

High Gate Voltage MOSFETs for Li-ion Battery-Monitoring IC

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In this paper, we propose a novel type of high gate voltage metal-oxide-semiconductor field-effect transistor (MOSFET) with long-term reliability that uses STI (shallow trench isolation) for the gate oxide film of the transistor mounted on the Battery-Monitoring IC. Battery-Monitoring ICs are semiconductors installed in BMUs (Battery Management ECUs) for ensuring the safety and improving efficiency of many lithium-ion (Li-ion) batteries installed in electric vehicles. As the capacity of Li-ion battery cells installed in vehicles is increasing, ICs are required to have higher voltage capability and higher density than ever before. With this new MOSFET, we succeeded in reducing the number of MOSFETs mounted on the IC and reduced the chip size to 1/3 compared to the conventional one.

Key words :

Li-ion Battery, Battery-Monitoring IC, MOSFET, STI, high gate voltage

1. Introduction

Electrified vehicles with installed batteries such as hybrid electric vehicles (HEVs), battery electric vehicles (BEVs), and plug-in hybrid electric vehicles (PHEVs) are used widely around the world to reduce greenhouse gas (GHG) emissions from fossil fuel combustion. To use high-power traction motors efficiently, these electrified vehicles generally have high-voltage lithium-ion (Li-ion) batteries (500 V or higher) installed (Fig. 1)¹⁾. High-voltage Li-ion batteries tend to feature numerous cells arranged in series. For that reason, managing the voltage and temperature of each cell carefully during charging

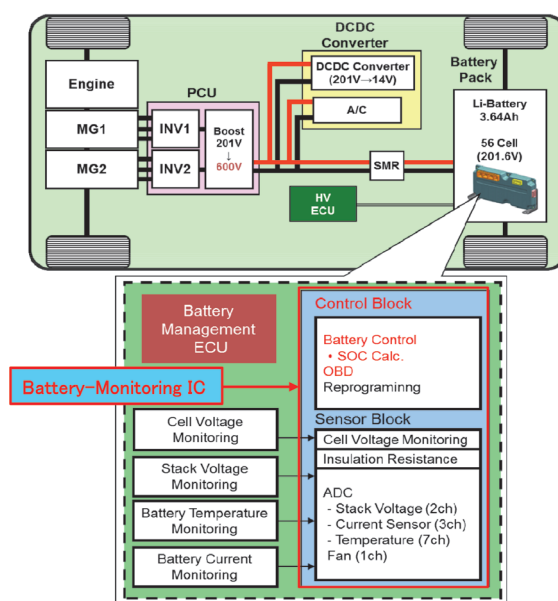


Fig. 1 HEVs System Configuration

and discharging is crucially important. To accomplish this objective, Battery-Monitoring ICs in the Battery Management ECU (BMU) must monitor the status of each cell constantly.

In this paper, we propose high gate voltage drive of MOSFET for the purpose of miniaturization of IC and simplification of circuit design, and describe the result of actual design and evaluation.

2. High Gate Voltage MOSFET Technology

2.1 Structure and Manufacturing Method

Generally, the Battery-Monitoring ICs consist of low-voltage and high-voltage blocks that are fabricated using sub-micron semiconductor process technology, as shown in Fig. 2. A conventional IC for managing 20 battery cells includes 2,688 low gate voltage MOSFETs with complex circuit topology in the high-voltage block. The reason why so many MOSFETs are needed is that the gate oxide of these MOSFETs are less than $0.05\mu\text{m}$ thick and cannot achieve high gate voltages (150 V and above). In general, the gate oxide is formed by thermal oxidation. However, the thermal oxidation causes an unexpected impurity distribution in the MOSFETs. It is therefore difficult to form a thick gate oxide by thermal oxidation.

Therefore, we focused on shallow trench isolation (STI) to realize thick gate oxides in MOSFETs, as shown in Fig. 3. The process of STI consists of dry etching for Si and silicon dioxide deposition by chemical vapor deposition (CVD) at low temperatures. This process has been used conventionally for element-to-element separation on IC chips, but it has never been used to form a gate oxide of MOSFETs. To use STI processing for gate oxide formation, two problems had to be overcome: (1) uniformity of gate oxide thickness and (2) suppression of hydrogen inward-outward diffusion.

