

Automotive 48V

Whitepaper

ON Semiconductor®



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Car evolution with ON Semi: the green age

The automobile (car) is one of the greatest inventions in human history. In general, it is a motorized wheeled vehicle capable of transporting a small group of passengers over long distances. It is typically driven by an Internal Combustion Engine (ICE). Modern car design is based on a concept patented back in 1886, by a German inventor Karl Benz (Benz Patent-Motorwagen). Ever since the Ford Motors company launched its mass-produced Model T back in 1908, the number of cars increases each year. Although vastly improved since its early days, the working principle of the ICE remains more or less the same: a four-stroke engine that runs on energy produced by combusting liquid fuel and oxygen mixture, generating CO2 gas as a by-product.

How CO2 legislation affects the automotive industry?

Today, there are many companies in the world producing cars. With so many vehicles on the streets worldwide, CO2 emissions have become a real problem, contributing approximately 12% to the global CO2 pollution. CO2 pollution is the main culprit for the greenhouse effect and extreme climate changes. In an attempt to reduce CO2 emissions, more and more countries are adopting CO2 legislation with strictly defined CO2 emissions targets. The new Regulation (EU) 2019/631 of the European Parliament goes into effect this year (Jan. 01, 2020), setting even lower CO2 g/km targets and higher penalties than the previous ones (less than 95 CO2 g/km). Car manufacturers are forced to find alternative solutions to their traditional

ICE designs, shifting their focus to alternative energy sources, such as electricity. The “ripple effect” of CO2 legislation can also be felt among semiconductor manufacturers, as they now have a completely new market to cover: an unforgiving automotive market with a stringent set of standards and regulations, pushing the engineers beyond conventional thinking.

MHEV: an electrified eco-friendly alternative to a traditional car

Although the main goal is to ban fossil fuels throughout the industry, the electrification will come in waves or phases. Mild Hybrid Electric Vehicles (MHEV) offer the best ratio between CO2 emissions reduction and the production cost. With their engines electronically augmented, MHEVs can remain well below the legislation CO2 targets, still offering reasonable prices to the end customers. According to predictions from several different sources, by the year 2025, one of every ten vehicles sold worldwide will be an MHEV. With their capability to utilize the existing conventional car infrastructure, MHEVs provide the same level of freedom as any other traditional fuel-driven car, representing an excellent and well-balanced eco-friendly alternative to the conventional car, in the years to come.

There are several different approaches to car electrification, resulting in different CO2 reduction/production cost ratios. The scope of this paper is medium power or mild electrification, based on a 48 V on-board power grid (48 V boardnet).

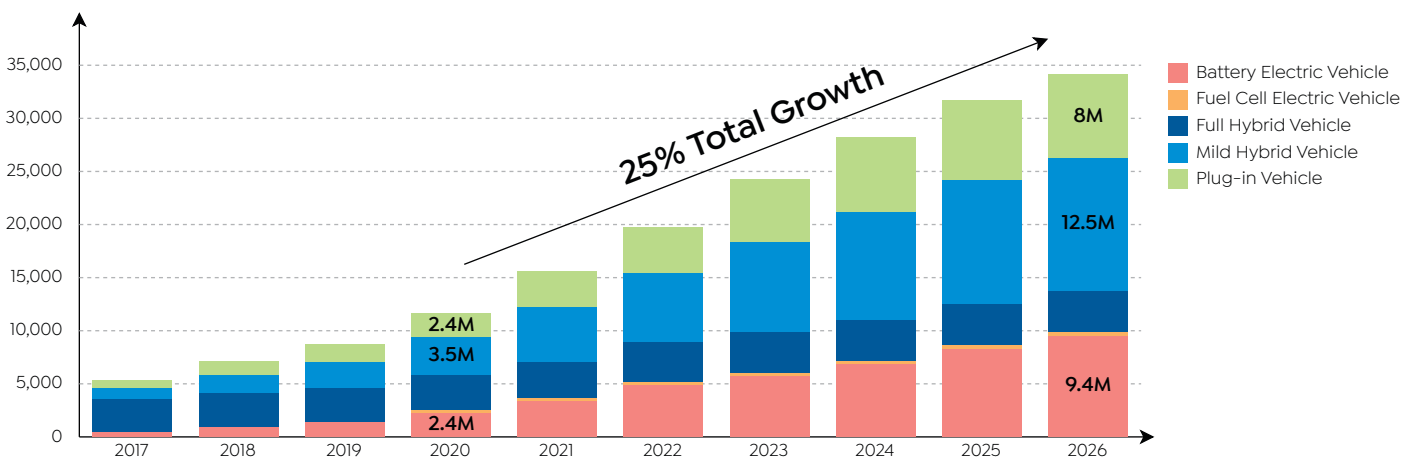


Figure 1: Market predictions for different types of vehicles (credits: Metrix Live) Figure 2: Typical 48 V power architecture

48 V boardnet

Conventional cars use 12 V boardnet, which is based around a 12 V lead-acid battery. However, 12 V is only sufficient for the essential functions. Adding more comfort features requires more power. In a typical MHEV, the highest power consumption comes from the Starter motor/Generator (SG). Depending on the hybridization topology (P0 to P4), the power consumption of the SG alone can reach up to 35 kW. Other (auxiliary) systems such as the E-supercharger, AC compressor, EPS, roll stabilization, cooling fan, fluid pumps, air conditioning compressor, and PTC heaters, can also reach power consumption in the magnitude of kilowatts. It is clear that in a typical MHEV, 12 V is far from sufficient.

