

Semiconductor Device Technologies for Battery Monitoring Systems of Eco-Friendly Automobiles

In the automobile industry, strengthening of environmental regulations related to automobiles throughout the world has led to the accelerated development of eco-friendly automobiles (green vehicles), including electric vehicles (EVs) and hybrid EVs (HEVs), as a countermeasure for global warming and air pollution. The battery monitoring system (BMS), which controls the charging and discharging of the rechargeable battery system and manages its operating conditions for efficient running, plays a key role in expanding the cruising range of these eco-friendly automobiles.

Toshiba Electronic Devices & Storage Corporation has been developing and supplying various automotive semiconductor devices that are contributing to the enhancement of BMS performance. These include photocouplers to transfer signals between battery monitoring integrated circuits (ICs) and the microcontroller in the BMS circuit, photorelays to switch from preliminary charging to main charging and to detect any ground fault in the BMS circuit, and metal-oxide-semiconductor field-effect transistors (MOSFETs) to implement cell balancing corresponding to increased battery capacity.

1. Introduction

In response to growing concerns about global warming, air pollution, and other environmental issues, governments in many countries and regions are tightening environmental regulations for automobiles (Figure 1)⁽¹⁾. To comply with strict environmental regulations, automobile manufacturers have been accelerating the development of green vehicles, including EVs and HEVs, releasing an ever-increasing number of green vehicles onto the market. In addition, an increase in gasoline prices, tax incentives for green vehicles, and the heightened public impression created by the entry of luxury automobile manufacturers into the green vehicle market are driving consumer preference for green vehicles. Under these circumstances, sales of green vehicles are steadily increasing. According to the latest forecast, the worldwide sales volume of green vehicles is expected to exceed 10 million units in 2020 and 20 million units in 2023.

The environmental performance of green vehicles is represented by electricity efficiency, i.e., the driving distance per unit amount of battery energy used. An improvement

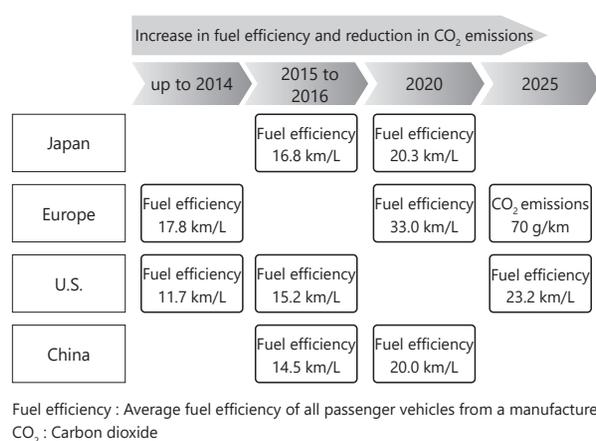


Figure 1. Trends in laws and regulations related to fuel consumption of passenger vehicles

Automotive regulations for fuel efficiency and exhaust emissions are being tightened in many countries and regions.

in electricity efficiency leads to an increase in the cruising distance on a single battery charge.

The driving battery is a major component that affects the environmental performance. Green vehicles are equipped with a battery monitoring system (BMS) for the efficient use of a driving battery. A BMS is composed of many semiconductor devices, including photocouplers for transferring electronic signals in the BMS; photorelays for detecting the contact melting of mechanical relays for controlling a precharge-to fast-charge transition and

a short-circuit-to-ground fault in the BMS circuit; and MOSFETs for battery cell balancing.

Toshiba Electronic Devices & Storage Corporation develops and sells photocouplers, photorelays, and MOSFETs, contributing to the improvement of the BMS performance. This report discusses these semiconductor devices that help improve the BMS performance and thereby the environmental performance of green vehicles.

