150V Power MOSFET U-MOSⅩ-H series for Telecom and data server Application note

Overview

Contents that require high-capacity and communication speeds, such as video streaming, have increased, and launched 5G (5th-generation mobile communications system) services cause base stations and data servers have dramatically increased in power consumption. As a result, there is a growing demand for more efficient switching power supplies. High-performance MOSFET are required for switching power supplies for these communication base stations and data servers, and the importance of improved device performance is growing day by day to improve efficiency of power supply.

Toshiba Electronic Devices & Storage Corporation ("Toshiba") has developed a U-MOSX-H 150V processed power MOSFET (metal-oxide semiconductor-type field-effect transistor) with drastically improved on-resistance and charge-capacity trade-off characteristics for highly efficient power supplies for communication base stations and data servers.

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1. Application of 150V MOSFET

1.1. Application using 48V power line, for which demand increasing

DC-48V is used to power for telecom base stations from the start of fixed-line phones to the present. It is said that the reason for the negative voltage is to prevent ionization of copper wire due to long wiring. DC-48V are also used to power for telecom infrastructures including present-day base stations, and demand for switching power supplies is increasing day by day due to growing demand for telecommunications. The base station is equipped with a AC-DC converter that generates DC-48V (actually, it is acceptable to use it up to DC-60V in anticipation of a voltage-drop) from AC 200V (up to 240V) of the commercial AC power supply. In addition, the high-frequency amplifiers used in base station radio transmitters work with DC 52V (up to 56V) and that voltage is generated by integrated DC-DC converters converting from DC-48V BUS line to DC 48V (up to 60V). Until more than 10 years ago, the performance of MOSFET was insufficient, and the output power of radio base stations was also not required to be so high because of low demand for communications. Therefore, the rectifier circuits for these switching power supplies were mainly diode-based. However, in recent years, synchronous rectifiers have been used for almost all of them in communication base stations that require high-efficiency due to improvements in control and MOSFET performance.

On the other hand, the data server was using DC 12V as common computing, which is distributed from AC-DC power supply in racks. However, in case of recent server power dissipation exceeds 10kW, the slight loss of resistance on wiring is not negligible for energy saving. Therefore, the power distribution using DC 48V become popular for server application as well as telecom base station.

1.2. Application circuit topology and operation
1.2.1. AC-DC converter for Telecom

This chapter introduces typical circuitry of AC-DC converter that receives AC 200V (up to 240V) of the commercial AC power supply and outputs DC-48V (up to -60V) as the standard voltage for telecom and the drain-source voltage required for the MOSFET as synchronous rectification (SR) on such circuit.

The maximum voltage supplied on the MOSFET as the center-tap SR in type-1 circuit shown in Table 1.2.1. is more than double the output voltage including the safety margin for voltage spike. Based on this, 150V MOSFET is a good choice for SR for this circuit type. The driving circuit for this can be simplified thanks to less MOSFETs and same voltage potential between the driving circuit and MOSFETs.

In terms of the full-bridge SR in type-2 circuit in Table1.2.1., the maximum voltage supplied on the SR-MOSFET is half the voltage of SR-MOSFET of center-tap. It means that 80V MOSFET is applicable for full-bridge SR, and it enables less conduction losses on SR-MOSFETs in total due to lower total on-resistance of two 80V MOSFETs in series compared with that of single 150V MOSFET in center-tap. Even though the multitude of SR-MOSFETs and different voltage potential

between driver and the source of high-side MOSFET require complicated circuit diagram and make the total cost higher relatively, full bridge SR is commonly used topology in high-power high-efficiency power supplies.

Table1.2.1 Typical Circuit of AC-DC Converter for Telecom/Base Station

Topology	Circuit	SR Waveform	SR voltage	Merit/demerit
Type-1 PFC + LLC + Center-tap SR		*It doesn't work as ZCS under over load condition	150 V	Merit : ・The smallest quantity is 2pcs in SR part. ・The drive circuit can be made easily because the circuit works based on GND. Demerit : ・The device needs two times break down voltage as Full-bridge SR
Type-2 PFC + LLC + Full-bridge SR		*It doesn't work as ZCS under over load condition	80V	Merit : ・The device needs half of break down voltage as Center-tap SR Demerit : ・Full-bridge SR circuit needs 4 devices minimum. ・The drive circuit of high-side doesn't work based on GND, so it needs pull-up circuit like boot strap.

SR: Synchronous Rectifier

PFC: Power Factor Correction

LLC: Resonant Converter with L(inductor: Lp) + L(inductor: Lr) + C(Capacitor)

1.2.2. DC-DC converter for RF amplifier of Telecom

This chapter introduces typical circuitry of DC-DC converter that receives DC-48V (minimum: -36V, maximum: -60V) as the standard voltage of telecom and outputs DC 52V (up to 56V) for RF amplifiers and the drain-source voltage required for the MOSFET as synchronous rectification (SR) on such circuit.

DC-DC converter regulates output voltage by controlling duty cycle for covering input voltage variation. (PFC in AC-DC converter plays the similar role.) The duty ratio is designed to be maximum (about 100%) for regulation when the input voltage is minimum and output power is maximum. When the input voltage increases, the duty ratio decreases accordingly, while the voltage applied to the rectifier element increases in proportion to the input voltage.

The maximum voltage supplied on the SR-MOSFET in the full-bridge SR in type-1 circuit in Table 1.2.2. is half the voltage of SR-MOSFET of center-tap. Considering doubled input voltage, the voltage applied on SR-MOSFET should be more than double the output voltage. Therefore, the MOSFETs of full-bridge SR in DC-DC converter that accept double range of input voltage with 56V maximum output voltage shall have at least 112V as drain-source voltage rating. Actually, 150V MOSFET is preferred among general product line-up based on this point of view, with the safety margin taken in consideration.

In terms of the center-tapped SR circuit shown in type-2 circuit in table 1.2.2., considering doubled input voltage, the voltage applied on SR-MOSFET is more than 4 times the output

voltage. Therefore, the MOSFETs of center-tap SR in DC-DC converter shall be at least 224V as drain-source voltage rating. 250V is the best rating choice among general product line-up with the safety margin taken in consideration. Comparing on the same generation and the same technology, the on-resistance and reverse recovery characteristics of 250V MOSFET is less than that of 150V MOSFET, therefore in most of the cases the full-bridge SR topology using 150V MOSFET is preferred for PF amplifier application that require isolation.

In case of the buck-boost circuit of type-3 shown on table 1.2.2., the breakdown voltage required for MOSFETs in this circuit shall be more than the gap between the input voltage and the output voltage. For instance, the MOSFETs (both SW side and SR side) on the DC-DC converter which has -60V input and 56V output shall have more than 116V rating. As with other circuit schemes, the MOSFETs on SR side require low reverse-recovery charge and low on-resistance characteristics for higher efficiency, and SW side require high-speed switching and low on-resistance characteristics as well. The biggest advantage on the buck-boost converter comparing with the isolated converter is low cost due to less expensive components like as sophisticated controller IC and coupled transformer for isolation. In addition, downsizing of the DC-DC converter is also expected due to relatively higher operating frequency compared with isolated converter, however, the type of DC-DC converter, isolation or non-isolation, shall be selected based on the laws and/or regulations of each region that the telecom unit used.

