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A Design Direction of Low-Voltage Field-Plate Power MOSFETs for FOM Limit

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Abstract

The design direction of low voltage Field-Plate (FP) power MOSFETs was analyzed toward the figure-of-merit (FOM) limit by TCAD simulation. The results show that thin oxide and narrow mesa structure is desired for minimizing on-resistance $R_{on}A$ and opposite design of thick oxide and wide mesa structure is a good choice to reduce $R_{on}Q_{sw}$ for high switching frequency application. In addition, the potential of $R_{on}A$ reduction from the previous reports is maintained, however, it is difficult to reduce the $R_{on}Q$, which is $R_{on}Q_g$, $R_{on}Q_{sw}$, and $R_{on}Q_{oss}$. It is verified that FOM improvement of $R_{on}Q$ cannot be obtained only by the design parameter optimization and requires approach from the other direction.

1. Introduction

Power MOSFETs are key devices to realize more efficient power converters. Recently, FP power MOSFET has been studied to reduce the on-resistance $R_{on}A$ from the viewpoint of the optimization of electric field distribution for maximizing the doping concentration [1]-[6] and mobility enhancement by mechanical stress [7], [8]. Although the design for $R_{on}A$ reduction has been studied [9], it is not clear whether the same design direction obtains the FOM improvement including the switching characteristics and the design parameter optimization has a potential for further FOM improvement.

This paper reports the FOM limit of 60 and 100 V-class FP power MOSFETs by the parameter optimization and discusses the design direction for the FOM improvement.

2. Device Description and Optimization Steps

The designed FP power MOSFET structure is shown in Fig. 1(a). As design parameters, mesa width W, trench depth L, oxide thickness t_{ox} and drift doping concentration N_{D1}, N_{D2} were optimized in 100 V-class FP power MOSFET design, and the 100 V-class design was scaled down to 60 V-class structure. The design for each of $R_{on}A$ and $R_{on}Q_{sw}$ reduction was focused in this work. The device structure, mechanical stress and electrical characteristics were analyzed using TCAD process and device simulations, Sprocess and Sdevice of Synopsys as shown in Fig. 1 [10].

3. Simulation Results and Discussions

Lateral pitch narrowing reduces the on-resistance in the FP power MOSFET due to the increase of the drift layer doping concentration. The lateral pitch can be narrowed by the decrease of W and t_{ox}. The narrow mesa structure is desired for low on-resistance design due to the increase of stress induced electron mobility enhancement and drift layer doping concentration as shown in Fig. 2, 3. However, the device will be cracked by critical mechanical stress at the t_{ox} of 0.6 μm and the W of 0.4 μm, because the maximum mechanical stress in the drift region σ_{xmax} is over the crack limit [8] as shown in Fig. 2. In addition, too narrow mesa structure decreases the breakdown voltage and the dramatic increase of trench depth L is needed to maintain the breakdown voltage. Therefore, too narrow mesa structure leads to the high on-resistance and the $R_{on}A$ reduction by W narrowing is limited as shown in Fig. 4. Thin t_{ox} structure achieves low on-resistance comparing between t_{ox}=0.5 μm and t_{ox}=0.6 μm, although thick t_{ox} structure induces the electron mobility enhancement as shown in Fig. 2. This is verified that the effect of the increase of the drift layer doping concentration enabled by the lateral pitch narrowing is greater than that of the stress induced electron mobility enhancement. Therefore, thin oxide structure is a good choice for low on-resistance design.

However, the $R_{on}A$ reduction design increases the gate switching charge Q_{sw} because the lateral pitch narrowing by oxide thinning and mesa narrowing increases the FP trench gate density as shown in Fig. 5. Therefore, the $R_{on}A$ reduction design degrades the switching characteristics, and the opposite design is suitable for high speed switching application.

As a FOM considered with both the on-resistance and the switching characteristics, $R_{on}Q_{sw}$ was analyzed as shown in Fig. 6. Thick oxide and wide mesa structure is a good choice to reduce $R_{on}Q_{sw}$, although relatively thin oxide and narrow mesa structure is desired for $R_{on}A$ reduction. Therefore, $R_{on}A$ and $R_{on}Q_{sw}$ cannot be improved by the same design direction of the parameter optimization.

The FOM limits estimated by the optimum design parameters are benchmarked with the previous report data and the latest product FOMs, which are cited from the datasheet [11]. The parameters were optimized with two cases for the $R_{on}A$ reduction ($R_{on}A$ First) and the $R_{on}Q_{sw}$ reduction ($R_{on}Q_{sw}$ First) . The $R_{on}A$ First design obtains lower $R_{on}A$ compared with the previous reports as shown in Fig. 7. The FOM of $V_B^{2.5}/R_{on}A$ is improved by 12% and 13% compared with previous works in Ref. [3] and [5] for 60 V and 100 V-class, respectively.

On the other hand, it is difficult to improve $R_{on}Q$ from the latest product even by the $R_{on}Q_{sw}$ First design as shown in Table I. As mentioned above, $R_{on}Q$ improvement increases $R_{on}A$, and that makes FOM improvement more difficult. Therefore, $R_{on}Q$ improvement cannot be obtained only by the design parameter optimization and requires approach from the other direction, such as a new structure and gate control technology.