Therefore, in addition to the traditional Low Voltage (LV) 12V board net, a typical MHEV also includes the Medium Voltage (MV) 48 V boardnet. The 48 V boardnet is capable of delivering up to four times more current through the

same wire gauges while running the motor loads more efficiently. There is no risk of electric shock in the 48 V boardnet, so the need for special cable insulation and specialized accessories in the event of maintenance or accidents is entirely avoided. In essence, the 48 V boardnet cabling installation has no specific requirements over the 12 V boardnet cabling, which significantly simplifies the implementation, and reduces additional costs.

At the time of writing (2020), worldwide standardization of the 48 V boardnet is still ongoing. With the LV148/VDA320 specification already in place, there is a need for a widely accepted standard, which would include many different regions and OEMs. The International Organization for Standardization (ISO) still works on the ISO/FDIS 21780 standard, but once completed, it will contribute to even faster development and deployment of 48 V MHEVs. Figure 1 represents a typical 48 V power architecture.

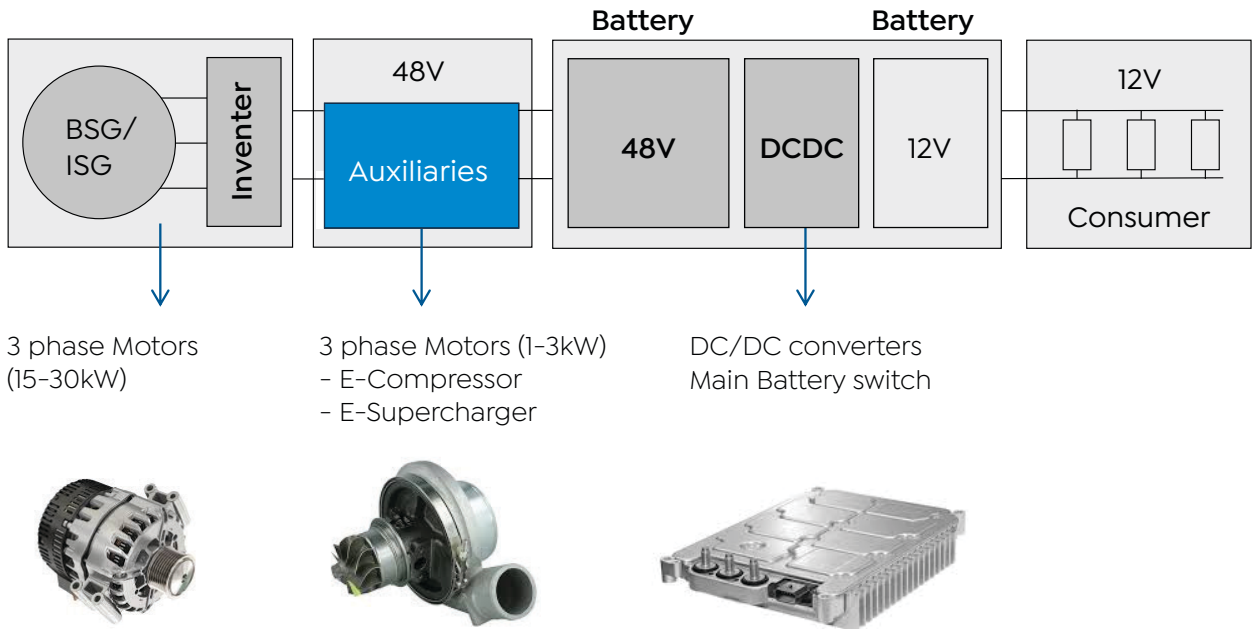


Figure 2: Typical 48 V power architecture

Starter motor/generator and associated components

The SG plays the most significant role in an MHEV. There are several different MHEV topologies (P0 to P4), depending on how the SG is implemented. In essence, it can be mechanically linked with the ICE through the accessory belt (BSG), or it can be integrated into the transmission or crankshaft (ISG). Without going deeper into the details of the different topologies, suffice it to say that from the electrical perspective, the SG plays a dual role: it can both generate and consume energy from the boardnet.

The belt-driven SG topology (P0) is the most dominant on the market, as it is the simplest one to implement while offering the best CO₂ emissions reduction/implementation costs ratio. Although enabling a slightly different set of functionalities than the P0 topology, other topologies work similarly, using the same basic principles.