Table 1.2.2 Typical Circuit of DC-DC Converter for RF Amplifier in Base Station

Topology	Circuit	SR Waveform	SR voltage	Merit/demerit
Type-1 Full-bridge + Full-bridge SR		Minimum break down voltage : Output voltage * input voltage ratio (min/Max)	150 V	Merit : ・The device needs half of break down voltage as Center-tap SR. Demerit : ・Full-bridge SR circuit needs 4 devices minimum. ・The drive circuit of high-side doesn't work based on GND, so it needs pull-up circuit like boot strap.
Type-2 Full-bridge + Center-tap SR		Minimum break down voltage : Output voltage * input voltage ratio * 2	250V	Merit : ・The smallest quantity is 2pcs in SR part. ・The drive circuit can be made easily because the circuit works based on GND. Demerit : ・The device needs two times break down voltage as Full-bridge SR
Type-3 Buck Boost		Minimum break down voltage : Output voltage – input voltage (<0)	150V	Merit : ・The smallest quantity is 2pcs sum of SW-side and SR-side. ・The device needs half of break down voltage as Center-tap SR. ・Both SW-side and SR-side can be driven by simple 1-piece driver-controller. Demerit : ・This topology cannot be isolated between input and output.

2. Introduction of U-MOSⅩ-H 150V process

2.1. Features

The essential characteristics for the MOSFET to increase the efficiency of the power supply are low on-resistance ($R_{DS(ON)}$) for reducing conduction loss and low gate switch charge (Q_{sw}), low output charge (Q_{oss}), low reverse-recovery charge (Q_{rr}) for reducing switching loss. Generally, the miniaturized cell pitch design enables to reduce $R_{DS(ON)}$, whoever it makes Q_g, Q_{oss}, Q_{rr} increase as trade-off. Therefore, the F.O.M (Figure of Merits) like as on-resistance and gate-switch charge ($R_{DS(ON)} \cdot Q_{sw}$), on-resistance and output-charge ($R_{DS(ON)} \cdot Q_{oss}$), and on-resistance and reverse-recovery charge ($R_{DS(ON)} \cdot Q_{rr}$) shall be visible indicators reflecting the MOSFET's total performance.

Aiming to reduce power losses during both conduction and switching in switching power supply, 150V N-channel power MOSFET that uses the latest generation process, "U-MOSX-H" has been released for industrial equipment including those deployed in data centers and communications base stations, which has with the improvements of $R_{DS(ON)}$ by 38%, $R_{DS(ON)} \cdot Q_{sw}$ by 12%, $R_{DS(ON)} \cdot Q_{oss}$ by 20%, and $R_{DS(ON)} \cdot Q_{rr}$ by 57% comparing with the conventional-generation process, "U-MOSVIII-H". Furthermore, especially for synchronous rectifier application, high-speed diodes (HSD) type has been added on the line-up, which incorporates lifetime control technology to reduce losses and spike-voltage during the time period of reverse-recovery and enables further characteristic improvements as $R_{DS(ON)} \cdot Q_{rr}$ by 74% comparing with STD type. In addition, U-MOSX-H guarantees 175°C as the maximum rating of channel temperature against 150°C on conventional U-MOSVIII-H.

These features contribute to realize value-added power supply by efficiency improvement, downsizing, and cost saving. (Fig. 2.1.)
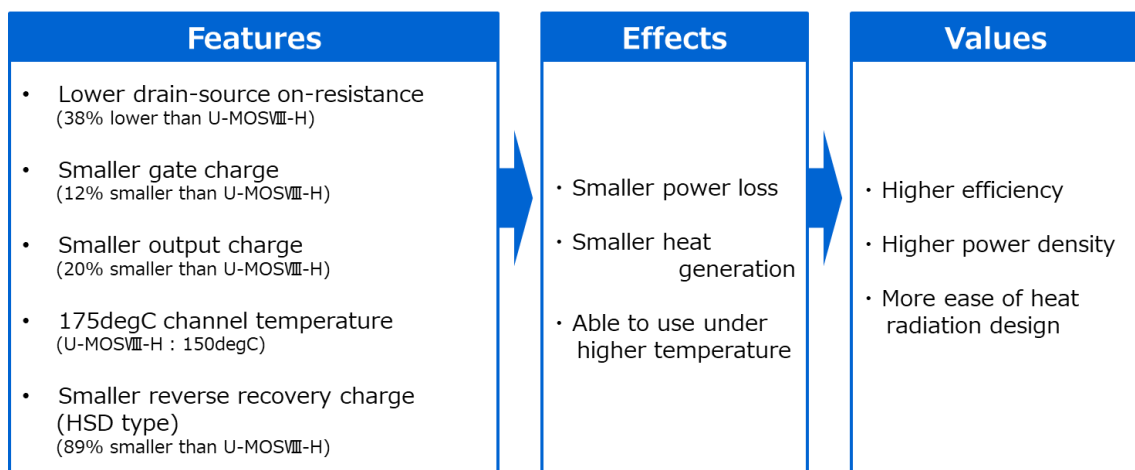
Features	Effects	Values
• Lower drain-source on-resistance (38% lower than U-MOSⅧ-H) • Smaller gate charge (12% smaller than U-MOSⅧ-H) • Smaller output charge (20% smaller than U-MOSⅧ-H) • 175degC channel temperature (U-MOSⅧ-H : 150degC) • Smaller reverse recovery charge (HSD type) (89% smaller than U-MOSⅧ-H)	· Smaller power loss · Smaller heat generation · Able to use under higher temperature	· Higher efficiency · Higher power density · More ease of heat radiation design

Figure 2.1. Features, Effects and Values of U-MOSX-H 150V

2.2. Characteristics
2.2.1. Drain to source on-resistance ($R_{DS(ON)}$)

U-MOSX-H 150V has achieved an on-resistance reduction of 38% compared to conventional U-MOSVIII-H 150V by using a state-of-the-art trench gate design (Fig. 2.2.1). Besides this silicon process improvement, the package resistance also has been reduced by Cu-connector technology adopted on all of the line-up of SOP Advance (N) (5x6) and TSON Advance (3x3), which covers FET area widely on chip (Fig. 2.2.2).

