes coordination with the Chiplet suppliers, assurance that standards are met, validation of the Chiplet System as a whole, etc., which may lead to higher costs than for monolithic SoCs.

New Value Chain Dynamic Can Be Enabled by Open Ecosystem of Chiplet Systems

The modularity of Chiplet Systems may open up the value chain, as depicted in Exhibit 3. Generally speaking, there are four major steps in the automotive compute value chain based on monolithic chips: design, manufacturing, assembly in vehicle computer on a printed circuit board (PCB), and application software. Typically, fabless players such as NVIDIA, Qualcomm, and Mobileye focus on SoC Design, while players such as TSMC, Global Foundries, and UMC cover SoC manufacturing. Automotive Tier-1s such as Bosch, ZF, and Continental traditionally take over the integration step in which the vehicle computer is built using the SoC. The application software is usually provided by the fabless players, Tier-1s, or OEMs (e.g., Tesla or Volkswagen/Cariad).

Exhibit 3 - Chiplet Trend Will Open Up Value Chain for New Plays



Source: BCG analysis

In a Chiplet world, the first two steps are now disaggregated up into four steps: The first step involves the design and verification of a Chiplet System architecture, including the necessary middleware software. In the second step, the individual Chiplets are designed such that they conform with the defined architecture, followed by manufacturing and integrating (including automotive grade validation) onto one chip using innovative packaging methods—usually 2.5 or 3D packaging—to ensure die-to-die interconnects with high performance. The remain-ing two steps (assembly on PCB and software) stay largely the same as before.[5]

While the disaggregated steps could be covered by the same fabless players as before in a closed value chain, Chiplet Systems also provide the opportunity to open up the value chain. They offer the possibility to spread out competencies to multiple parties, which enables new players to enter this value chain. For example, specialists for HPC, ML/AI, communications, sensor preprocessing, security, automotive safety, and many more can each deliver their functional competency as a Chiplet, as long as it conforms to the Chiplet System architec-ture. In this way, players without the know-how to design a whole automotive compute SoC in-house can jointly develop a chip and profit from scalability and modularity benefits of Chiplet Systems. These new players might include semiconductor players that are more specialized or have no presence in automotive compute, as well as automotive Tier-1s and automakers.

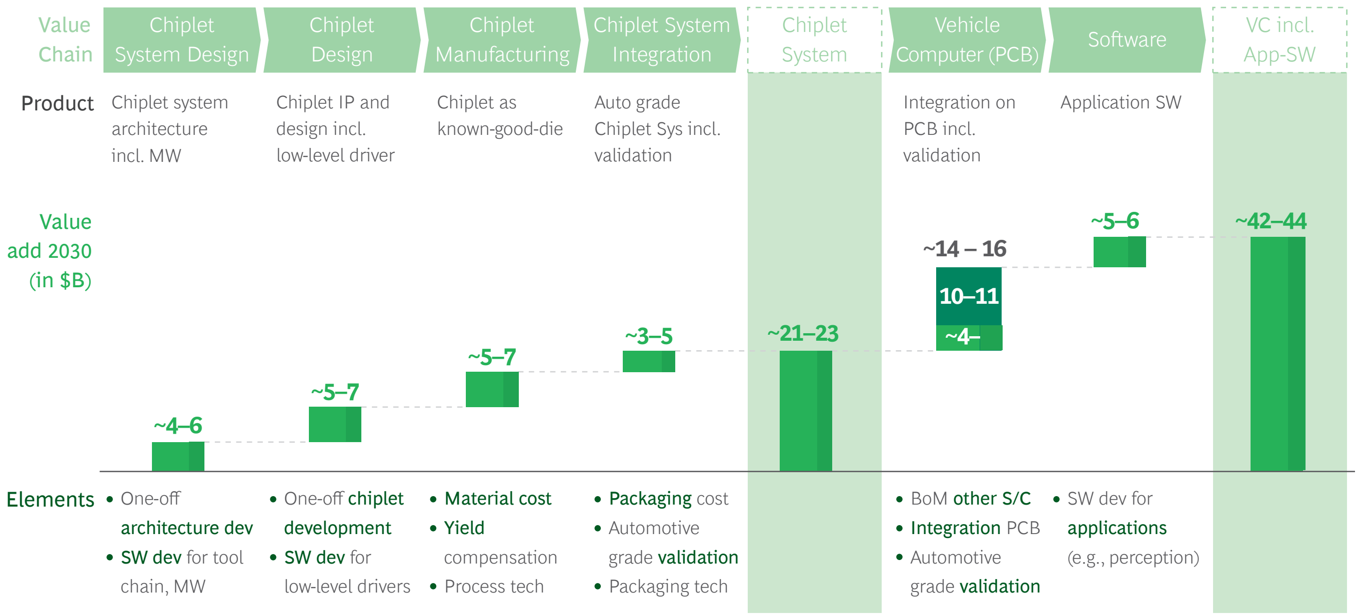
However, such an open ecosystem of Chiplet players would require significant orchestration efforts, clearly defined standards, and full coverage of the new disaggregated value chain. Regarding the die-to-die interconnect and orchestration, a consortium initiated by Intel called Universal Chiplet Interconnect Express (UCIe) is currently the most prominent exam-ple. UCIe has gained traction with many strong semiconductor players, and recently also made a connection to the automotive industry with Mercedes-Benz. Another initiative is the standard Bunch of Wires (BoW), which was initiated by the Open Compute Project, an indus-try trade group for the server HPC market. Both initiatives aim for an open ecosystem of Chiplets. It remains to be seen whether this endeavor will be successful for the automotive industry or a closed-system approach will ultimately prevail.