While draining the 48 V Li-Po battery, the SG generates a torque that can be utilized in several different ways:

- **ICE Start & Stop:** SG enables instantaneous starting and stopping of the ICE when not in use (traffic lights or a brief stop during a traffic jam), preventing it from burning fuel while idling, and thus reducing CO₂ emissions. However, for the cold-start, the 12 V starter is still in use on most MHEV designs.
- **Torque Assist and Torque Boost:** ICE produces the most CO₂ while accelerates or when high torque is required. The SG contributes to the total torque output, allowing ICE to accelerate gradually, thus reducing overall CO₂ emissions.
- **Electric Drive/Crawl:** when the car moves at very low speeds (e.g., parking), its ICE operates very inefficiently. The SG can be used to replace ICE in such situations, allowing the ICE to shut down completely. However, this option is not available for P0 topology and requires integrated SG (ISG).
- **Power can also be restored to the 48 V battery,** by using the SG in the power generator mode.
- **Energy Recuperation:** during the deceleration, the SG converts the kinetic energy of the car into electrical energy and uses it to charge the battery.
- **Brake Regeneration:** pressing the brake pedal sends a signal to the ECU, which splits the braking torque between the foundation hydraulic brakes and the SG while keeping the torque applied to the SG below its limit. Again, the SG converts the kinetic energy of the car into electrical energy and uses it to charge the battery.
- **Engine Load Shift:** the ICE is most effective when operating at a specified RPM range. While running at a constant speed, the SG can be used as a load, forcing the ICE to work at the optimum RPM range, optimizing its efficiency.

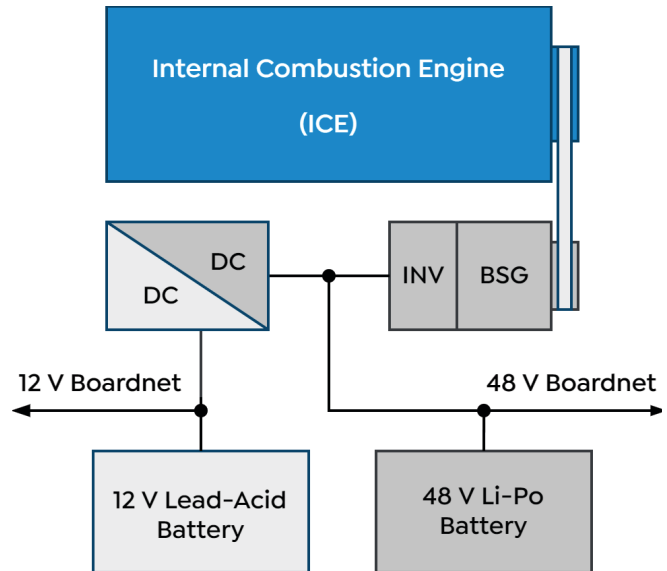


Figure 3: Block diagram of a typical BSG (P0) topology

- **Idle Charging:** the SG generates battery-charging power while driven by ICE at idle. The ICE slightly increases RPM during the Idle Charging period, thus burning more fuel. Therefore, this mode is used for emergencies only when both batteries are empty.

The 48 V boardnet is a DC power grid. On the other hand, the SG requires a three-phase AC voltage for its operation, in most cases. The primary purpose of the inverter is to drive the SG and allow conversion between these two voltage types. As such, it is a vital component to the proper operation of the entire system, significantly affecting the overall driving performance of the car. Electronic and electrical components of the SG driver circuitry must withstand highly dynamic working conditions while operating at elevated temperatures (TAMB). Only the AEC-qualified components, compliant with the stringent set of rules and regulations for car safety, can ensure controlled behavior, even in the event of failure.

As an example, the list below provides some basic characteristics of a typical water-cooled BSG (source: Continental):

- Peak Torque: 60 Nm
- Peak Power: 15 kW in generator mode
- Speed: up to 20,000 RPM, continuous
- Weight: less than 13.5 kg
- Ambient Temperature: from -40 to +140 °C
- Cold Start Approved: at -30 °C
- Stack Length: adjustable (40 to 80 mm)
- Functional Safety: ASIL-B

There are many different approaches to implementing a converter/inverter circuit. Most typically, it is a three-phase half-bridge topology. Designs may include integrated modules or discrete components, depending on the design requirements and other

constraints (operating temperature, available space, performance). The simplified schematic in Figure 3 illustrates how the various components fit into the system: a 48 V half-bridge power stage with a 32-bit microcontroller subsystem and associated components.