This reduces conduction loss and improves efficiency of power supply and contribute to downsizing and cost saving of power supply by reducing the number of parallel MOSFET usage and minimizing the cooling system.
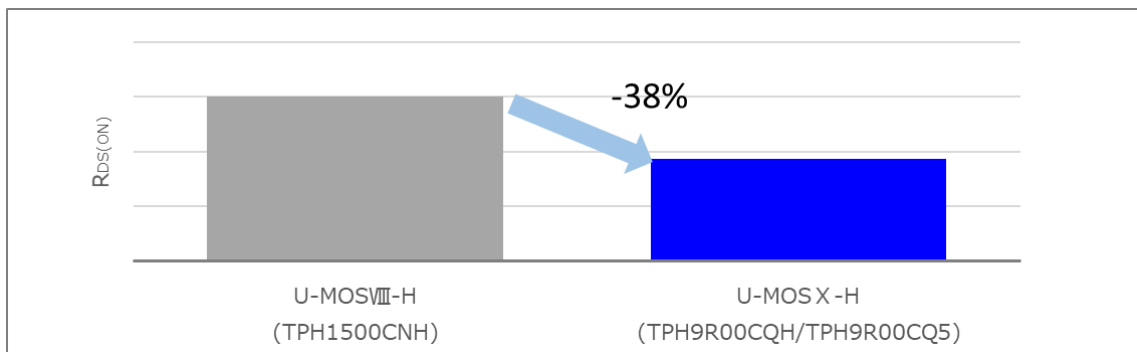
Figure 2.2.1. $R_{DS(ON)}$ comparison by generation
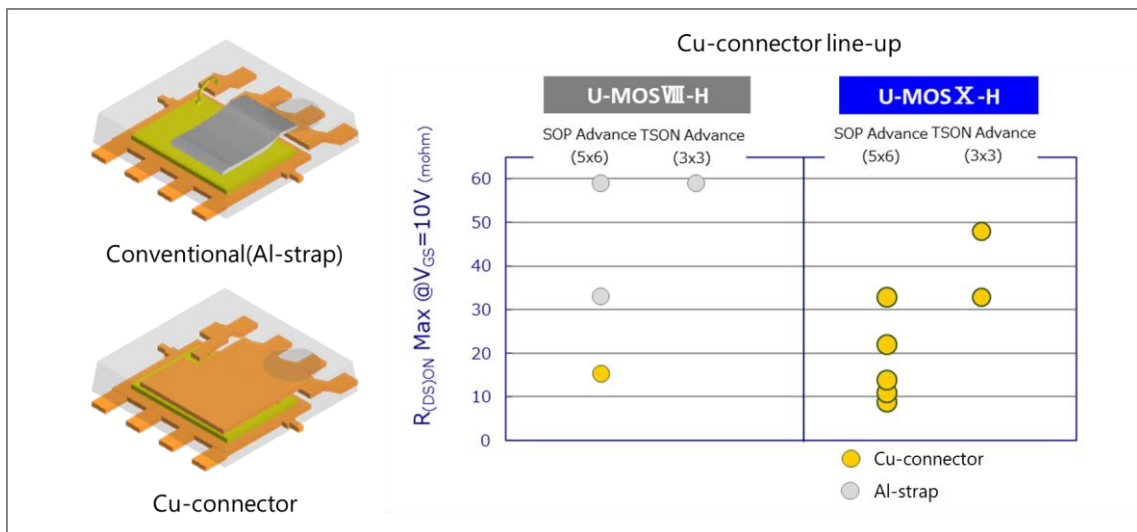
Figure 2.2.2. $R_{DS(ON)}$ comparison between Cu-connector and conventional structure

2.2.2. Output charge (Q_{oss})

The output charges (Q_{oss}) repeated charge and discharge in switching operation through the gate capacitance (C_{oss}) make power loss as a part of switching loss. U-MOSX-H 150V reduces Q_{oss} by 20% in comparison with the same on-resistance device of U-MOSVIII.   (Fig. 2.2.3)
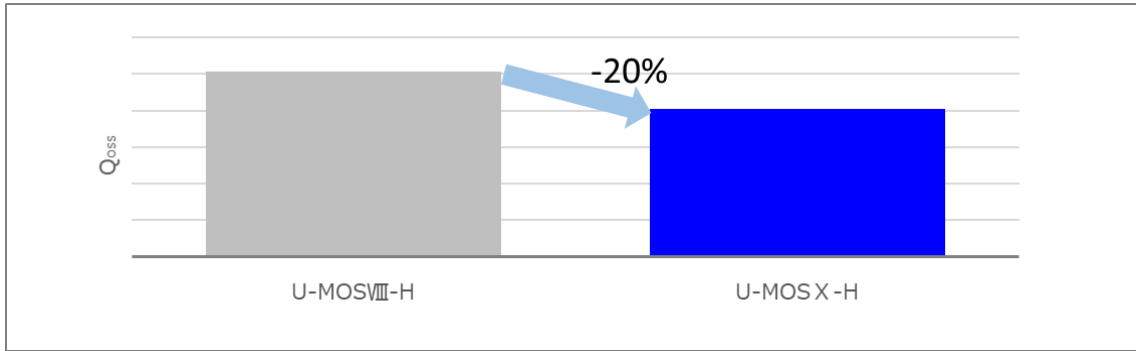
Figure 2.2.3.　Q_{oss} comparison by generation with same on-resistance device

2.2.3. Reverse recovery charge (Q_{rr})

The reverse recovery mode is observed in SR-MOSFET at the timing of changing the bias direction steeply just after the forward conduction of the body-diode. A reverse current (I_{DR}) flowing remains in the body-diode for the time (t_{rr}: reverse recovery time) until the carriers (holes and electrons) accumulated in n-type semiconductor are extinguished by discharge or recombination (Fig. 2.2.4). The reverse charges (Q_{rr}) make switching loss called as reverse-recovery loss.
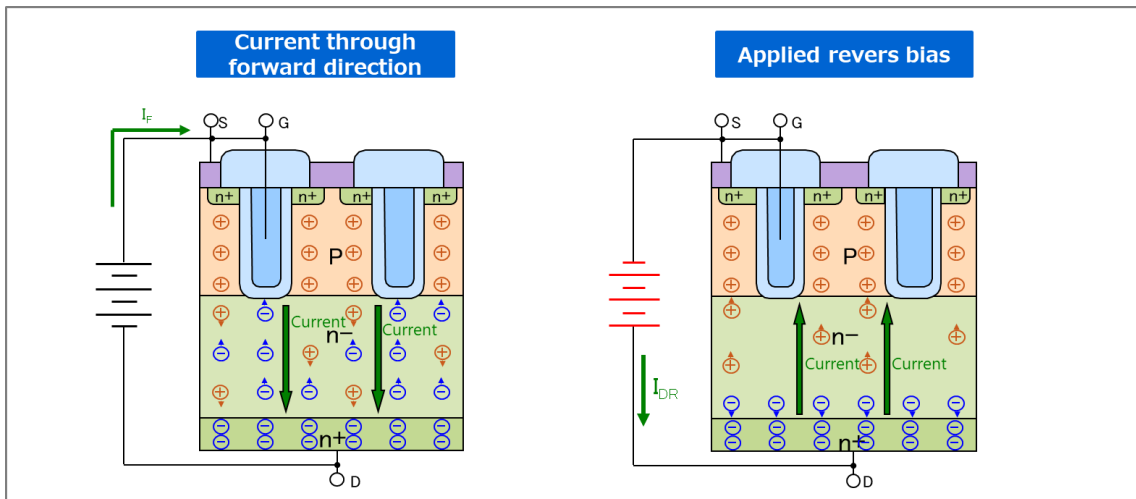
Figure 2.2.4. Hole and electron behavior during reverse recovery mode

