Performance Analysis of Lateral and Trench Power MOSFETs for Multi-MHz Switching Operation

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Outline

- Introduction
- Trench and lateral power MOSFETs
- Definition of individual loss terms of power MOSFETs
- Figure-of-Merit (FOM) in the MHz frequency range
- Comparison of lateral and trench power MOSFETs
- Conclusion

Introduction

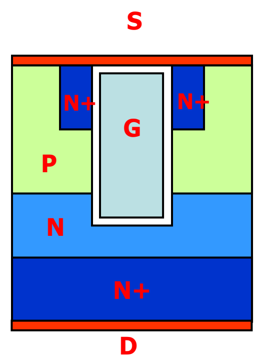
- Power SoC/SiP concept pushes operating frequency into 10's or even 100's MHz ranges
- Power MOSFET performance in the MHz range become critical to achieve reasonable efficiency
- Focus on the case study of 1-10MHz hard switching buck topology (similar investigation on 10-100MHz resonant topologies in process)

Open Issues

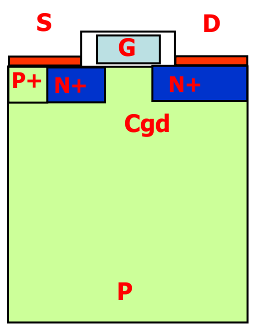
- What power MOSFET technologies are suitable for MHz operation?
- What are the individual power loss contributions of the power MOSFETs?
- Does the RDS(ON)×QG Figure of Merit (FOM) still correlate to the overall converter efficiency into the MHz frequency range?

Power MOSFET: Trench vs. Lateral

- Trench power MOSFETs are widely used as control and synchronous rectifier switches in today's buck converters. They offer very low Rdson but suffer from high Qg
- Various types of integrated or discrete LDMOS devices with very low Qg are available for both RF and switching power applications