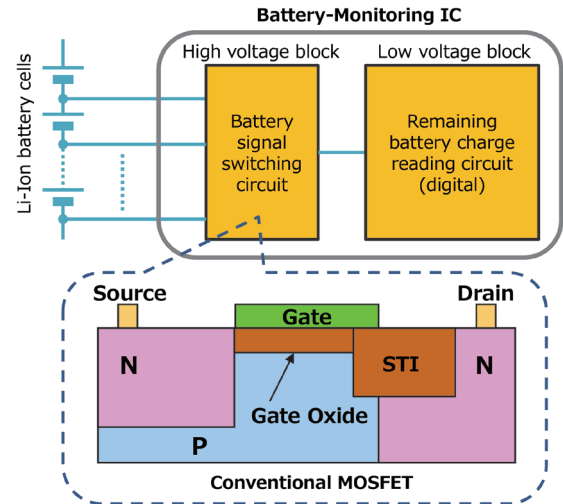


Fig. 2 Battery-Monitoring ICs configuration and sectional view of conventional MOSFET

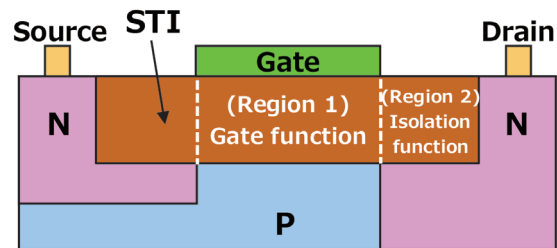


Fig. 3 Sectional view of new MOSFET

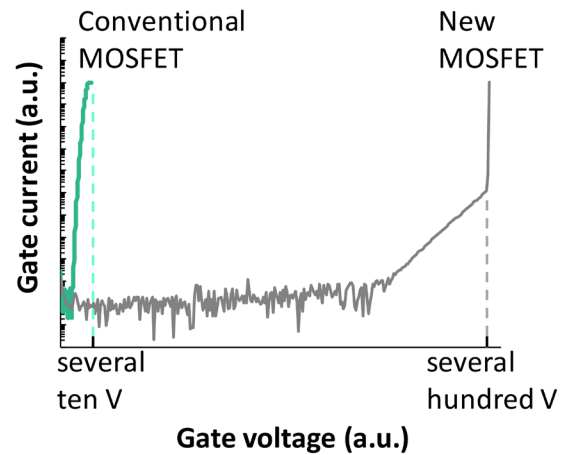


Fig. 4 Dielectric breakdown voltage of the gate oxide

Key point (1):

We applied the STI process. Then the silicon dioxide was etched back using chemical mechanical polishing (CMP) to obtain good uniformity of the thick gate oxide. As a result, we formed thick silicon dioxide for gate function and isolation function at the same time (Regions 1 and 2 in Fig. 3). The dielectric breakdown

voltage of the gate oxide is shown in Fig. 4. The oxide layer thickness is roughly seven times greater than that of the conventional oxide layer, thereby enabling gate breakdown voltage of several hundreds of volts.

Key point (2):

During silicon dioxide deposition by CVD, H atom is introduced into the silicon dioxide from the silane gas, which is the Si atom source. The H atom induces threshold voltage fluctuation of ΔV_{th} (Fig. 5) during device operation. To resolve this difficulty, the STI film is modified by process conditions such as heat treatment to prevent H from entering and exiting the STI film, and gate oxide formed by STI processing.

2.2 Reliability

To identify the long-term reliability of the STI gate oxide several decades later, an accelerated stress test was conducted using the following parameters: ambient temperature (T_a), applied gate voltage (V_g),

and time stress (t_s).

Fig. 5 shows Negative Bias Temperature Instability (NBTI) test results for (a) n-type and (b) p-type MOSFETs. When a negative bias ($V_g = -74$ to -150 V) is applied to the gate electrode, H^+ atoms (+ ions) in the STI diffuse to the gate from the vicinity of the channel up to the initial < 50 s. Then, H^+ atoms are accumulated under the gate, resulting in a ΔV_{th} increase ((A) in Fig. 4). Because the gate bias affects the H^+ atom diffusion, ΔV_{th} depends on V_g . Subsequently, at > 50 s, hole traps are generated at the STI– Si interface; the resulting ΔV_{th} decreases ((B) in Fig. 5).

The ΔV_{th} value after 19 years was calculated by extrapolation from the obtained curve. This method reflects a report stating that, in the case of interface charge trap density, ΔV_{th} changes with respect to time in accordance with the relation $\ln(t)^{-2}$. Results demonstrate that ΔV_{th} after 19 years rises in