Selecting the MOSFET with lower on-resistance or connecting MOSFETs in parallel helps to reduce total on-resistance, however in contrast, these approaches may increase the reverse-recovery loss exceeding the conduction loss due to increased Q_{rr}. In order to solve this dilemma, high-speed diode (HSD) type has been developed to realize further Q_{rr} reduction without any sacrificing on other characteristics, in which carrier traps are introduced to restrict carrier migration through recombination. Figure 2.2.5. shows the difference in behavior during reverse-recovery operation between HSD and standard (STD) product that does not incorporate this process.

In addition to the Q_{rr} reduction by 57% on standard (STD) U-MOSX-H against U-MOSVIII-H in comparison with the same on-resistance class, HSD type of U-MOSX-H achieves Q_{rr} reduction by

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74% against STD type of U-MOSX-H and 89% against U-MOSVIII-H in comparison with the same on-resistance class. (Fig. 2.2.6)
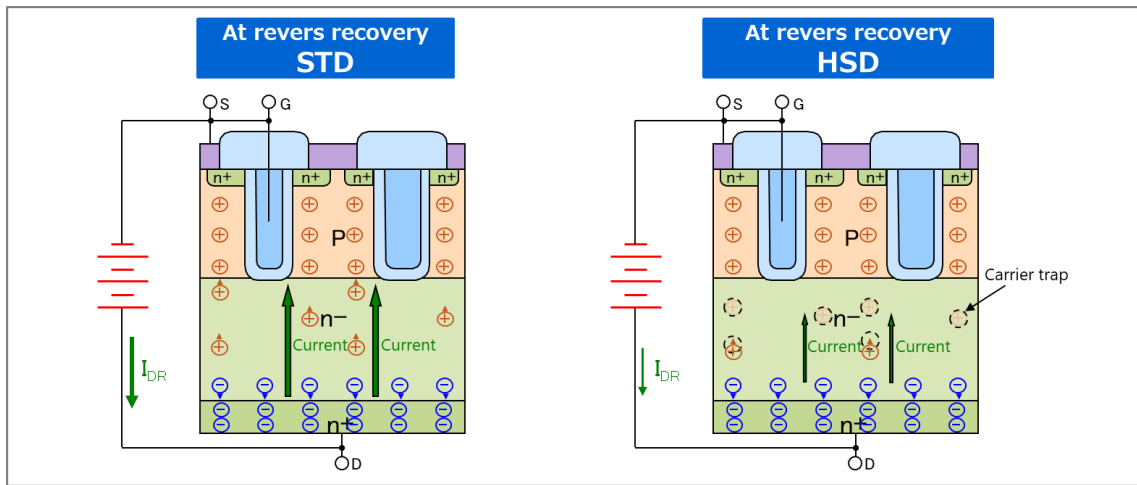

Figure 2.2.5. Differences in Bias-Inverted Behavior of Standard (STD) and High-Speed Diode (HSD)
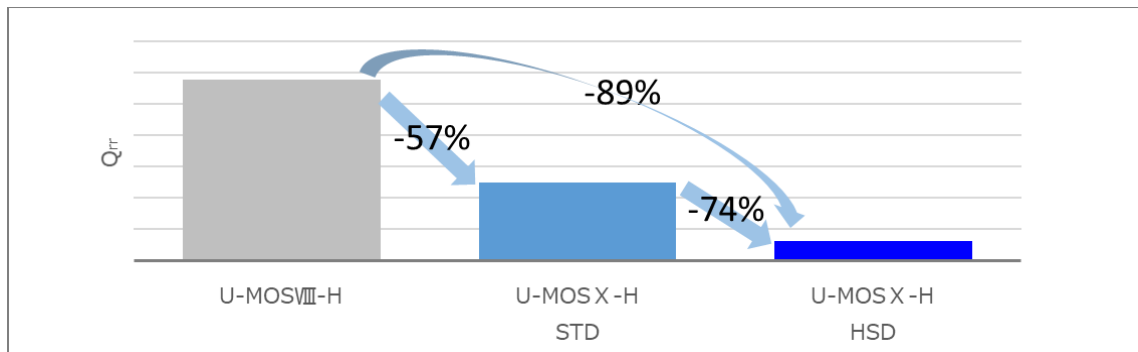

Figure 2.2.6. Q_{rr} comparison by generation with same on-resistance device

AC-DC and DC-DC, both converters consist of switching (SW) device and synchronous rectification (SR) device. Duty ratio for regulation is controlled by SW device, and then SR devices rectify and convert it into direct current. Generally, the faster switching condition is preferred in order to reduce the switching loss on SW device, however on the other hand, it may increase the reverse recovery loss on SR device since Q_{rr} increase in proportion to dI/dt as shown in Fig.2.2.7.
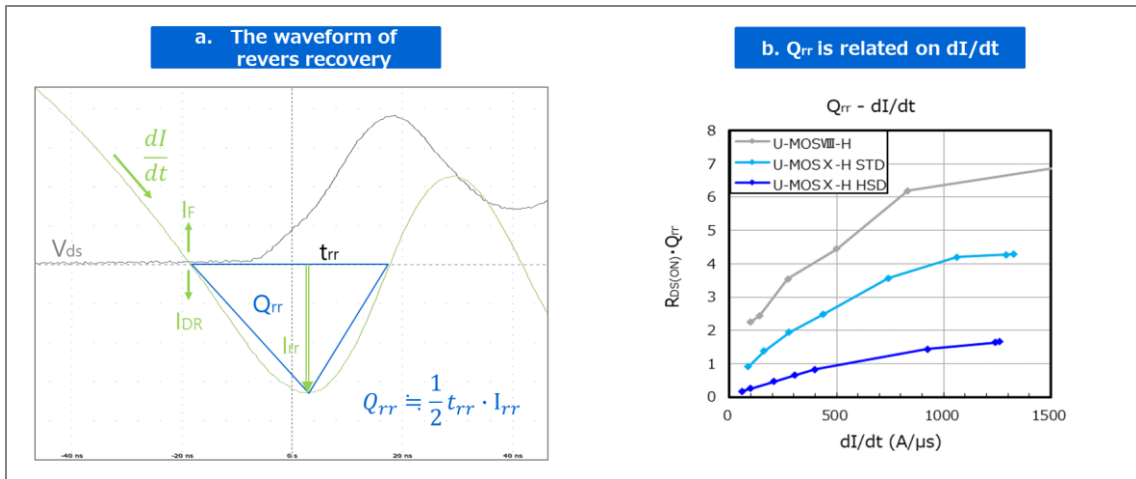   U-MOSX-H (especially HSD type) is more effective in reducing loss due to Q_{rr} under large dI/dt condition.