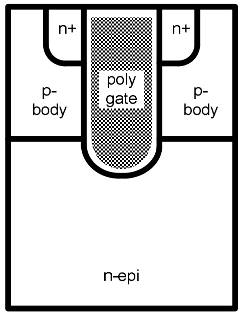


Vertical Trench MOSFET

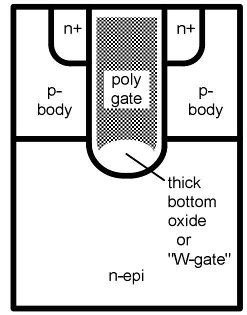


Lateral MOSFET

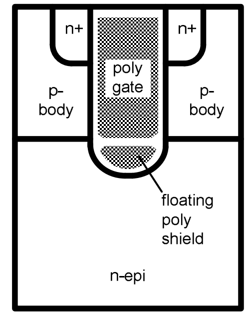
Various Trench Power MOSFETs



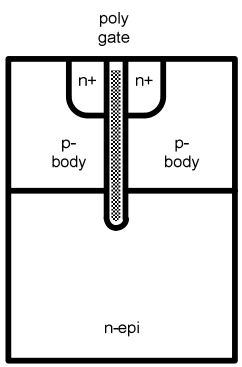
Base Line



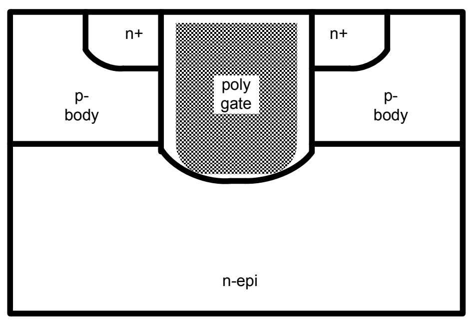
Thick Bottom



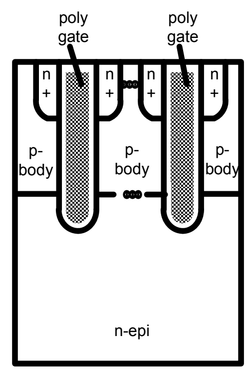
Floating poly plug



Narrow Trench



Low Density

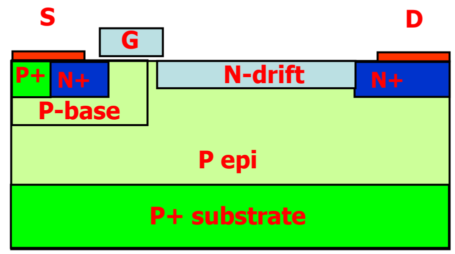


High Density

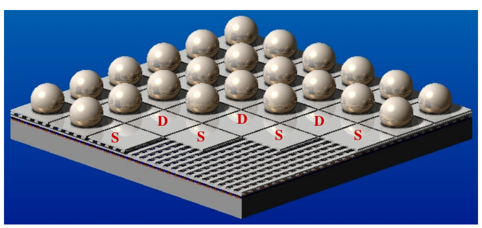
30V trench MOS cell density has increased from 20M to 450M cell/in^2 and Rdson has decreased from 30 mΩmm^2 to 10 mΩmm^2 in the past decade.

Various Lateral Power MOSFETs

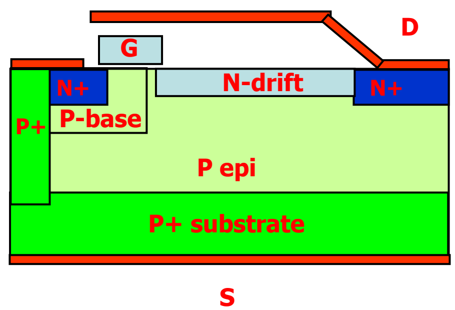
Basic RESURF LDMOS Structure widely used in power ICs up to over 100V. Benchmark Rdson for 30V LDMOS is 20 mΩmm^2



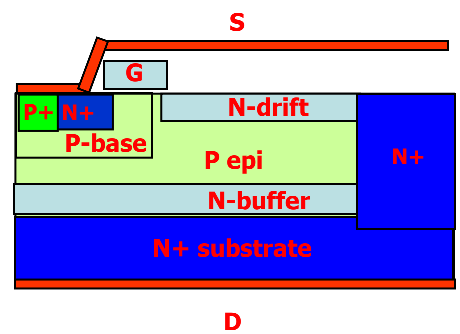
Very low Qg!!!
But metal interconnect resistance is a limiting factor!



