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The Impact of Sub-threshold Current on Ultra High Density Trench MOSFET for Synchronous Rectifier Application

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Abstract: **This paper provides a thorough study of body diode reverse recovery issues for low voltage (30V) rated ultra high-density trench MOSFET. Further more, a ultra density trench MOSFET structure with R_{on_spec} (Vgs=5V)=10.4mΩmm^2, Q_{gd}=1.1nC/mm^2 and Q_{oss}=2nC/mm2, is proposed.**

I. INTRODUCTION

Power MOSFET acting as a synchronous switch has been widely used in place of a regular rectifier due to its low conduction loss. In many step down voltage regulators that power the digital devices such as the microprocessor, 30V trench MOSFETs are usually used. However, for high switching frequency applications, the synchronous MOSFET body diode reverse recovery loss has become a major concern. As a result, a Schottky diode is usually put in parallel with the synchronous MOSFET in many practical circuits, which works fine when the switch transition is slow enough so that the parasitic inductor will not fully prevent the Schottky diode from conducting during the dead time period. Although monolithically integrating the Schottky diode with the synchronous MOSFET will help to reduce the parasitic inductance problem, it may not be chip area efficient as the voltage rating going down, e.g. in the range of 20 to 30V which are wildly used in 12V to 1V down conversion circuitry.

II. SIMULATION COMPARISON

Based on our Medici mixed mode simulation results, we found that in the future generation ultra high density trench MOSFET[1,2], with the increased sub-threshold current, the barrier lowering effect will actually help to reduce the hole injection current from the body to the drain, as a result, less storage charge need to be removed during the reverse recovery as shown in Figure 1. Table 1 summarizes the simulated results from three cases shown in Figure 2, it shows that the body diode recovery in the trench MOSFET behaves neither like a normal PIN diode nor a BJT enhanced diode with a trench capacitor at the side, but has a much less forward current density dependence. The flow-line in Figure 3 indicates that most of the current is actually confined near the channel oxide surface, while Figure 4 shows that there is very little carrier lifetime dependence.

With virtually negligible storage charge, the recovery behavior can therefore be modeled as charging a normal output capacitor C_{oss}, which is a combination of drain to source junction cap C_{ds} and drain to gate miller cap C_{gd} (Table 2). For the same P-body dosage, a thinner gate oxide thickness will result in a stronger barrier lowing effect. However, the leakage current during the blocking stage will also increase. Among the three MOSFETs in Table 1 (case 3), even though the BVDSS are designed to be the same of about 35V, the one with 200Å gate shows a strong kink effect at about 15V when Vgs=5V, which is less desirable due to reliability concerns, while the one with 300Å guarantees a 25V rating and 400Å can be rated at 30V.

A further comparison between MOSFETs with or without monolithically integrated Schottky diode (20% extra area of the trench MOSFET) indicated that the extra Schottky diode actually degraded the reverse recovery behavior due to the extra output capacitance as shown in Figure 5, although, it will help to reduce the conduction loss during dead time when both switches are turned off. With present device technology, and commercially available switch drivers, this dead time is about 40 nano-seconds per side or about 80 nano-seconds per period, which is undesirable for future high frequency switching applications. Once more advanced predictive drivers are implemented, as they should be, where the dead time can be reduced significantly, the benefit of adding Schottky diode may eventually be cancelled out by the extra output cap recovery loss.

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Therefore, for future generation power switches, an integrated Schottky diode is not necessary.

III. DEVICE OPTIMIZATION

The typical loss due to synchronous switch can be categorized into three parts, namely the conduction loss, the gate charge loss and the output reverse recovery loss. For a certain switching frequency and load current, the optimal size can be reached when the first loss equals the sum of the latter two [3]. An even better way to further improve the device performance is to reduce the trench pitch size and the trench opening, since it will significantly reduce the output cap while keeping the R_{on} about the, while the gate charge and R_{on} can be reduced simultaneously by reducing the channel length. Without further degradation of the device blocking capability and unclamped inductive switching robustness, an optimal structure with the present available technology [4] has been proposed as shown in Figure 6. It has the gate trench pitch of 1 um, trench opening of 0.3um and trench depth of 1um, the effective channel length about 0.65um and channel gate oxide thickness of 400Å and bottom oxide thickness of 1000Å. The P-Body doping density of 1.75×10^{17} cm^{-3} will provide a threshold voltage V_{th} of about 1.9V, and with a 0.8um N- drift region with 1×10^{16} doping density the device has a BVDSS of 33.5V. Assuming 160um thick N+ substrate ($2.5m\Omega mm^2$), the device will have a specific on resistance of about $10.4m\Omega mm^2$ at V_{gs}=5V and specific input capacitance $C_{iss_spes_off}$ (V_{ds}=12V)=800pF/mm^2 and $C_{iss_spes_on}$(V_{ds}=0,Vand V_{gs}> V_{th})= 1360pF/mm^2, and Q_{gd} (V_{ds}=12V to 0V)=1.1nC/mm^2 and Q_{oss} (V_{ds}=-0.59 to 23.5V, Iload=3.3A/mm^2 and di/dt=1A/mm^2/nsec)=2nC/mm^2.