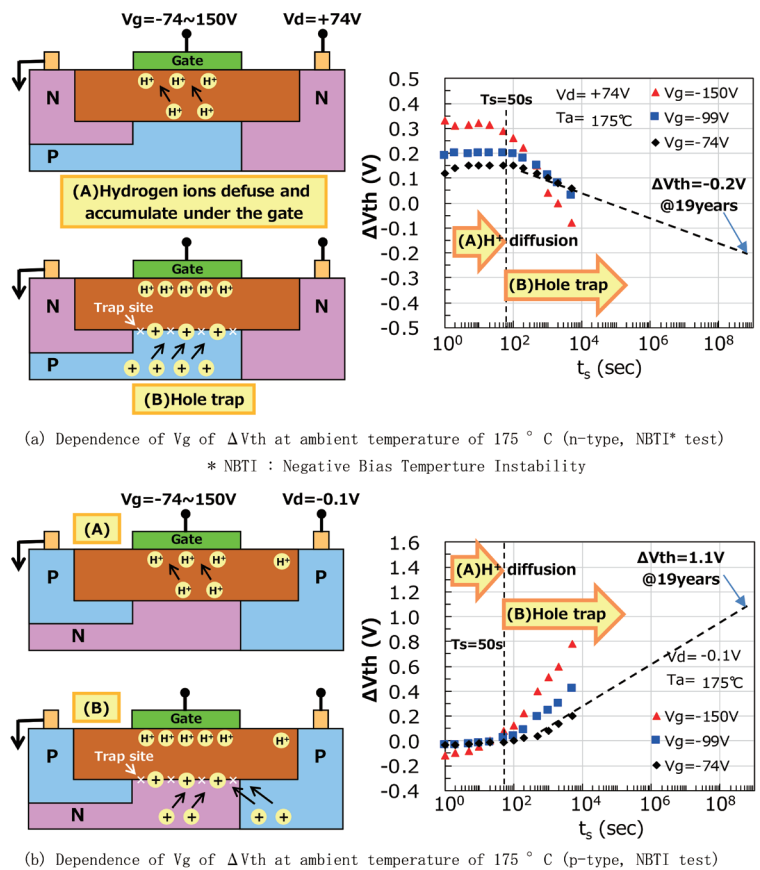


Fig. 5 ΔV_{th} Fluctuations in the STI Gate Oxide Layer Stress Test

accordance with the increase in T_a and V_g . However, when T_a is 175 °C and V_g is -74 V, the n-type voltage fluctuation in Fig. 4 is as small as -0.2 V; also, the p-type voltage fluctuation is as small as 1.1 V. Furthermore, it is presumed from this result that long-term reliability can be ensured by setting V_g to -74 V or less. Results also show that the charge density of the interface trap was of an amount that presented no difficulty (Fig.4, Table 1).

Based on the results presented above, High-Gate voltage MOSFET that uses STI have been found to be practical for Battery-Monitoring ICs.

Table 1 Summary of STI Gate MOSFET Interface Trap Charge Density, and ΔV_{th}

New MOSFET	Interface trap charge density (cm ⁻²)	Estimated fluctuation in ΔV_{th} after 19 years (V) @ $T_a=175^\circ\text{C}$
N type	1.5×10^{10}	-0.2
P type	7.8×10^9	+1.1

3. Effect on Battery-Monitoring IC

Fig. 6 presents a comparison of a single IC in the high-voltage block with conventional and new Battery-Monitoring ICs. The high-voltage block of the conventional IC requires 2,688 low gate voltage MOSFETs to monitor 20 Li-ion battery cells. By contrast, the new IC uses only 320 high gate voltage MOSFETs to monitor 24 Li-ion battery cells. Therefore, its number is approximately one-eighth of the conventional IC.

Fig. 7 presents the number of MOSFETs mounted on the Battery-Monitoring ICs for a battery system with total voltage of 480 V. In the conventional BMU (Fig. 7(a)), each Battery-Monitoring IC is monitoring 20 cells; the total required five Battery-Monitoring ICs to monitor 96 cells. Consequently, the conventional BMU requires 13,440 low gate voltage MOSFETs to monitor all 96 cells. Because the number of low

gate voltage MOSFETs mounted on an IC must be increased to match increases in the total battery system voltage, the conventional IC might be unable to respond easily to future increases in battery system voltage. However, in the new Battery-Monitoring ICs with high gate voltage MOSFETs, a single IC is capable of monitoring 24 cells. Therefore, four new Battery-Monitoring ICs, which only require 1,280 high gate voltage MOSFETs, are used to monitor 96 cells.

Fig. 8 shows that a single conventional Battery-Monitoring IC is divided into a low voltage chip and high voltage chip. For the new Battery-Monitoring IC, because the size of the high voltage block can be reduced, both the low and high voltage blocks can be integrated into a single chip. Consequently, the single Battery-Monitoring IC size can be reduced by approximately 62%. This reduction simplifies the mounting of IC chips, supporting the production of a low cost and highly competitive product.

The performance characteristics of the conventional and new Battery-Monitoring IC are presented in Table 2.