Great Wall Semiconductor chip scale LDMOS approach

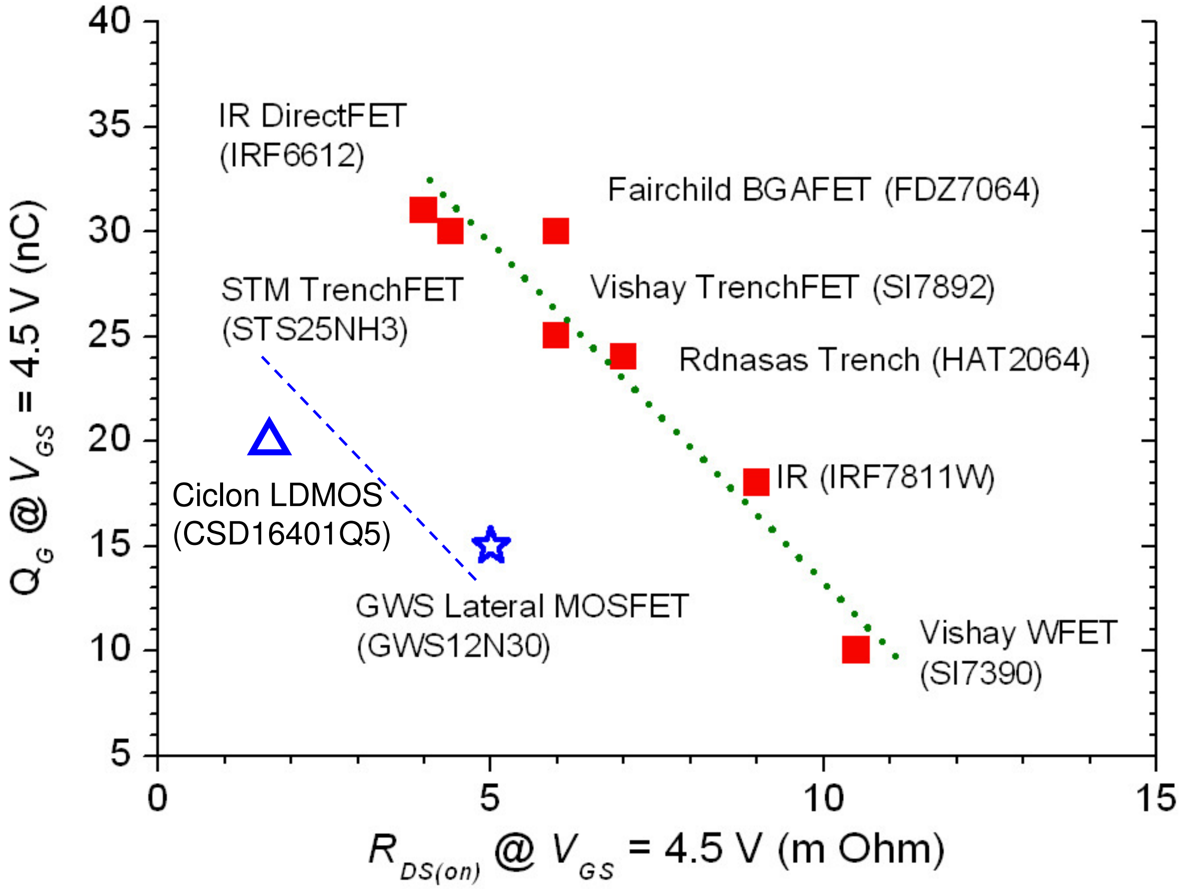


Bottom-Source LDMOS (widely used in RF power amplifier applications)



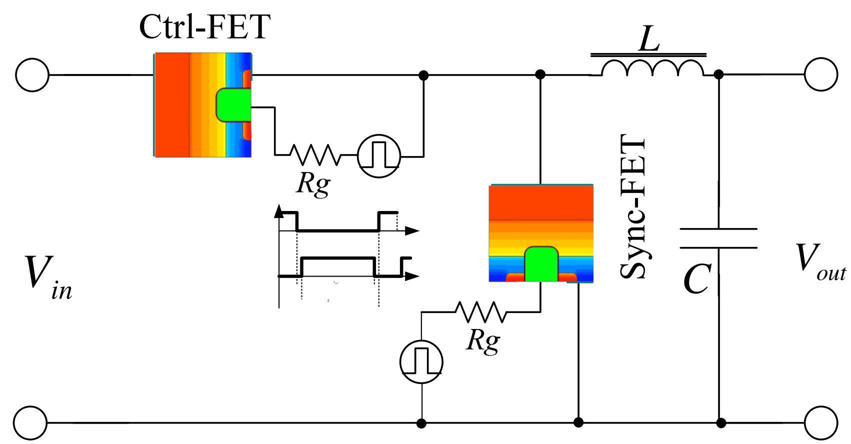
Bottom-Drain LDMOS (Ciclon Semiconductor's new benchmark device)

Comparison of 30V Trench and Lateral Power MOSFETs



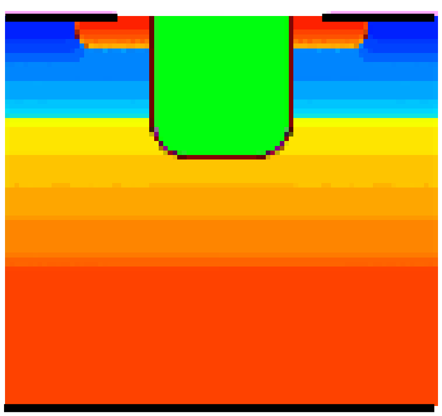
Mixed-Mode Device/Circuit Modeling

- Physically-based, numerical MOSFET models (the "virtual" MOSFETs) are directly incorporated into circuit simulation.
- The models faithfully represent the behavior of realistic trench MOSFETs, and prove to be a very powerful tool for our investigation
- ModelingTools – *Synopsis TCAD*