4. Conclusions

The design direction of low voltage FP power MOSFETs was analyzed toward the FOM limit by TCAD simulation. As a result, thin oxide and narrow mesa structure is desired to minimize $R_{on}A$ for low switching frequency application and opposite design of thick oxide and wide mesa structure is a good choice to reduce $R_{on}Q_{sw}$ for high switching frequency application. 60-100V-class FP power MOSFETs have a potential of 12-13% $R_{on}A$ reduction from the previous reports. However, it is difficult to reduce FOM of $R_{on}Q$ even from the latest product. It is verified that FOM improvement of $R_{on}Q$ cannot be obtained only by the design parameter optimization and requires approach from the other direction, such as a new structure and gate control technology.

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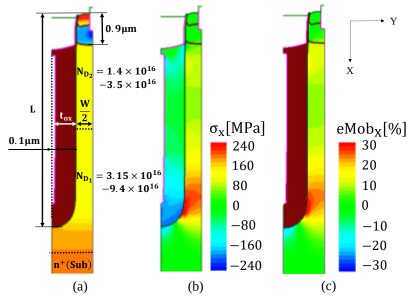

Fig. 1 (a) The device structure, (b) the stress distribution, and (c) stress induced electron mobility enhancement of the FP power MOSFET

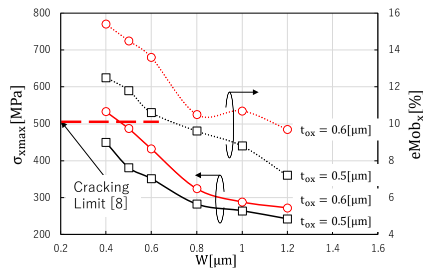

Fig. 2 Maximum mechanical stress and average stress induced electron mobility enhancement in the X direction in the drift region

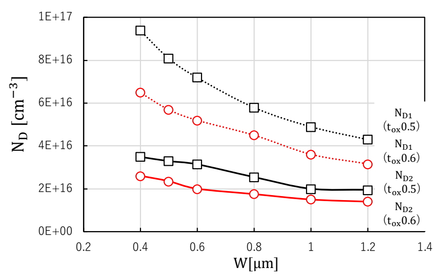

Fig. 3 Doping concentrations in the drift region

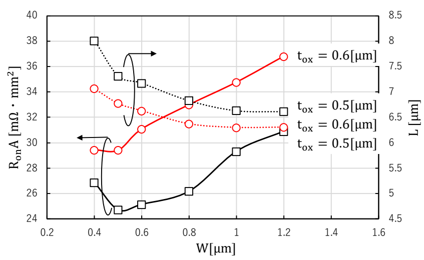

Fig. 4 On-resistance and trench depth maintaining the V_B of over 110 V dependence on mesa width for constant oxide thickness

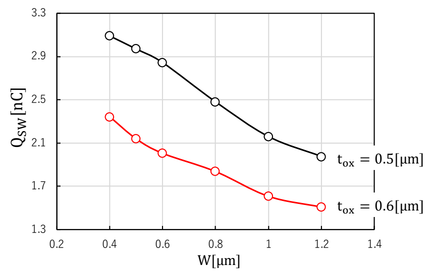

Fig. 5 The gate switching charge, Q_{sw}

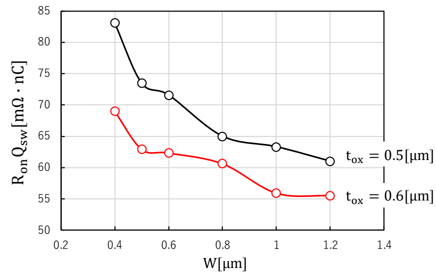

Fig. 6 Figure-of-merit, $R_{on}Q_{sw}$

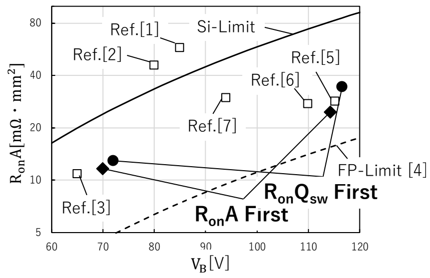

Fig. 7 $R_{on}A$-V_B relationships of the estimated limit and the previous reports

Table I Key Electrical Characteristics Summary

Voltage Class	Device Structure	$R_{on}A$ [mΩ · mm²]	$R_{on}Q_g$ [mΩ · nC]	$R_{on}Q_{sw}$ [mΩ · nC]	$R_{on}Q_{oss}$ [mΩ · nC]
60 V	$R_{on}A$ First	11.7	138	29.5	187
	$R_{on}Q_{sw}$ First	13.0	119	25	121
	Company A [11]	-	87.4	21.1	74.4
100 V	$R_{on}A$ First	24.7	262	73.5	506
	$R_{on}Q_{sw}$ First	34.8	220	55.9	329
	Company A [11]	-	208	65.1	229