Figure 2.2.7. dI/dt dependency on Q_{rr}

In addition, Q_{rr} has a negative influence not only on loss increase, but also on voltage spike. In the reverse recovery mode, as the carriers eject or disappear, the depletion layer expands and V_{DS} increases. Due to the parasitic inductances of the elements and circuitry, V_{DS} increase become steep while I_{rr} change, and keep rising until reverse recovery completion while t_{rr}. The   peak voltage of V_{DS} is defined as V_{DS_peak} here. As shown in Fig.2.2.8.a, V_{DS_peak} increase as Q_{rr} increase, since Q_{rr} has a positive dependence on dI/dt and V_{DS_peak} has a positive dependence on dI/dt as well (Fig.2.2.8.b). Comparing under dI/dt=100A/μs condition, U-MOSX-H HSD achieves a 45% reduction in V_{DS_peak} compared to STD and a 66% reduction against U-MOSVIII-H (Fig. 2.2.9).
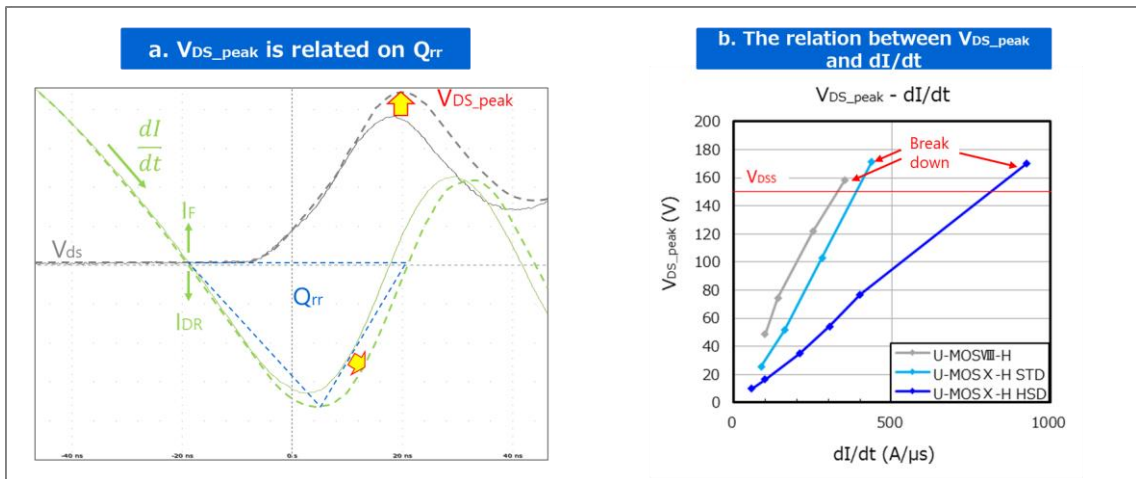

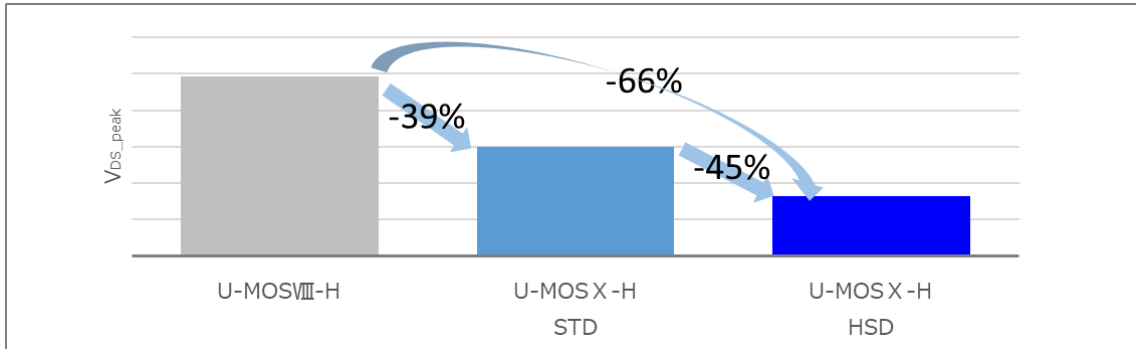Figure 2.2.8. The factors influenced on V_{DS_peak}

Figure 2.2.9. V_{DS_peak} comparison by generation and type of technology

V_{DS_peak} shall be required to be less than the maximum rating of $V_{(BR)DSS}$. Therefore V_{DS_peak} reduction allows relatively higher dI/dt condition which reduces the switching losses on SW devices. This is a big impact to improve the efficiency of switching power supply in total. Fig. 2.2.10. shows an example. In comparison at V_{DS_peak}=150V, U-MOSX-H HSD allows 212% higher dI/dt against STD type and 250% higher dI/dt against U-MOSVIII-H.
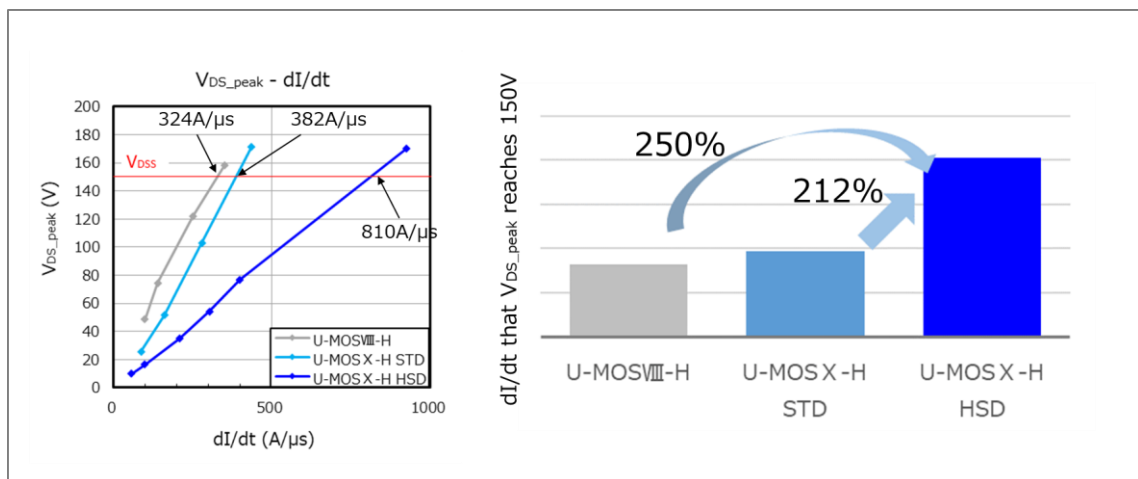

Figure 2.2.10. Comparing dI/dt availability by generation

2.2.4. Characteristics comparison

Table 2.1. comparing the properties of U-MOSVIII-H, U-MOSX-H STD, U-MOSX-H HSD.