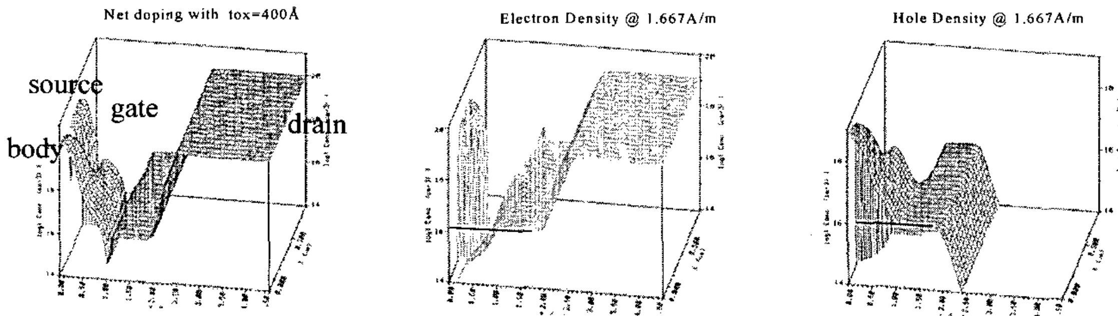

Figure 1. Net doping concentration against electron and hole concentration under body diode conduction condition. Notice that the minority carriers are still below background doping level.

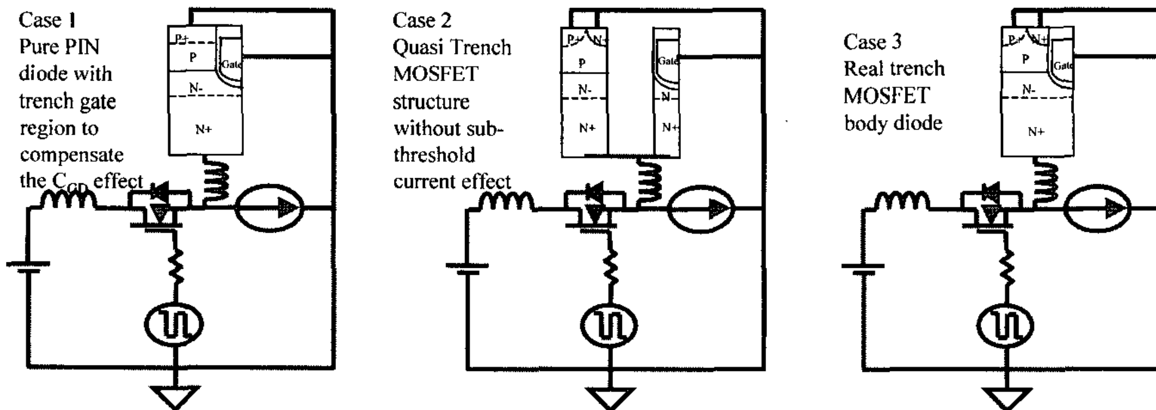

Figure 2. Buck converter circuit schematics to study for Trench MOSFET body diode reverse recovery

Table 1: Mixed mode Medici simulation result based on circuits in Figure 1, Trench pitch=1.6um, trench open=0.6um, trench depth=1.1um and N- drift region=0.8um. Total channel width=6 M.

	Case 1	Case 2	Case 3		
t_{ox_ch} (t_{ox_bot} = 1000 Å) (V_{th}, R_{on}(@V_{gs}=5V)	200 Å	200 Å	200 Å 0.8V, 2.3mΩ	300 Å 1.3V, 2.5mΩ	400 Å 1.7V, 2.8mΩ
Q (V_{in}=12V, I_{load}=0.5A, di/dt=1.7A/ns)	6.9nC(-0.629-0V) 15.5nC(0 - 27.3V)	1.2 nC (storage) 11.1nC(-0.651 - 20.8V) 4.25nC (-0.651 - 20.8V) due to Cgd (bottom)	1.18nC(-0.4035-0V) 11.2nC(0 - 20.57V)	1.18nC(-0.5374-0V) 11nC(0 - 20.4V)	1.18nC(-0.5942-0V) 10.9nC(0 - 20.35V)
$\beta = I_S/I_B$ (V_{SD})	N/A (0.629V)	6.37 (0.6538V)	20864 (0.4035V)	564 (0.5374V)	72.5 (0.5942V)
Q (V_{in}=12V, I_{load}=10A, di/dt=3.9A/ ns)	21.6nC(-0.778-0V) 23.6nC(0 - 37.7V) (Breakdown)	3.98 nC (storage) 16.1nC(-0.515 - 28.5V) 5.72nC (-0.515 - 28.5V) due to Cgd (bottom)	1.20nC(-0.5729-0V) 12.9nC(0 - 23.4V)	1.23nC(-0.6718-0V) 13.4nC(0 - 23.8V)	2.11nC(-0.7199-0V) 14.9nC(0 - 25.5V)
$\beta = I_S/I_B$ (V_{SD})	N/A (0.7782V)	6.74 (0.7539V)	4186 (0.5729V)	104 (0.6718V)	22.7 (0.7199V)