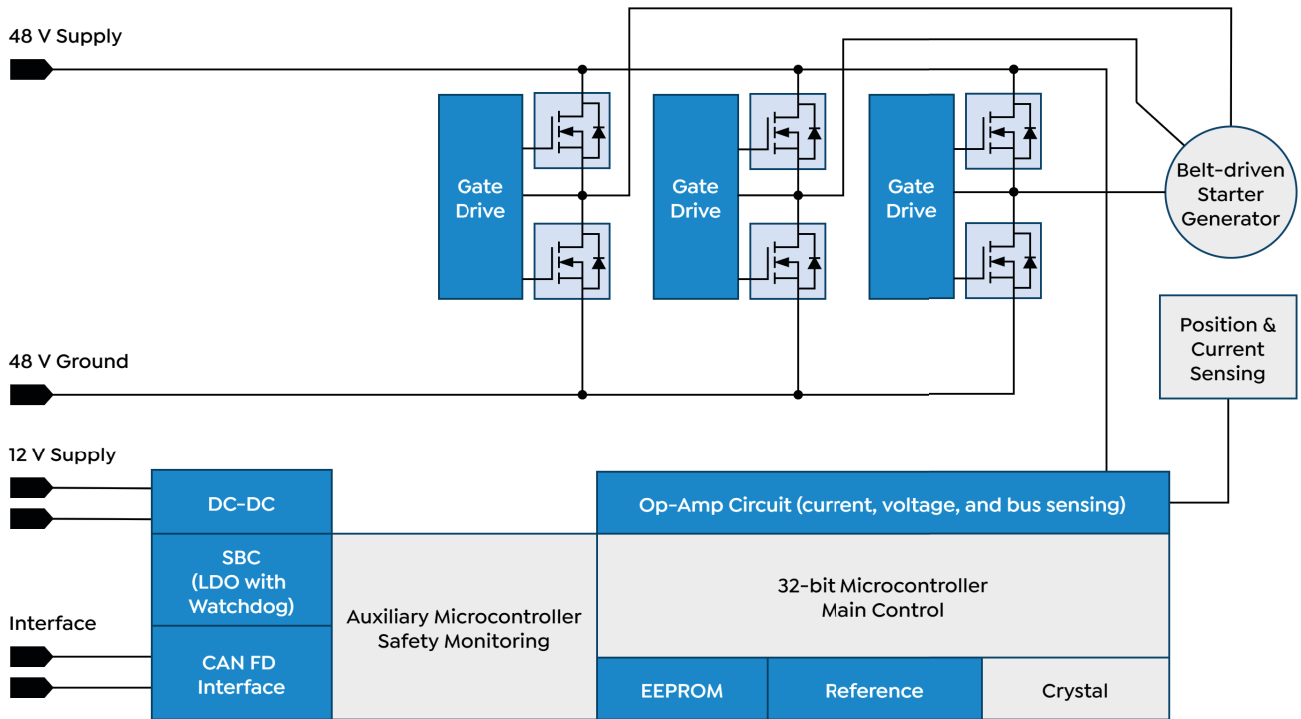


Figure 4: Simplified schematic of a 48 V BSG system

DC-DC power converter

There are two separate voltage domains in an MHEV: one is the LV (12 V boardnet), and the other is the MV (48 V boardnet) domain. These two domains must stay isolated from each other; otherwise, all equipment connected to the LV domain may be damaged. The only point where the two domains can interact with each other is the DC-DC converter.

Since it replaces the traditional 12 V alternator, the only component that generates electricity in the MHEV is the 48-volt SG. Before generated electrical energy can be used in the LV domain, the voltage must be reduced. Similarly, if only 12 V is available at some point (e.g., 48V Li-Po battery is low on power), the voltage level must be increased (e.g., for the 48V Li-Po battery charger). Therefore, the primary function of the DC-DC power converter is to enable bi-directional energy transfer between the two voltage domains. Sometimes, it can also provide a stabilization function for the 12 V boardnet, which is mostly used for the infotainment cluster and other similar low power and low voltage power consumers. The DC-DC power converter is a vital component for successful energy management in an MHEV.

The DC-DC power converter can be operated in the step-down or buck mode (when converting from 48 V to 12 V) or in the step-up or boost mode (when converting from 12 V to 48 V). It must also provide very high operating efficiency in a limited available space. This is only possible by using the latest generation of electronic components with a very low figure of merit FOM ($RDSON \times QG$) and efficient driving circuitry.

As an example, the list below provides some basic characteristics of a typical air-cooled 48 V DC-DC power converter (source: Continental)

- Power (in step-down mode): up to 3.8 kW continuous, 271 A
- Power (in step-up mode): up to 3.5 kW continuous, 73 A
- Efficiency: up to 97%
- Input Voltage: from 24 to 54 V (VDA320 compliant)
- Output Voltage: from 6 to 16 V
- Protection Class: IP6K9K
- Functional Safety: ASIL B, up to ASIL C possible

The modular architecture of a DC-DC converter allows for higher and more efficient power delivery through paralleling. The simplified schematic in Figure 4 illustrates one such modular converter with the 32-bit microcontroller subsystem and its associated components.