Table 2.1. Characteristics

Item	U-MOSⅧ-H TPH1500CNH	U-MOSⅩ-H STD TPH9R00CQH	U-MOSⅩ-H HSD TPH9R00CQ5
Channel Temperature	150degC	175degC	175degC
V_{th}	2.0V～4.0V	3.3V～4.3V	3.1V～4.5V
$R_{DS(ON)typ}$ at 8V	-	7.9 mΩ	7.9 mΩ
$R_{DS(ON)typ}$ at 10V	13 mΩ	7.3 mΩ	7.3 mΩ
$Q_{SW(V_{DS}=75V)}$	8.3 nC	11.7 nC	11.7 nC
$Q_{oss(V_{DS}=75V)}$	67.4 nC	87 nC	87 nC
$Q_{rr(dI/dt=100A/\mu s)}$	192 nC	133 nC	45 nC

2.3. Evaluation result on the application circuit

2.3.1. 1kW Phase-Shift Full-Bridge Synchronous Rectifier DC-DC Converter Reference Design

2.3.1.1. Reference Design Overview

This reference design is a 1kW phase-shifted-full-bridge (PSFB) synchronous rectified DC-DC converter that conforms to the standard of telecom power supply, which has the input voltage range as DC-60V to -36V and transforms to 54V output for high power RF amplifier. TI's Phase-Shift Full-Bridge Controller UCC28951PWR is used for the controller, and 5mm x 6mm sized surface mount power MOSFET are selected (Fig. 2.3.1).
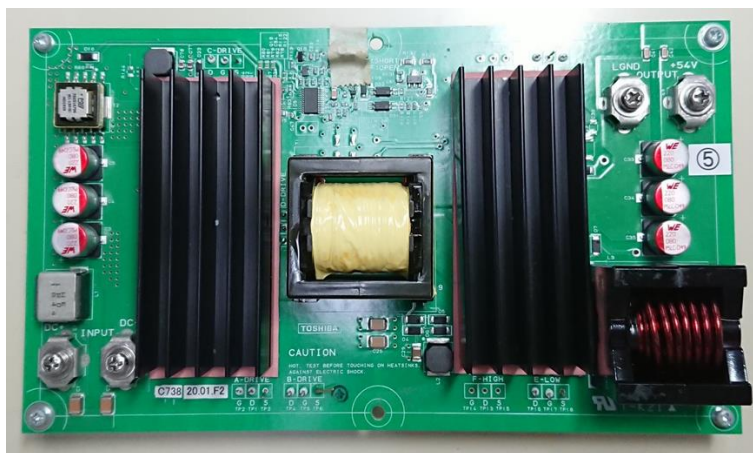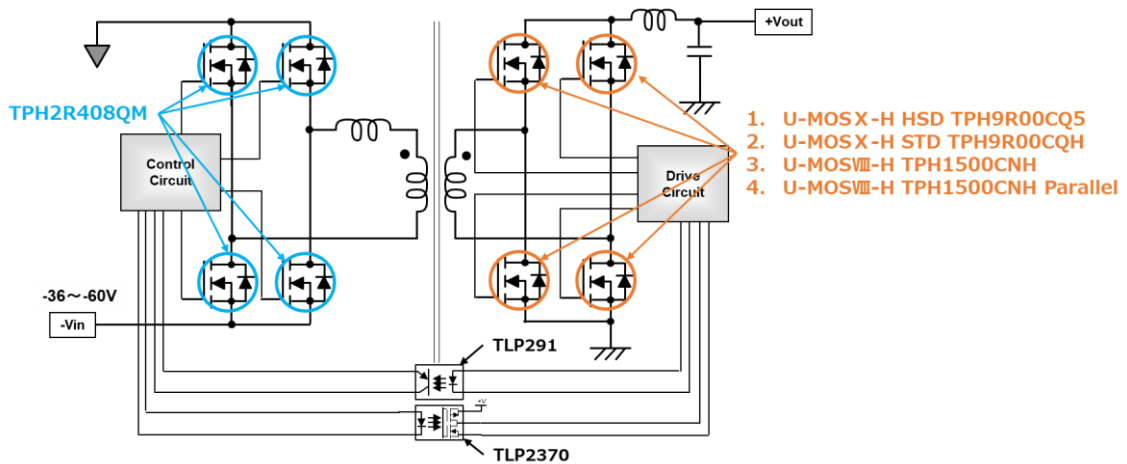

Figure 2.3.1. Full-bridge synchronous rectified DC-DC converter reference design

2.3.1.2. Efficiency

Figure 2.3.2. shows the circuit block diagram and the MOSFET combinations for efficiency measurement. The MOSFET on the primary side is a fixed device, 80V U-MOSX-H TPH2R408QM, and the MOSFETs on secondary side are replaced by #1 to #4 as below for variation analysis.

1. 150V U-MOSX-H HSD TPH9R00CQ5
2. 150V U-MOSX-H STD TPH9R00CQH
3. 150V U-MOSVIII-H TPH1500CNH
4. 150V U-MOSVIII-H TPH1500CNH in parallel

Figure 2.3.2. Circuit block diagram and MOSFET combinations for efficiency measurement

Figure 2.3.3. shows the efficiency result on a 1kW PSFB synchronous rectified DC-DC converter reference design. In short, U-MOSX-H HSD TPH9R00CQ5 is a best SR-MOSFET enables best efficiency in whole load condition.

Switching loss and recovery loss are the majority in total loss in light load condition, Iout=4A to 10A. In fact, in comparison to the 94.44% efficiency of both parallel and single connected U-MOSVIII-H TPH1500CNH, U-MOSX-H STD TPH9R00CQH achieved 94.66% efficiency as 0.22% improvement by reducing switching loss, and U-MOSX-H HSD TPH9R00CQ5 reached 94.87% efficiency as 0.21% further improvement against STD type by reducing reverse recovery loss.