Table 2: Analytical Q_{oss} results

Case 3 t_{ox_ch} (t_{ox_bot} = 1000 Å)		200 Å	300 Å	400 Å
0.5A	Medici Results	12.3nC(-0.4035-20.57V)	12.2nC(-0.5374-20.4V)	12.0nC(-0.5942-20.35V)
	Analytical Model	12.7nC(-0.4035-20.57V)	12.9nC(-0.5374-20.4V)	13.1nC(-0.5942-20.35V)
	Differences	-0.4nC	-0.7nC	-0.9nC
10A	Medici Results	14.1nC(-0.5729-23.4V)	14.6nC(-0.6718-23.8V)	17.0nC(-0.7199-25.5V)
	Analytical Model	14.2nC(-0.5729-23.4V)	14.8nC(-0.6718-23.8V)	15.8nC(-0.7199-25.5V)
	Differences	-0.1nC	-0.2nC	1.2nC

$$Q_{oss}(V_{min}, V_{max}) = \int_{V_{min}}^{V_{max}} \left(C_{gd}(V) + C_{ds}(V)\right) dV$$

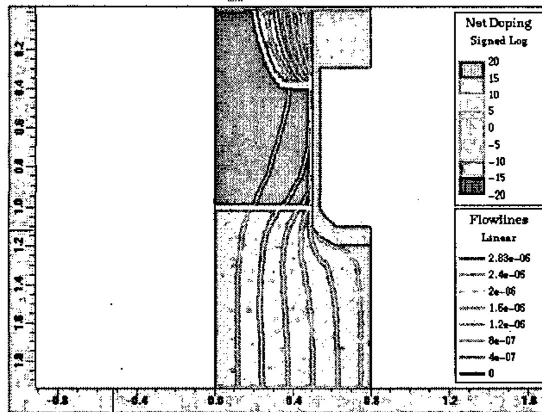

Figure 3. Current flow line for MOSFET under body diode conduction condition, Vgs=0, Vsd=0.59V, J=1.6A/m. It is clear that majority of current flow near the channel oxide surface.

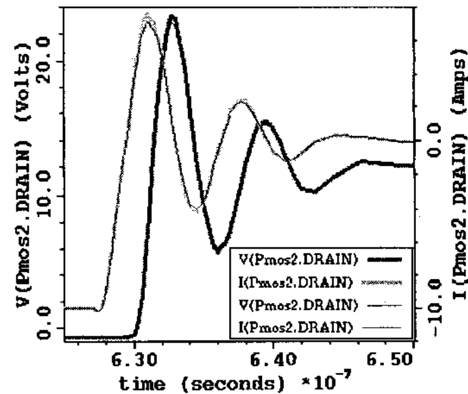

Figure 4. Recovery comparison of trench MOSFET (tox=400 Å), with TAON=TAOP=10^{-7}second (thicker line) and TAON=TAOP=$5x10^{-6}$ second.

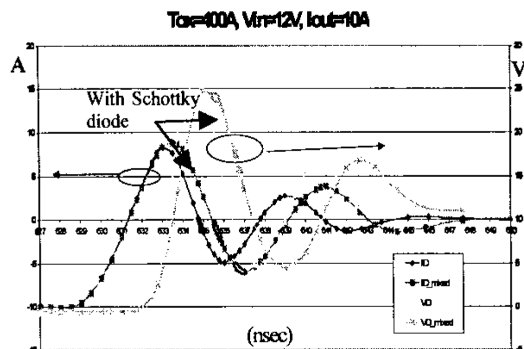

Figure 5. Recovery comparison of trench MOSFET with or without integrated Schottky diode, with total channel width of 6 meter and active area of 4.8mm^2 for MOSFET and 0.96mm^2 for extra Schottky diode.

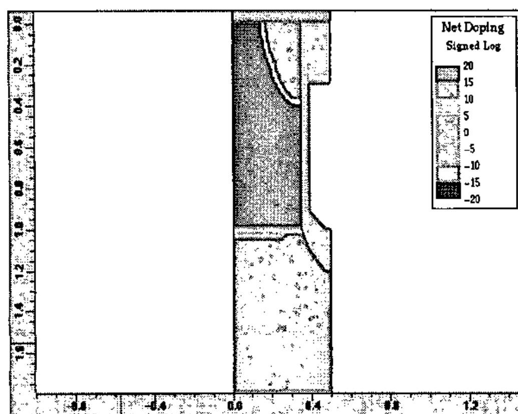

Figure 6. Proposed optimal structure with present technology available, with R_{on_spec}=10.4mΩmm^2 at V_{gs}=5V and BVDSS=33.5V

IV. CONCLUDION

Sub-threshold channel current impact on future generation high-density low breakdown voltage rating trench MOSFET for synchronous rectifier application has been studied. Simulation results show every little minority charge need to be removed, therefore no further integration with Shottky diode is needed for reducing the reverse recovery loss.

V. ACKKNOWLEGEMENT

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