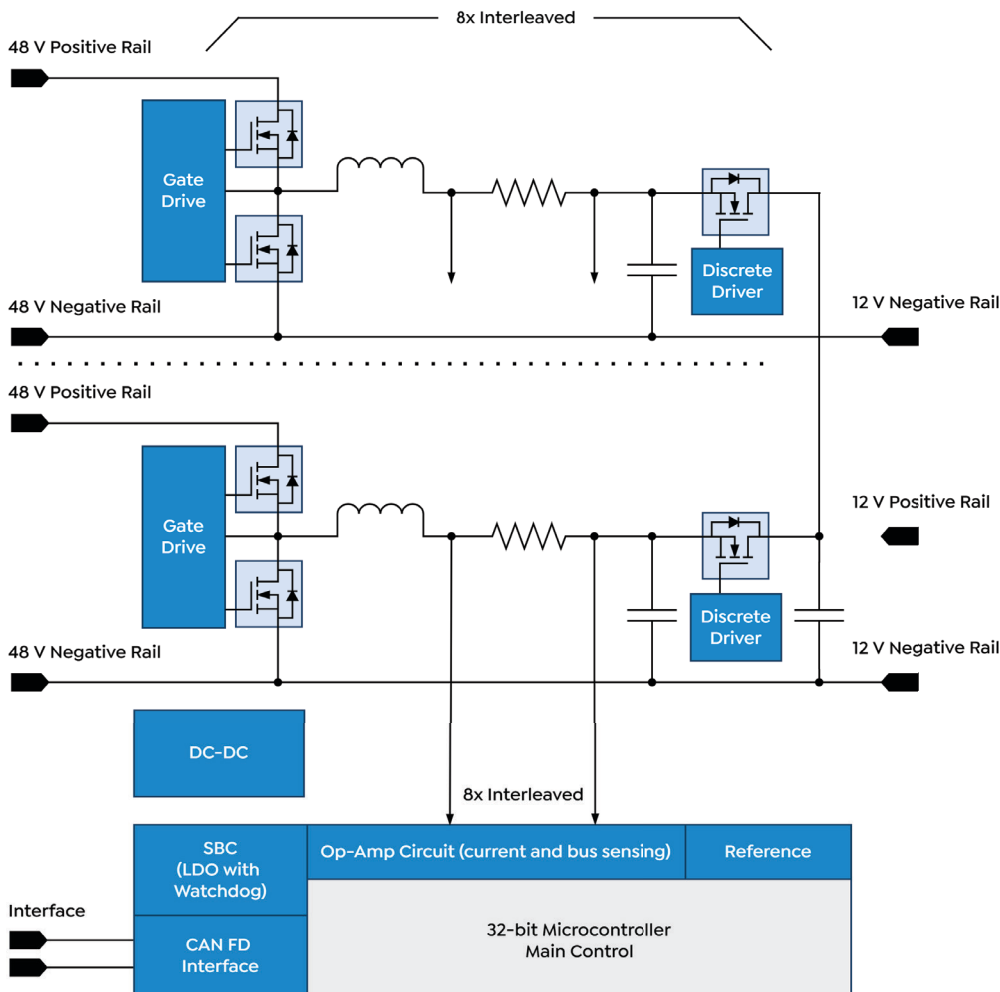


Figure 5: Simplified schematic of a 48 V to 12 V converter

Auxiliary power

Auxiliary subsystems play a vital role in a modern car. These subsystems generally consist of a variety of comfort features that enhance the overall driving experience. In a conventional car, the ICE drives large power consumers (using the accessory or 'serpentine' belt), such as the air-conditioning compressor, power steering pump, water pump, engine fan, and various other components. All these auxiliary subsystems add extra load to the ICE, increasing CO₂ emissions even further. With up to four times more power available from the 48 V boardnet, it is now possible to move all these subsystems into the electrical domain, significantly reducing overall CO₂ emissions. Electrification of these subsystems also provides some additional benefits, such as faster startup and greater efficiency. As already mentioned, all subsystems that include an electromotor can operate more efficiently, thanks to the higher voltage of the 48 V boardnet.

The combined power consumption of the auxiliary systems in a typical MHEV can be significant. For example, an E-compressor used to improve the overall torque transient response of the engine, can consume up to 5 kW of electrical energy. For illustration, the list below provides some characteristics of a typical water-cooled E-compressor (source: Continental)

- Electric Motor: permanent-magnet, synchronous
- Supply Voltage: 48 V
- Peak Shaft Power: 5 kW
- Maximum Speed: 70,000 RPM
- Response Time to 90%: less than 0.25 s
- Integrated Electronics with CAN Interface

However, some subsystems still draw power from the traditional 12V board, which now has better voltage regulation thanks to voltage regulation features of the DC-DC converter. For example, the 12 V cold-start motor (starter) is still available on most of the BSG-driven MHEVs. The infotainment cluster can also benefit from using regulated power from the 12 V boardnet. The low voltage 12 V boardnet has been the de facto standard for a long time, which is why many manufacturers are opting for dual-voltage architecture. Over time, as 48 V technology evolves even further, more and more auxiliary and comfort features will shift to the MV domain, until the 12 V board becomes completely obsolete.

Innovative automotive-grade solutions from ON Semi

ON Semiconductor (ON Semi) offers a broad portfolio of electrical and electronic components for the automotive industry, including a full range of products specifically focused on car electrification. Successfully delivering innovative AEC-qualified semiconductor solutions to the market for over two decades, ON Semi is one of the most reliable partners for the automotive industry on a global level. Supported by EBV Elektronik, an integral part of Avnet's global distribution network, ON Semi provides a scalable and steady supply chain of high-performance components, a critical deciding factor for most automakers. ON Semi's portfolio of automotive components perfectly fits within current market trends, offering a wide range of high-performance automotive components while covering all aspects of car electrification: from powertrain to infotainment.