On the other hand, conduction loss is the majority in total loss in heavy load condition as Iout=12A to 18A. U-MOSX-H HSD TPH9R00CQ5 achieved 94.54% efficiency at Iout=18A as best result in SR-MOSFET comparison due to lowest on-resistance (7.3mOhm) with lowest Q_{rr}. The next-highest efficiency is 94.46% achieved by parallel connected U-MOSVIII-H TPH1500CNH, however taking unit cost and unit size into consideration, the next-best choice of SR-MOSFET will be U-MOSX-H STD TPH9R00CQH achieving 94.4% efficiency.
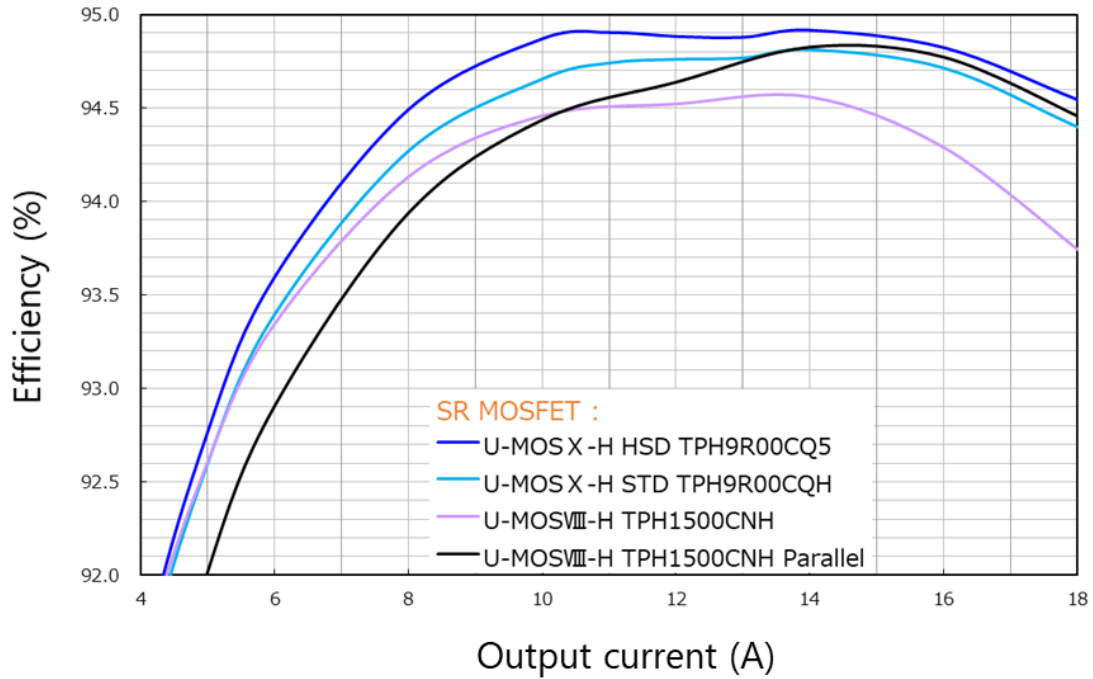
Figure 2.3.3. 1kW Phase-Shift Full-Bridge Synchronous Rectifier DC-DC Converter
Reference Design Efficient Results
(-54Vin / 54Vout, SW-side is fixed (TPH2R408QM), f=113kHz)

2.3.2. 1kW Buck Boost DC-DC Converter Reference Design
2.3.2.1. Reference Design Overview

This reference design is a 1kW buck-boost DC-DC converter that conforms to the standard of telecom power supply, which has the input voltage range as DC-60V to -36V and transforms to 54V output for high power RF amplifier. Maxim's MAX15158A is used for the controller, and 5mm x 6mm sized surface mount power MOSFET are selected (Fig. 2.3.4).
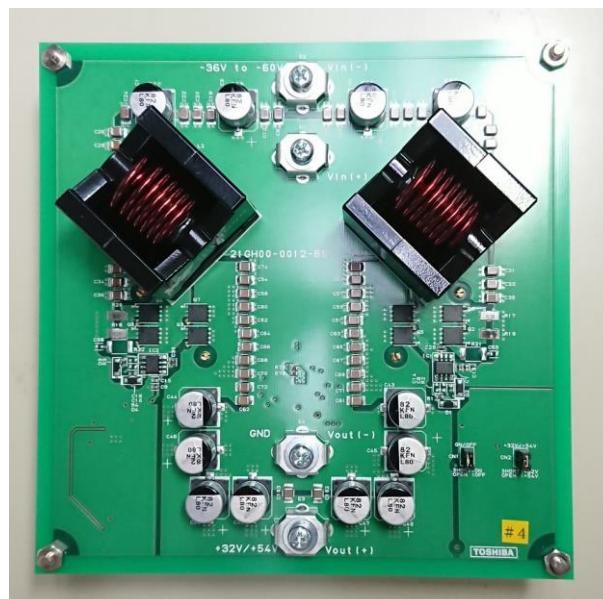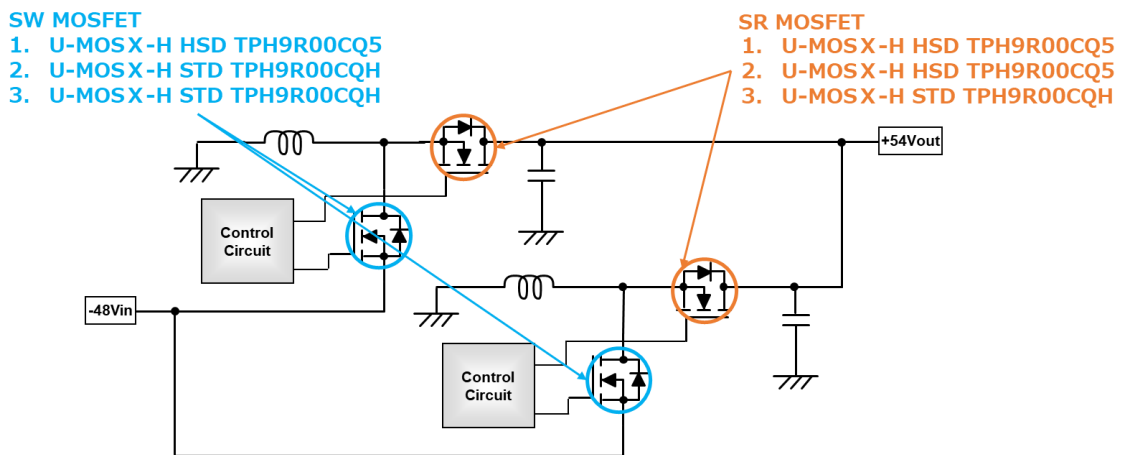

Figure 2.3.4. 1kW buck boost DC-DC converter reference design

2.3.2.2. Efficiency

Figure 2.3.5. shows the circuit block diagram and the MOSFET combinations for efficiency measurement. The combinations of the MOSFET are shown as #1 to #3 as below for variation analysis.