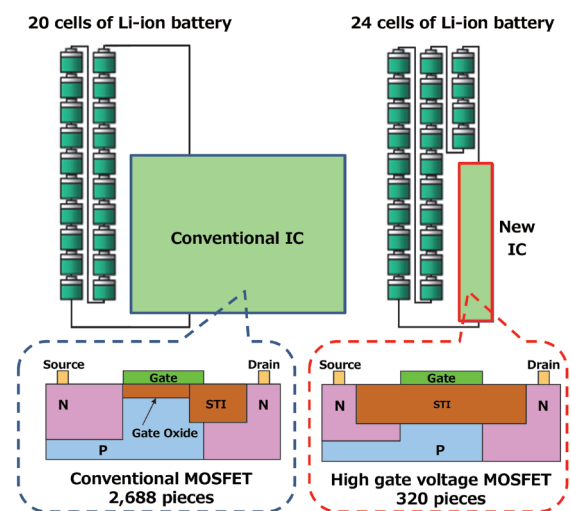


Fig. 6 Numbers of MOSFETs Mounted Respectively on Conventional and New ICs

Table 2 Comparison of Numbers of MOSFETs and Sizes in Conventional and New Battery-Monitoring ICs

Battery-Monitoring IC	Number of MOSFETs	Size (%)
Conventional	2,688	100
New	320	38

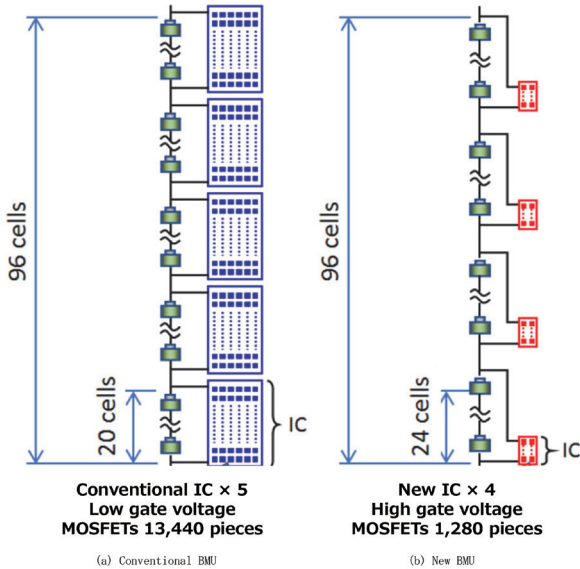


Fig. 7 Configuration of Conventional and New Battery-Monitoring ICs

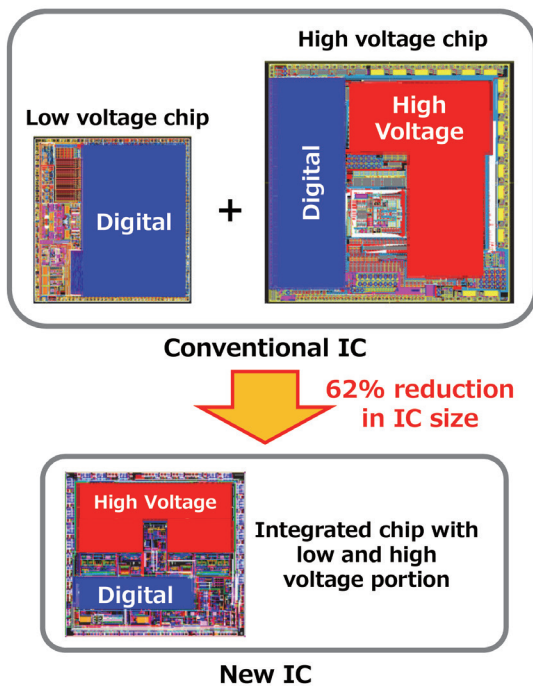


Fig. 8 Conventional and New Battery-Monitoring ICs

4. Conclusion

Joint research by DENSO Corporation and TOYOTA CENTRAL R&D LABS., INC. has developed a new MOSFET for a new Li-ion Battery-Monitoring IC. Although the new IC size is only one-third of the size of a conventional IC, it can monitor battery cells with 1.2 times higher capacity than the conventional IC. Development of high gate voltage MOSFETs is necessary for size reduction because the density of battery cells that must be monitored in an electrified vehicle is expected to increase in the future. This project achieved the world's first MOSFET with gate breakdown voltage of several hundred V by adoption of STI for the gate oxide layer. Durability of the developed MOSFET was verified under practical conditions. Since 2020, these high-gate voltage MOSFETs have been installed in the high-voltage part of the new lithium-ion Battery-Monitoring IC of BMU for HEV. The newly developed Li-ion Battery-Monitoring IC can also be adopted for applications other than vehicle technology, such as electrification systems for aircraft and home energy Monitoring systems (HEMS).

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