Discrete devices (Power MOSFETs)

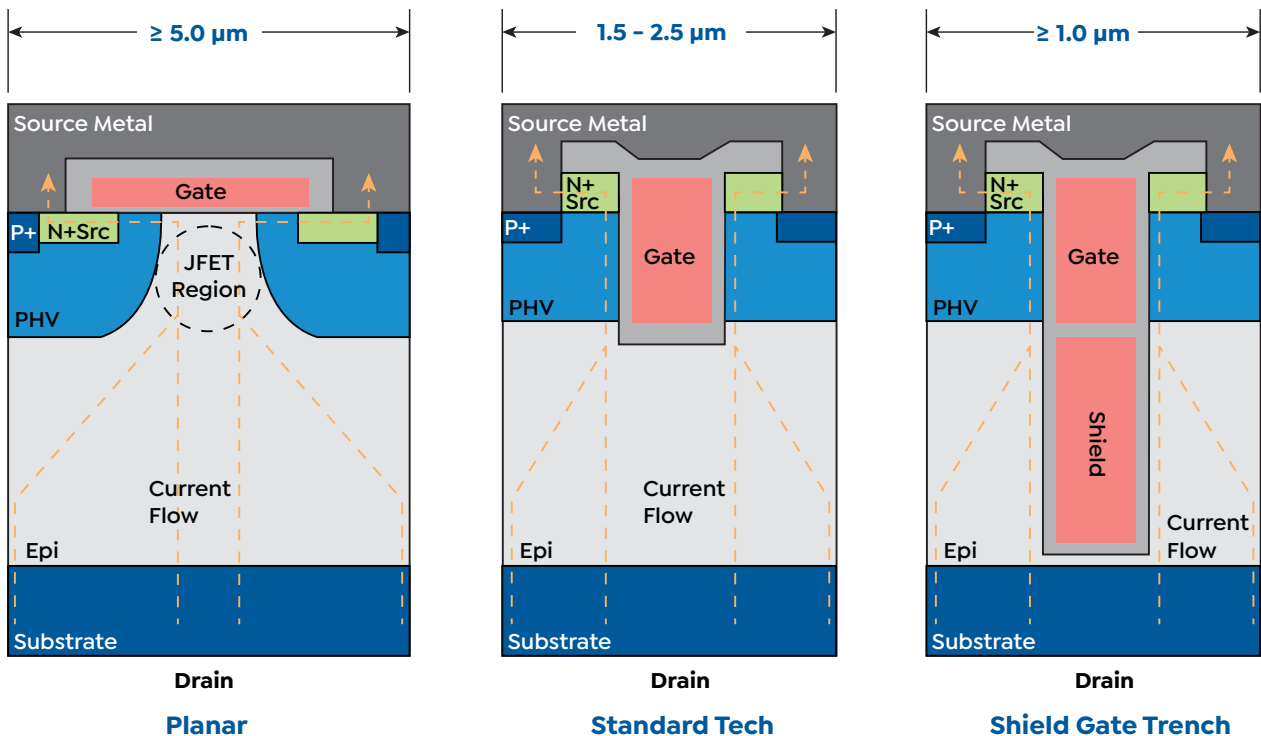
The ON Semi's extensive 48 V automotive portfolio includes AEC-Q101 qualified and PPAP capable MOSFETs, available in some of the best performing packages on the market such as TOLL, SO-8FL, DPAK, and more. The MOSFETs are also available as power modules, and as a bare die to be used in custom power module solutions. ON Semi's automotive MOSFETs are manufactured using Shield Gate Trench technology, which offers significantly reduced RDSON (low ON resistance) and exceptionally low QG (total gate charge) parameters. Their low to medium voltage families MOSFETs are the perfect solution for various types of automotive applications.

Technology	Breakdown Voltage [V]
T6	30, 40, 60
T8	80
MV5 - MV7	80 (MV7), 100 (MV5), 150 (MV5)
PTNG	100, 150

The T8 technology provides an extremely low QG (total gate charge) parameter, which, combined with the low RDSON results in best-in-class Figure of Merit (FOM) value, allowing for improved switching performance and a simpler driving circuit.

The PowerTrench® PTNG technology offers outstanding QRR (reverse current recovery), which helps to reduce the ringing phenomenon in circuits with inductive loads. Fast reverse current recovery allows smaller gate resistor values to be used for dampening, thus enhancing the dV/dt characteristic even further. These devices also feature excellent avalanche ruggedness, characterized under the Unclamped Inductive Switching conditions (UIS capability).

The 40 V MOSFETs lineup features the incredibly low RDSON down to 0.65 mΩ, which is ideally suited for battery cell balancing and other Battery Management System (BMS)-related LV applications.



Part number	Voltage Max [V]	Current Max [A]	RDSON Max [mΩ]	Package
FDBL0200NI00	100	300	2.0	TOLL
FDBL86062_F085	100	300	2.0	TOLL
FDBL86361-F085	80	300	1.4	TOLL
FDBL86363-F085	80	240	2	TOLL
NVMFS6H800N	80	203	2.1	SO-8FL
NVMFS6H801N	80	157	2.8	SO-8FL
NVMFS6H818N	80	123	3.7	SO-8FL
FDD86367-F085	80	100	4.2	DPAK
FDD86369-F085	80	90	7.9	DPAK
NVMFS6H836N	80	80	7	SO-8FL
NVTFS6H850N	80	68	9.5	u8FL
NVMFS5C404N	40	378	0.7	SO-8FL
FDBL9401-F085	40	300	0.65	TOLL
FDB9403-F085	40	110	1.2	D2PAK

ON Semi actively develops innovative MOSFET solutions based on wideband gap technologies (GaN), especially useful in high-frequency switching applications such as DC-DC converters, allowing both weight and size reduction, while increasing efficiency even further.