5. With the shift to Chiplet Systems, the integration of components and their automotive validation may be shifted from the PCB to the Chiplet System integration, since more semiconductor components may be integrated into a Chiplet System than a monolithic SoC Design.

The Chiplet System's value chain contains sizeable opportunities, as our analysis of the value add per processing step in Exhibit 4 shows. The market size for Chiplet Systems in automotive compute will amount to about \$21 billion to \$23 billion in 2030, of which each of the four processing steps will contribute a billion-dollar amount in the mid-single digits. New plays are likely to evolve in Chiplet System Design and Chiplet Design, which both offer attractive margins in the range of 25%–35%.

The integration in a vehicle computer—meaning, on a PCB—adds the largest amount of value (~\$14 billion–\$16 billion) but offers only a small margin (~5%) due to the high BoM share of other semiconductor content (~\$10 billion–\$11 billion) in this processing step. Marginwise, application software is the most attractive opportunity, with ~30%–40% margins. All in all, the market size for the Chiplet System-based vehicle computer, including application software, will reach ~\$42 billion–\$44 billion by 2030.

Exhibit 4 - Chiplet System Value Pools



Source: arXiv, expert interviews, BCG analysis

Note: Directional indication based on value add for initial generation of Chiplet Systems assumed at same price as SoC based Systems.

Conclusion

On the one hand, taking the characteristics of Chiplet Systems and the new value chain dynamics into account, this technology has the potential to be beneficial for the automotive compute offering. Chiplet Systems can serve as a bridging technology, as their modularity and scalability could allow for better tailoring to applications in hybrid and also future centralized E/E architectures. The option to interchange and configure chips for specific applications or clients without a complete chip re-design, and the possibility to combine different node sizes, might lead to lower price points, depending on the batch sizes. The possibility of opening up the value chain might lead to an enablement of new players and therefore a broader chip offering, reducing the risk of lock-in effects and increasing supply chain resilience.

On the other hand, for Chiplet Systems to be successful in the automotive industry, there are still many hurdles to overcome. First, necessary standards for the architecture, the die-to-die interfaces, etc. need to be defined. The UCIe and BoW initiatives are only a first step in this direction. A suitable orchestrator who is responsible for the chip as a whole and also decides whether an open or closed ecosystem will be realized is needed. Second, a complete value chain needs to be formed. A Chiplet System can only be produced if all necessary parts are provided, so players need to be found for each step of the value chain. In the case of an open ecosystem, this could lead to additional challenges, as certain steps might be difficult to cover (limited availability of players, lower margins in certain steps, etc.). Third, the cost competitiveness of a Chiplet System in comparison with monolithic SoCs still needs to be proven. If the expected benefits of Chiplet Systems being manifested, in reality, depends on several factors, including the R&D efforts to design the Chiplet System's initial architecture and the single Chiplets themselves, the realized batch sizes, and the chosen packaging technology, it is expected that only a cost-competitive solution will be successful in the automotive industry.