2. BMS overview

2.1 Need for a BMS

Green vehicles draw electricity from a high-voltage battery to turn a motor so as to generate the driving force. When a vehicle is braking, the motor acts as a generator and stores energy in the battery. This means that the battery mounted on a green vehicle is exposed to frequent charge/discharge cycles. Generally, the types of vehicles that undergo battery charge/discharge cycles are HEVs, plug-in hybrid electric vehicles (PHEVs), and EVs in the ascending order of their frequency. This reflects the percentage of the time during which a vehicle runs on a motor.

Batteries are broadly divided into primary batteries that are non-rechargeable and secondary batteries that can be charged and discharged repeatedly. Secondary batteries are used as driving batteries for green vehicles. Instead of conventional nickel-hydrogen batteries, current green vehicles commonly use lithium-ion batteries because they provide higher energy density and charge/discharge efficiency, which affect a vehicle's per-charge cruising distance, and because it is relatively easy to increase the capacity and reduce the size of lithium-ion batteries.

Despite these advantages, a weakness of the lithium-ion battery is the tendency of its materials to become unstable while it is being recharged. To avoid instability, the lithium-ion battery requires extremely precise voltage regulation with a tolerance of a few tens of millivolts. In addition, overcharging can cause a lithium-ion battery to overheat, which could result in an explosion or a fire. Overcharging and overdischarging also cause rapid degradation of the battery. Because of these characteristics,

it is crucial to control the charging and discharging of the lithium-ion battery while monitoring its state of charge (SOC). A solution for this requirement is a BMS.

2.2 Basic configuration of a BMS

Figure 2 shows an example of a powertrain configuration for typical green vehicles⁽²⁾.

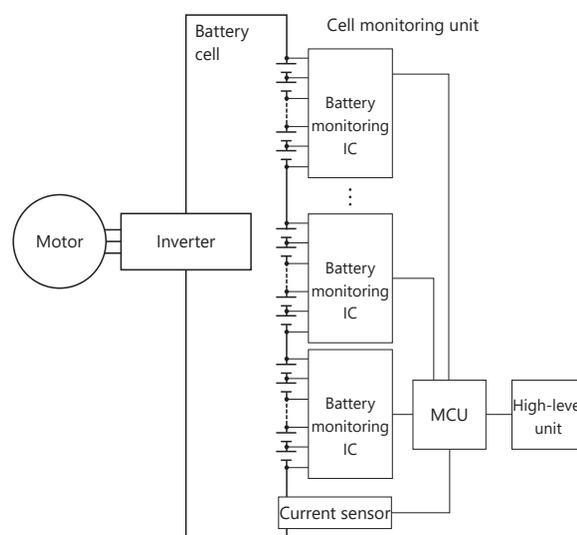


Figure 2. Example of configuration of powertrain and BMS for green vehicles

An inverter and motor are connected to series-connected battery cells. Since one battery monitoring IC monitors 8 to 16 battery cells, multiple battery monitoring ICs are used in green vehicles.

A lithium-ion battery (battery cell module) consisting of dozens to hundreds of series-connected battery cells is connected to a load, i.e., an inverter that drives a motor. It is difficult to monitor all these battery cells with a single battery monitoring integrated circuit (IC) because a battery cell module has a total voltage as high as several hundred volts. Generally, one battery monitoring IC monitors an array of 8 to 16 battery cells; so, a vehicle incorporates multiple battery monitoring ICs. Major functions of battery monitoring ICs include the measurement of the voltage and temperature of battery cells as well as cell balancing (i.e., balancing the SOC of adjacent cells). A BMS also incorporates a current sensor to measure the total current flowing in the lithium-ion battery. In addition, a BMS contains a microcontroller unit (MCU) to control the battery monitoring ICs and the current sensor. A typical BMS for automotive lithium-ion batteries simply outputs the results of battery voltage measurement without evaluating the voltage of individual battery cells.

The MCU determines a battery's SOC based on the results of battery voltage and current measurement as well as battery temperature data, and provides a high-level unit with information about the SOC. The high-level unit, in turn, determines whether to enable or disable charging⁽²⁾.

2.3 Functions of photocouplers and MOSFETs in a BMS

Photocouplers, photorelays, and MOSFETs are important to achieve the functionality of a BMS.