Power Modules

To address the most demanding requirements of power density and integration, ON Semiconductor offers the APM19 module platform, a flexible and well-performing transfer-molded package technology. In a 40 x 25 mm

package, ON semiconductor was able to integrate best in class LV/MV MOSFETs in different topologies and configurations, focusing on the most critical power applications in the 48 V domain. With an electrically Isolated DBC substrate for low thermal resistance and the possibility to integrate current and temperature sensing features, as well as the RC snubber network for lower EMI, the APM19 platform represents the perfect solution for highly demanding 48V automotive applications. The power modules based on the transfer-molded APM19 module platform are AEC-AQG324 Qualified.

Part number	Voltage Max [V]	Current HS / LS Max [A]	Features	Package
FTCO3V85A1	80	125 / 160	2.5 mΩ, Rth (typ) 0.92 / 0.7 (K/W)	APM19
NXV08V110DB1	80	190 / 190	2.1 mΩ, Rth (typ) 1 (K/W)	APM19
NXV08V080DB1	80	130 / 130	3.0 mΩ, Rth (typ) 0.1 (K/W)	APM19

Enabling even higher level of integration and pushing the level of power density to its limits, ON Semiconductor is developing an entire family of transfer-molded power modules designed explicitly for BSG/ISG applications. By integrating best in class LV MOSFET technologies combined with the high thermal performances of the package, this family of power modules based on the APM17M package addresses the most stringent requirements of thermal and power efficiency, low EMI,

reliability and lowest cost of ownership. The power modules based on the APM17M module package, reduce the design phase, improve overall system performances, simplify the assembly in production, and ultimately reduce time to market. For additional information, please contact the Automotive or Analog Power experts from EBV Elektronik, or visit the official web page at <http://www.onsemi.com>

Gate drivers

Gate drivers are the most critical components for the efficient operation of switching applications. Digital circuits used to control various MOSFET (or IGBT) topologies (e.g., three-phase BLDC motor driving) typically operate with TTL voltage levels, which are not sufficient to drive the MOSFETs. The primary purpose of a gate driver is to act as a bridge between the control circuit and the power MOSFETs stage, providing sufficient current and voltage for MOSFET driving. Gate drivers can have one or more TTL inputs, and can be designed to drive various MOSFET topologies. ON Semi gate drivers fully meet the requirements of their discrete and modular MOSFET solutions, ensuring the most efficient and reliable operation.

The table below shows three gate driver devices, well suited for the 48 V MHEV applications. All listed devices feature high driving currents, sufficient for high-frequency switching applications, even when driving MOSFETs with substantial gate capacitances. These gate driver ICs are non-isolated, AEC-Q100 qualified solutions, compatible with the industry-standard pinout:

The NCV5183 is a two-channel low and high-side MOSFET driver. The driver uses the bootstrap technique for the high-side driver. The NCV5183 does not integrate the bootstrap capacitor and diode, allowing the high-side

floating supply to operate with up to 600 V while retaining compact dimensions of the standard SOIC-8 NB package. Other features include undervoltage lockout, matched propagation delays for both channels, and two independent TTL-compatible inputs (3.3 and 5 V) accommodating various topologies (half-bridge, asymmetrical half-bridge, active clamp, and full-bridge).

In addition to the features found in the NCV5183, the FAN7191 offers some additional features, such as the common-mode noise cancellation circuitry, and buffered output stage for highly reliable operation. The FAN7191 is available in two different packages: SOIC-8 EB and SOIC-14 EF. Thanks to the higher pin count, the FAN7191 in SOIC-14 EF package offers separated logic and power ground pins for even more improved noise immunity, as well as the additional ENABLE pin. The FAN7191 is well suited for noisy applications, where other gate drivers can't support a reliable operation.

The NCV51511 is the fastest of the three devices, featuring a propagation delay of only 30 ns (compared to 120 ns and 140 ns on the other two devices). This gate driver integrates a fast bootstrap diode, which provides fast inverse recovery times, and low resistance of only 0.7 Ω . The NCV51511 is well suited for fast switching power applications where low power loss is required, such as DC-DC converters.

Part number	HS Floating Supply Offset Max [V]	Sink / Src Current Typ [A]	Package	Package
NCV5183	600	4.3 / 4.3	SOIC-8 NB	APM19
FAN7191	600	4.5 / 4.5	SOIC-8 EB, SOIC-14 EF	APM19
NCV51511	100	6 / 3	SOIC-8 EP	APM19

These devices listed in the table are just a sample of what ON Semi has to offer from its broad portfolio of gate drivers, in addition to many other innovative solutions in the MV and HV segment.

Other electronic components

Besides the broad range of automotive high-power switching solutions, ON Semi offers a comprehensive portfolio of Power Management and In-Vehicle Networking (IVN) devices for all ancillary functions in automotive applications. In the category of automotive power management and control, ON Semi offers a range of industry-standard current sensing and general-purpose operational amplifiers with low drift and offset architecture, covering a wide range of common-mode voltage ratings (CMVR). Their portfolio also includes battery-connected integrated DC-DC switching and linear regulators, and power management ICs (PMICs).

All power management and control devices boast a set of superior characteristics such as low quiescent currents (IQ, especially important for battery-connected SMPS and PMUs), high operation frequency for smaller dimensions and higher current capabilities (2 MHz switching frequency for post-regulation converters). Most importantly, these components can operate at elevated temperatures, very common in automotive applications (TJ in the range between 125 and 150 °C), in compliance with the AEC-Q100 qualification requirements.