Whether OEMs' interest in an open ecosystem of Chiplet Systems justifies the effort or they would prefer to stick with closed systems remains to be determined in the coming years. Players in the automotive compute industry are already publicly marketing precursors of Chiplet technology in a closed value chain (e.g., NVIDIA offering its customers a combination of two NVIDIA Drive Thor chips via its NVLINK-C2C interconnect technology).

Implications

All in all, the automotive compute industry is evolving quickly, and all involved players—mainly OEMs, chip developers, and Tier-1s—have an influence on which direction the industry is headed. While OEMs design their E/E architecture and ADAS/Autonomous Driving (AD) and In-Vehicle Infotainment (IVI) features—which leads to requirements for automotive compute chips—chip developers and Tier-1s will negotiate feasible requirements and possible implementations. Additionally, OEMs decide for themselves their level of engagement in chip design (or modification) in terms of whether they want to buy externally designed chips or invest in in-house chip development.

Chiplet Systems will enrich the automotive compute offering alongside monolithic SoCs. In case an open Chiplet ecosystem evolves, new players might be enabled to enter the disaggregated value chain of Chiplet Systems.

For OEMs, this pathway could lead to a more diverse chip supplier market, which is beneficial to avoid lock-in effects and increase supply chain resilience. Additionally, OEMs planning to be involved in chip development profit from lower barriers of entry in Chiplet Systems (compared with monolithic SoCs).

For Tier-1s, Chiplet Systems in an open ecosystem may enable them to participate in chip development for automotive compute and lead to new plays. In this way, Tier-1s may offer (together with other players) an automotive compute chip that enables them to provide hardware-software integration. Keeping in mind the additional competition from very price-competitive EMS enabled by chip suppliers, this pathway might provide Tier-1s with a way to differentiate themselves and mitigate the risk to be replaced.[6]

For chip developers, Chiplet Systems may increase the competition for today's leading players. In the case of open Chiplet ecosystems, smaller players would have the chance in this pathway to contribute their USPs even though they do not have the capabilities to develop the complete chip. In contrast, today's strong players may prefer to implement Chiplet System-based solutions as a closed system.

For Outsourced Semiconductor Assembly and Tests (OSATs), new business opportunities may evolve in this pathway, since Chiplet Systems are using innovative packaging technologies. One option for these technologies is advanced packaging methods, which are expected to lead to a higher margin than traditional ones. Therefore, OSATs may profit from these new business opportunities in this pathway.

For foundries, Chiplet Systems may lead to a slight shift in demand from bleeding-edge node sizes to larger node sizes, since the whole Chiplet System no longer needs to be on the same node size. The effect of this shift will probably be small due to the low volumes in automotive compared with other industries such as consumer electronics. Additionally, it will be mitigated by the generally rising demand for smaller node sizes to increase performance and efficiency.

For ecosystems, Chiplet Systems only lead to the major implications described herein if an open Chiplet ecosystem evolves. An open ecosystem requires significant effort for orchestration and standardization of interfaces. Additionally, full coverage of the value chain will be crucial for the success of a Chiplet System. In order to do so, an orchestrating consortium needs to identify players for each process step and convince them to participate. It remains to be seen whether this challenge will be resolved. In contrast, Chiplet Systems in a closed ecosystem do not face these challenges, but are also not expected to lead to significant changes in automotive compute ecosystems.

6. The shift toward a software-defined vehicle reduces the hardware complexity in the case of standardized SoCs. This could lead to an enablement of EMS by chip suppliers to produce vehicle computers. One example in this context is NVIDIA, which announced during CES 2023 that it would cooperate with Foxconn for its vehicle computer offering.