A BMS comprises a high-voltage block that contains a driving motor, a battery, and battery monitoring ICs and a low-voltage block that contains an MCU and a high-level unit (**Figure 3**). Photocouplers are used to transfer electronic signals between battery monitoring ICs in the high-voltage block and an MCU in the low-voltage block while providing

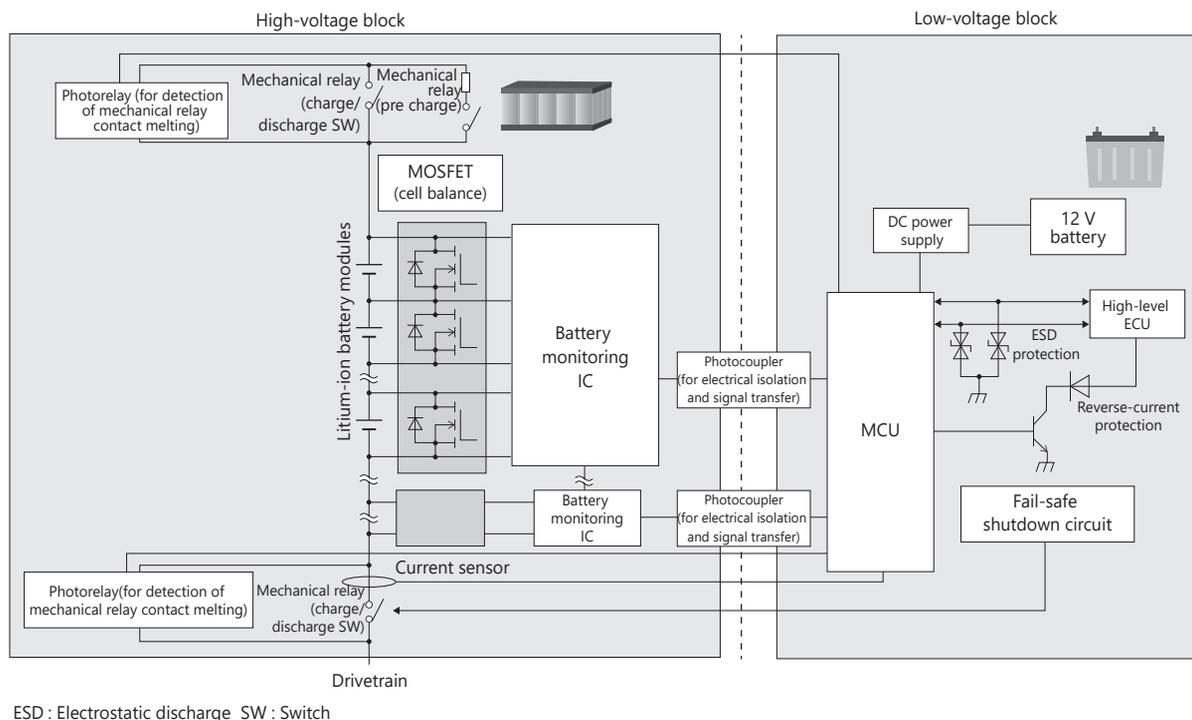


Figure 3. Example of configuration of BMS for lithium-ion battery modules

A BMS consists of a high-voltage block that contains a motor, a battery, and battery monitoring ICs and a low-voltage block that contains an MCU and a high-level unit. Photocouplers are used to transfer signals between the battery monitoring ICs in the high-voltage block and the MCU in the low-voltage block.

electrical isolation between them.

There are two charging methods for PHEVs and EVs: plug-in charging and rapid charging. Plug-in charging uses an on-board charger to charge a vehicle from a household power outlet (100 or 200 VAC) whereas rapid charging charges a vehicle with a DC current directly from a charging station installed at public facilities and elsewhere⁽³⁾. Both plug-in charging and rapid charging are constant-voltage, constant-current (CVCC) charging methods. At the beginning of the charging state, the CVCC charging method uses the constant-current charging until the battery terminal voltage reaches a predetermined level and then reduces the charging current while maintaining the battery terminal voltage. The charging process comes to an end when the charging current drops below a predetermined value. During charging, the charger and the BMS work in tandem to control the voltage and current of a lithium-ion battery.