From the digital perspective, there is a broad selection of automotive networking devices available (including LIN, CAN FD, and FlexRay transceivers), as well as the automotive EEPROM family, manufactured using the patented process technology and cell structure. The EEPROM devices feature high endurance (up to 1,000,000 program/erase cycles), up to 100 years data retention, and are qualified for the automotive applications (Grade 0 and Grade 1 temperature ranges).

Part number	Device Type	Operating parameters	Key Features
NCV21xR	Current Sense Amplifiers	Gain Err: 1%, VCMR: -0.3 to 26 V	Hi-precision integrated gain resistors
CAV25xxx	EEPROM	1 Kb - 1 Mb, SPI	Grade 1
CAV24Cxx	EEPROM	2 Kb - 1 Mb, I2C	Grade 1
NV25xxx	EEPROM	1 Kb - 64 Kb, SPI	Grade 0, Grade 1, Low VCC (1.7 V)
NV24Cxx	EEPROM	2 Kb - 64 Kb, I2C	Grade 1, Low VCC (1.7 V)

Electronic components used in car networking are more delicate than the robust power switching components (MOSFETs and Power Modules). These devices are far more susceptible to Electrostatic Discharge (ESD) phenomena, especially if equipped with contacts and receptacles. On contact, accumulated electrical charge can easily develop high voltage spikes and damage sensitive components if not handled properly. ESD protection diodes can clamp the voltage during the ESD spikes, protecting the rest of the circuit. However, they may introduce some additional capacitance on the communication lines. Therefore, careful selection of components is required, depending on the application.

Different IVN solutions work at different frequencies, and with different voltage levels. For example, high-speed Ethernet signals running over differential lines must use ESD protection diodes with very low capacitance (CIN) and low working voltages (VRWM), within the range from 3 to 5 V. Also, to ensure good signal symmetry, ESD protection components must be matched regarding their capacitance, which is only possible by using integrated ESD protection arrays. ON Semi offers a broad choice of ESD protection components for every use case, available in very compact packages. The table below shows a selection of ESD protection components, along with their typical use and ESD protection voltage ratings, according to the IEC6100-4-2 standard.

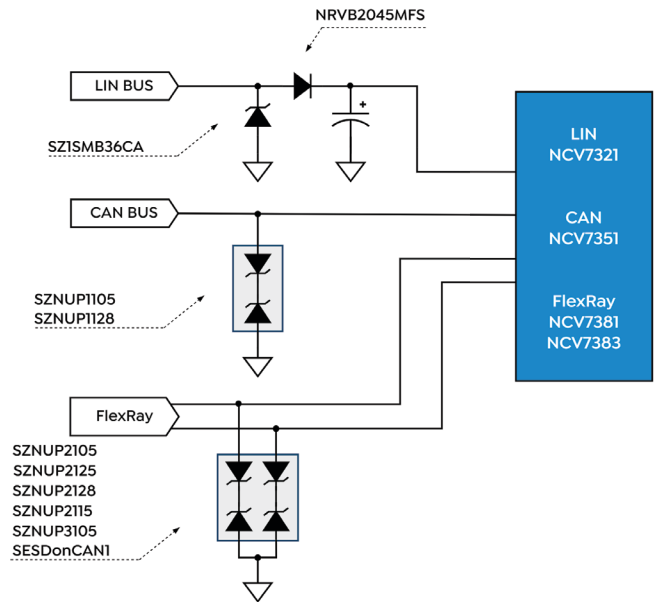


Figure 7: Simplified IVN diagram with suggested BUS / ESD components from ON Semi

Part number	VBR Min [V]	VRWM Max [V]	CIN Max [pF]	CH	IEC61000 4-2 (Contact)	Package	Target Application
SZNUP1105	25.7	24	30	1	±30kV / ±30kV	SOT-23	LIN / SW CAN
SZNUP2128	28	26.5	15	2	±30kV / ±30kV	SOT-323	HS CAN, CANFD (175 °C TJ)
SZNUP2105	26.2	24	30	2	±30kV / ±30kV	SOT-23	HS CAN
SZNUP2125	26.2	24	10	2	±30kV / ±30kV	SOT-323	HS CAN, CANFD
SESDonCAN1	26.2	24	10	2	±23kV / ±23kV	SOT-23	HSCAN, CANFD
SZNUP3105	35.6	32	30	2	±30kV / ±30kV	SOT-23	24 V System CAN
SZNUP3125	35.6	32	10	2	±21kV / ±21kV	SOT-323	24 V System CAN
SZNUP2115	26.2	24	10	2	±30kV / ±30kV	SOT-23	FlexRay
SZCMI213A-02SR	6	5	1.2	2	±12kV / ±12kV	SOT-143	BroadR-Reach Ethernet
SZESDIL001	16.5	16	0.50	4	±8kV / ±15kV	SC-88	STB OABR + 1 Gb Ethernet

For more information and a comprehensive listing of all automotive devices available from ON Semi, please contact the Automotive or Analog Power experts from EBV Elektronik, or visit the official web page at <http://www.onsemi.com>

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