Abbreviations

AD	Autonomous Driving
ADAS	Advanced Driver Assistance Systems
AI	Artificial Intelligence
ASIL	Automotive Safety Integrity Level
BoW	Bunch of Wires
CAGR	Compound Annual Growth Rate
CAN	Controller Area Network
CPU	Central Processing Unit
E/E	Electrical/Electronic
ECU	Electrical Control Unit
EMS	Electronics Manufacturing Service
GPU	Graphics Processing Unit
HPC	High Performance Compute
IDM	Integrated Device Manufacturer
IVI	In-Vehicle Infotainment
LIN	Local Interconnect Network
ML	Machine Learning
MW	Middleware
OEM	Original Equipment Manufacturer
OSAT	Outsourced Semiconductor Assembly and Test
PCB	Printed Circuit Board
R&D	Research & Development
SDK	Software Development Kit
SoC	System-on-Chip
SW	Software
TOPS	Trillions Operations per Second
UCIe	Universal Chiplet Interconnect Express
VS	Vehicle Server

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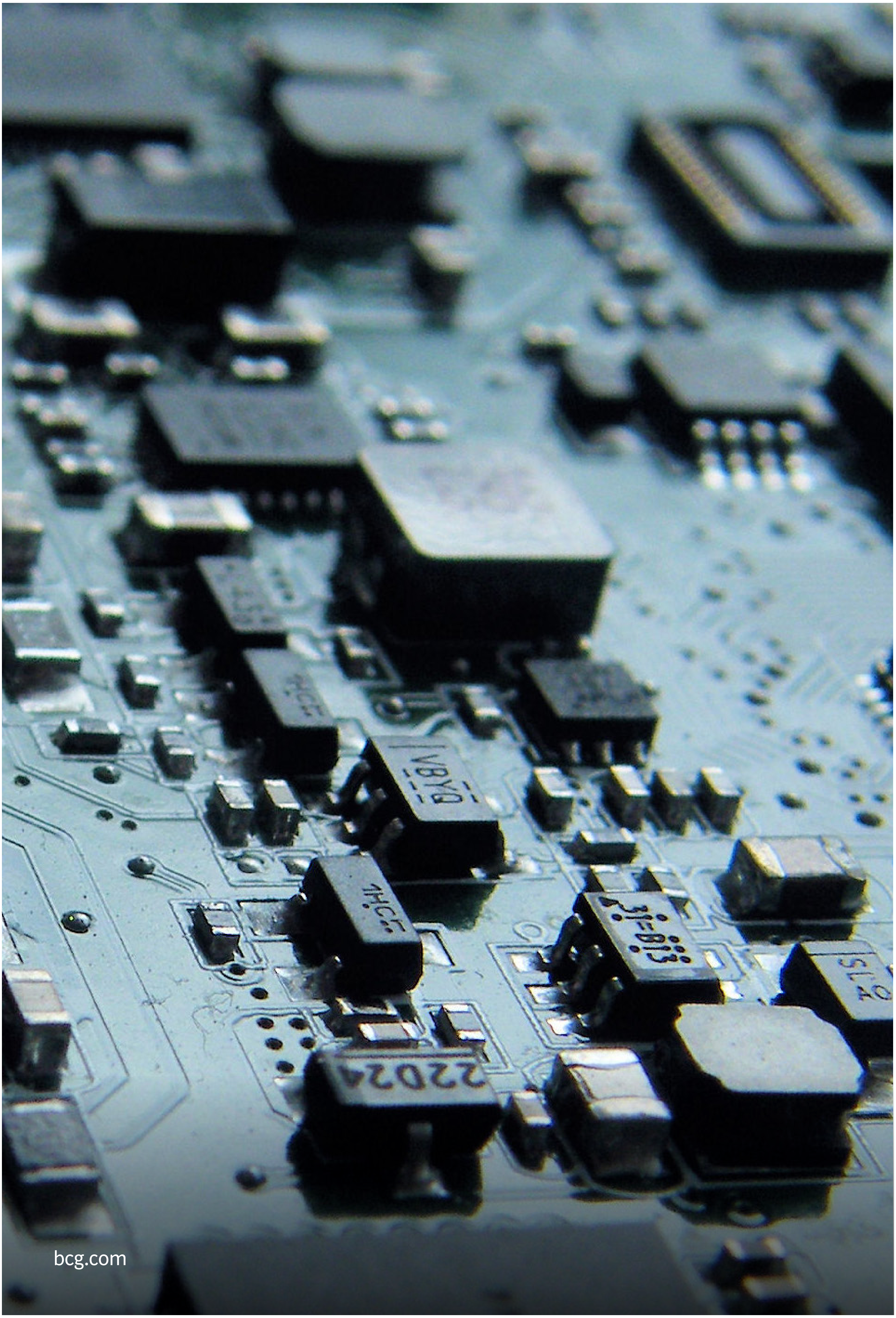

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