A lithium-ion battery exhibits high internal resistance when its SOC is low⁽³⁾. Therefore, rapidly charging a battery with a low SOC causes extra heating within the battery, leading to safety hazards during charging and a decrease in the battery's service life. To avoid these problems, a current sensor in a BMS measures the current flowing to a battery prior to charging. If its SOC is low, the BMS performs a precharge operation first and switches to fast charging when the SOC reaches a predetermined level.

Photorelays are used to detect: 1) the contact melting of

mechanical relays that control a precharge-to-fast-charge transition and shut down the charging process in the event of a battery fault and at the end of the charging process, and 2) a short-circuit-to-ground fault in the high-voltage block of the BMS circuit.

Cell balancing is also an important function of a BMS. Lithium-ion batteries deteriorate rapidly when they are overcharged or overdischarged. To prevent undesired battery deterioration, the BMS imposes limits on the battery cell voltage during charging and discharging. If there are differences in SOC among battery cells, the BMS disables the charging or discharging process when the voltage of the cell with the highest SOC reaches the charging limit or the voltage of the cell with the lowest SOC reaches the discharging limit. This means that the effective battery capacity decreases if there are differences in SOC among battery cells. To increase the effective battery capacity, cell balancing is necessary to equalize the SOC of all the battery cells.

There are two cell balancing techniques: active cell balancing that transfers charge from cells with higher SOC to those with lower SOC and passive cell balancing that discharges cells with higher SOC. At present, passive cell balancing is commonly used since it helps simplify the system configuration. Since a passive cell balancing technique uses MOSFETs as switches to discharge battery cells, it requires as many MOSFETs as the number of battery cells (**Figure 4**).

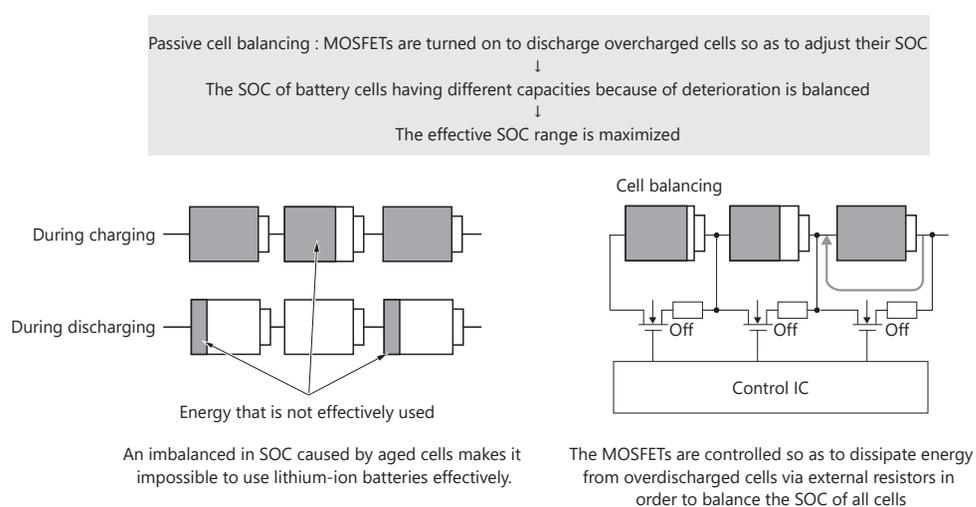


Figure 4. Passive battery cell balancing

The battery capacity is maximized by equalizing the SOC of all battery cells. Since MOSFETs are used as switches to discharge battery cells, a BMS requires as many MOSFETs as the number of battery cells.