1. SW: 150V U-MOSⅩ-H HSD TPH9R00CQ5, SR : U-MOSⅩ-H HSD TPH9R00CQ5
2. SW: 150V U-MOSⅩ-H STD TPH9R00CQH, SR : U-MOSⅩ-H HSD TPH9R00CQ5
3. SW: 150V U-MOSⅩ-H STD TPH9R00CQH, SR : U-MOSⅩ-H HSD TPH9R00CQH

SW MOSFET
1. U-MOSⅩ-H HSD TPH9R00CQ5
2. U-MOSⅩ-H STD TPH9R00CQH
3. U-MOSⅩ-H STD TPH9R00CQH

SR MOSFET
1. U-MOSⅩ-H HSD TPH9R00CQ5
2. U-MOSⅩ-H HSD TPH9R00CQ5
3. U-MOSⅩ-H STD TPH9R00CQH

Figure 2.3.5. Circuit block diagram and efficiency measuring element

Figure 2.3.6. shows the efficiency result of 1kW buck-boost DC-DC converter reference design. No significant efficiency difference is not observed over the whole load range between Combination-1 and Combination-2 since HSD type MOSFET does not have a beneficial effect on SW-MOSFET due to no reverse recovery mode on it. This indicates that either of TPH9R00Q5 (HSD type) and TPH9R00CQH (STD type) are applicable for SW-MOSFET, that have same electrical characteristics except for reverse recovery performance.

In contrast, TPH9R00CQ5 (HSD type) works well as SR-MOSFET for reducing the reverse recovery loss and achieve 0.18% better efficiency comparing to TPH9R00CQH (STD type). (Figure 2.3.6.)

According to this result, TPH9R00CQ5 (HSD type) covers TPH9R00CQH (STD type) in terms of the performance as for both SW-MOSFET and SR-MOSFET on buck-boost converter with the exception of the cost advantage on TPH9R00CQH (STD type). In brief, placing the right MOSFET on the right place enhances the value of the application.
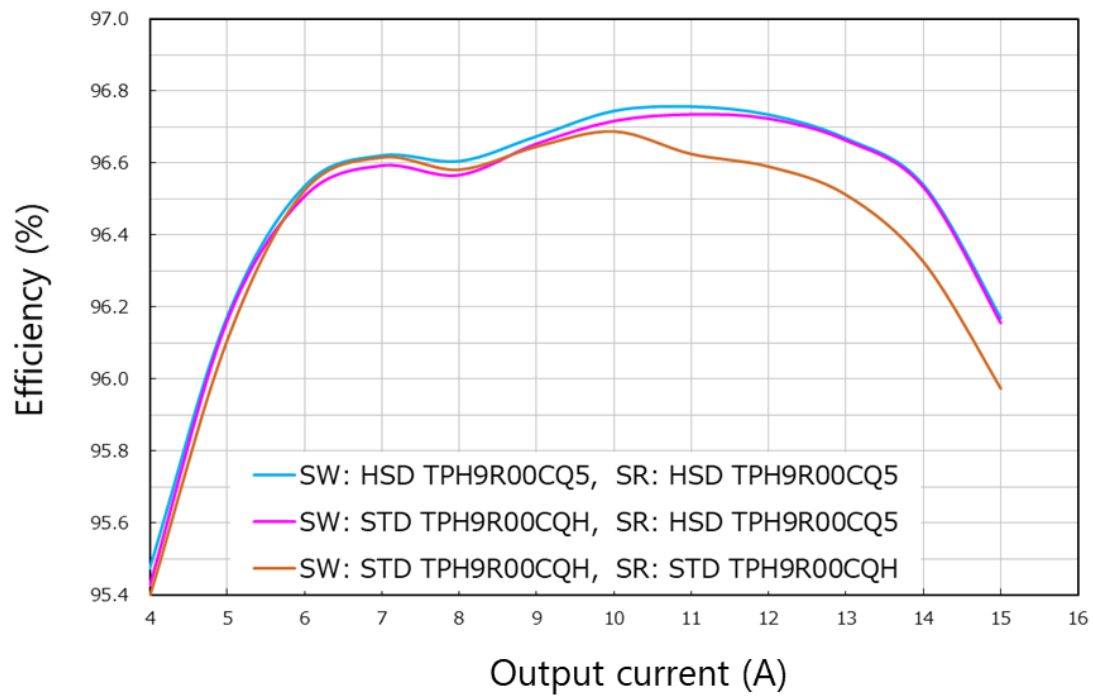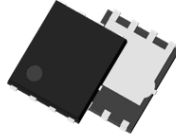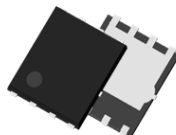
Figure 2.3.6. 1kW Buck Boost DC-DC Converter Reference Design Efficiency Results
(-48Vin / 54Vout, f=150kHz)

3. Line-up

Table 3. shows the lineup of U-MOSX-H 150V in surface mount package sized of 5x6 and 3x3 including the items under development. The portfolio covering wide range of on-resistance supports various applications and requirements.

Table 3. U-MOSX-H 150V lineup

V_{DSS} (V)	Package	Part No.	$R_{DS(ON)}$ (mΩ) V_{GS} = 10V max
150 STD	SOP Advance(N) 5x6	TPH9R00CQH	9
		TPH1400CQH	14.1
		TPH2200CQH	22
		TPH3300CQH	33
	TSON Advance 3x3	TPN3300CQH	33
		TPN4800CQH	48
150 HSD	SOP Advance(N) 5x6	TPH9R00CQ5	9
		TPH1100CQ5	10.5
		TPH1400CQ5	14.1
	TSON Advance 3x3	TPN3300CQ5	33

4. Summary

U-MOSX-H 150V series have been developed in order to contribute to reducing the power dissipation of switching power supplies for communication base stations and data servers. U-MOSX-H 150V series reduce $R_{DS(ON)}$ by 38%, $R_{DS(ON)} \cdot Q_{oss}$ by 20%, $R_{DS(ON)} \cdot Q_{rr}$ by 57% on STD type and 89% on HSD type compared with conventional U-MOSVIII-H, and enhanced the efficiency of both 1kW PSFB synchronous rectified DC-DC converter and 1kW buck-boost converter.

Toshiba will continue to expand its lineup that contribute to the realization of carbon neutrality by responding to the demands for reducing power consumption through further improvements in characteristics.

5. Support (Reference design, Simulation model)

Detailed information on the reference design used in this application note can be obtained from the following URL.

1kW Phase-Shift Full-Bridge Synchronous Rectifier DC-DC Converter Reference Design
https://toshiba.semicon-storage.com/ad/semiconductor/design-development/referencedesign/articles/1-kw-full-bridge-dc-dc-converter_power-supply_rd170.html

1kW Buck Boost DC-DC Converter Reference Design
https://toshiba.semicon-storage.com/info/lookup.jsp?pid=RD211

We provide a SPICE model (G0 model) that can verify circuit operation in a short time and a SPICE model (G2 model) with improved accuracy of transient characteristics as tools to support circuit design.

Description of high-precision SPICE models
https://toshiba.semicon-storage.com/jp/semiconductor/knowledge/highlighted-contents/articles/simulating-the-transient-characteristics-of-mosfet-more-accurately.html?utm_source=web&utm_medium=banner&utm_campaign=tdsc_semicon_carousel_g2

Description of the grade notation of the device model (SPICE model)
https://toshiba.semicon-storage.com/info/application_note_ja_20210621_AKX00044.pdf?did=70958

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