3. Trends in photocouplers, photorelays, and MOSFETs

3.1 Development of photocoupler and photorelay technologies

Since we released the first photocouplers and photorelays for automotive applications in 2000, we have more than 15 years of experience in this field. At present, we are developing new products that satisfy the requirements of batteries with an ever-increasing capacity by leveraging the technologies cultivated through our experience in automotive applications. As shown in **Figure 5**, these technologies include: 1) a technology to increase heat resistance of photocouplers and photorelays (i.e., double-molded packaging that reduces thermal stress on an internal device) and 2) a technology to reduce their power consumption (i.e., combining an in-house manufactured high-luminous-efficacy light-emitting diode (LED) and a high-sensitivity photosensor chip).

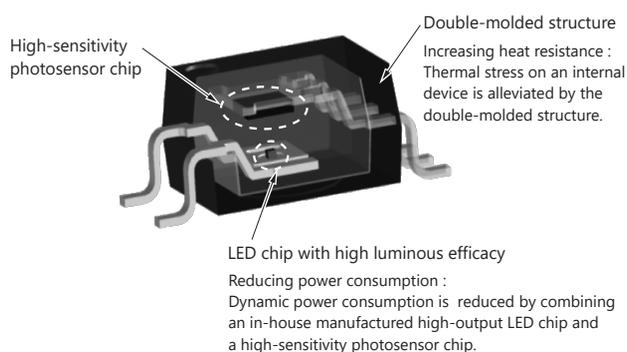


Figure 5. Technologies for photocouplers with high heat resistance and low power consumption

Our efforts for the development of photocouplers are focused on increasing heat resistance using a double-molded package and reducing power consumption through the combination of an LED and a high-sensitivity photosensor chip.

Accompanying the recent increase in the battery capacity, market demand is increasing for photocouplers and photorelays with higher breakdown voltage (BV, i.e., the maximum voltage tolerated across the input and the output) to ensure electrical isolation within a BMS as well as photorelays with higher off-state output terminal voltage (V_{OFF} , i.e., the maximum voltage that can be applied across output terminals in the off state).

To meet this market demand, we are currently developing the following products, which will be available in production quantities in 2020 or later.

- (1) IC-output and transistor-output photocouplers that provide a creepage distance (i.e., the shortest distance along the surface of an insulating material between two conductors) of 8 mm as against the current creepage distance of 5 mm so as to increase breakdown voltage to 5 kV
- (2) Photorelays with an increased creepage distance as is the case with photocouplers and an off-state output terminal voltage of 1,500 V, incorporating a newly developed high-voltage MOSFET chip fabricated using our power semiconductor technology.

3.2 Development of MOSFET technology

Conventionally, cell-balancing MOSFETs have been integrated in battery monitoring ICs. However, in response to a recent increase in battery capacity, MOSFETs are often placed between battery monitoring ICs and battery cells. It is therefore necessary to increase the permissible power dissipation and reduce the on-resistance (R_{on}) of the MOSFETs so as to reduce their heat generation and thereby power losses. Fabricated with a low- $R_{DS(on)}$ trench-gate process, our U-MOS VII n-channel MOSFET series and U-MOS VI p-channel MOSFET series provide more than 60% lower R_{on} than their previous series, reducing the heating of cell-balancing MOSFETs. MOSFETs in the small, thermally enhanced flat-leaded SOT-323F package measuring 2.1 mm × 2.0 mm provide 1.5 times higher permissible power dissipation than those in the gull-wing SOT-323 package having the same size as the SOT-323F. Furthermore, the 1.5-V gate-source voltage (V_{GS}) of the U-MOS VII and U-MOS VI series makes them suitable for low-voltage operation. We are meeting the market demand for higher battery capacity through these MOSFET and packaging technologies.

4. Conclusion

As the sales of green vehicles continue to grow, automobile manufacturers are expected to strive to reduce their prices and increase the per-charge travel distance.

As a result, the importance of the BMS will further increase in improving battery utilization efficiency and thereby reducing the size of a battery unit.

We will continue to provide semiconductor devices that satisfy various requirements of BMS applications so as to contribute to the development of the automobile industry.

References

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