Mixed-Mode Device/Circuit Modeling

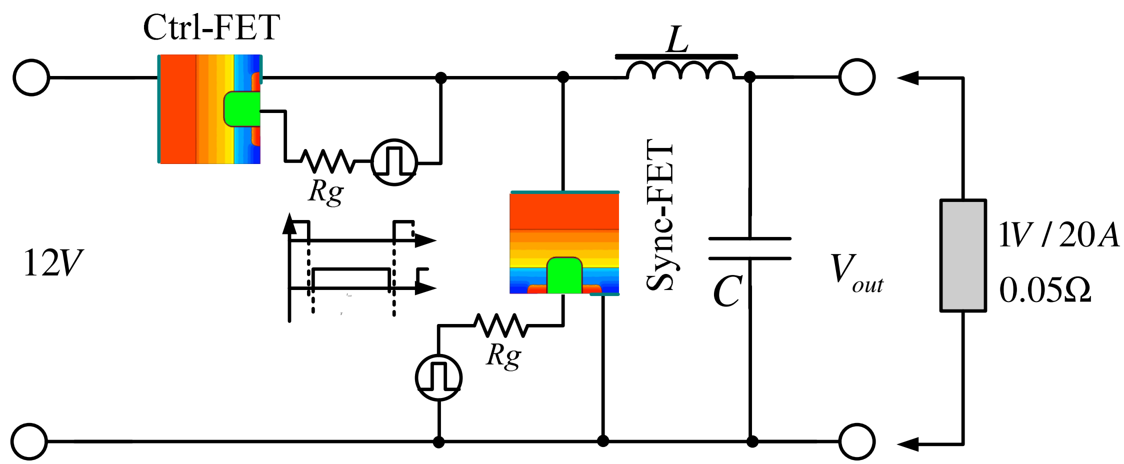
- 30V "virtual" trench MOSFET device structure (4µm cell pitch)



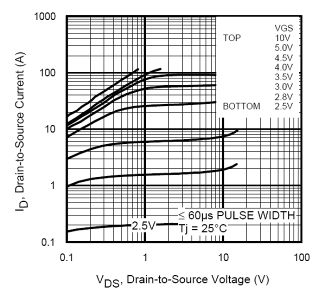
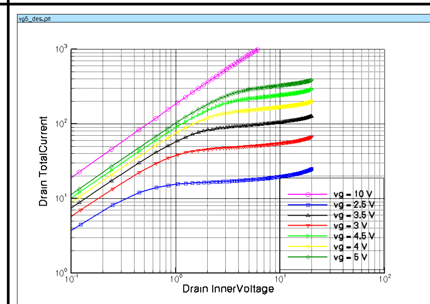
- Buck converter circuit:

  Typical VRM design spec,

  Vin=12V, Vout=1V, Iout=20A



Power MOSFET Characteristics: Modeling vs. Measurement

<table>
<tr><th>Ctrl-FET</th><th>IRF6617 Measured Characteristics</th><th>Virtual MOSFET Characteristics</th></tr>
<tr><td>Output characteristics</td><td>
</td><td>
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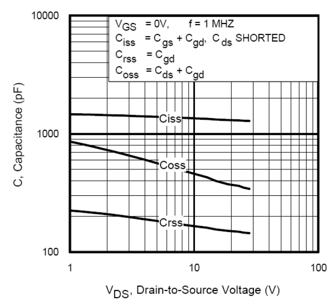
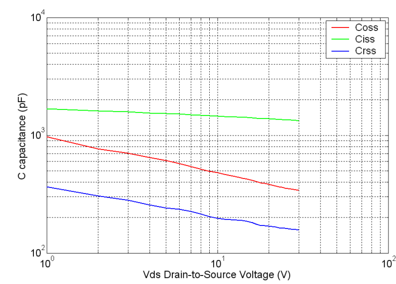
<tr><td>Capacitance characteristics</td><td>
</td><td>
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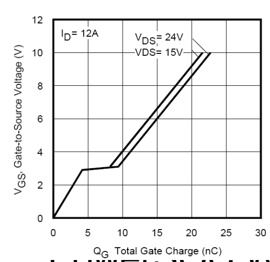
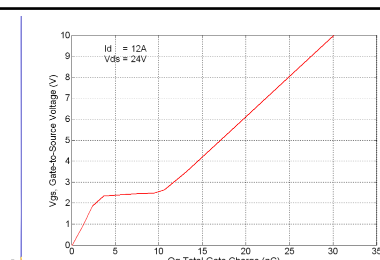
<tr><td>Gate characteristics</td><td>
</td><td>
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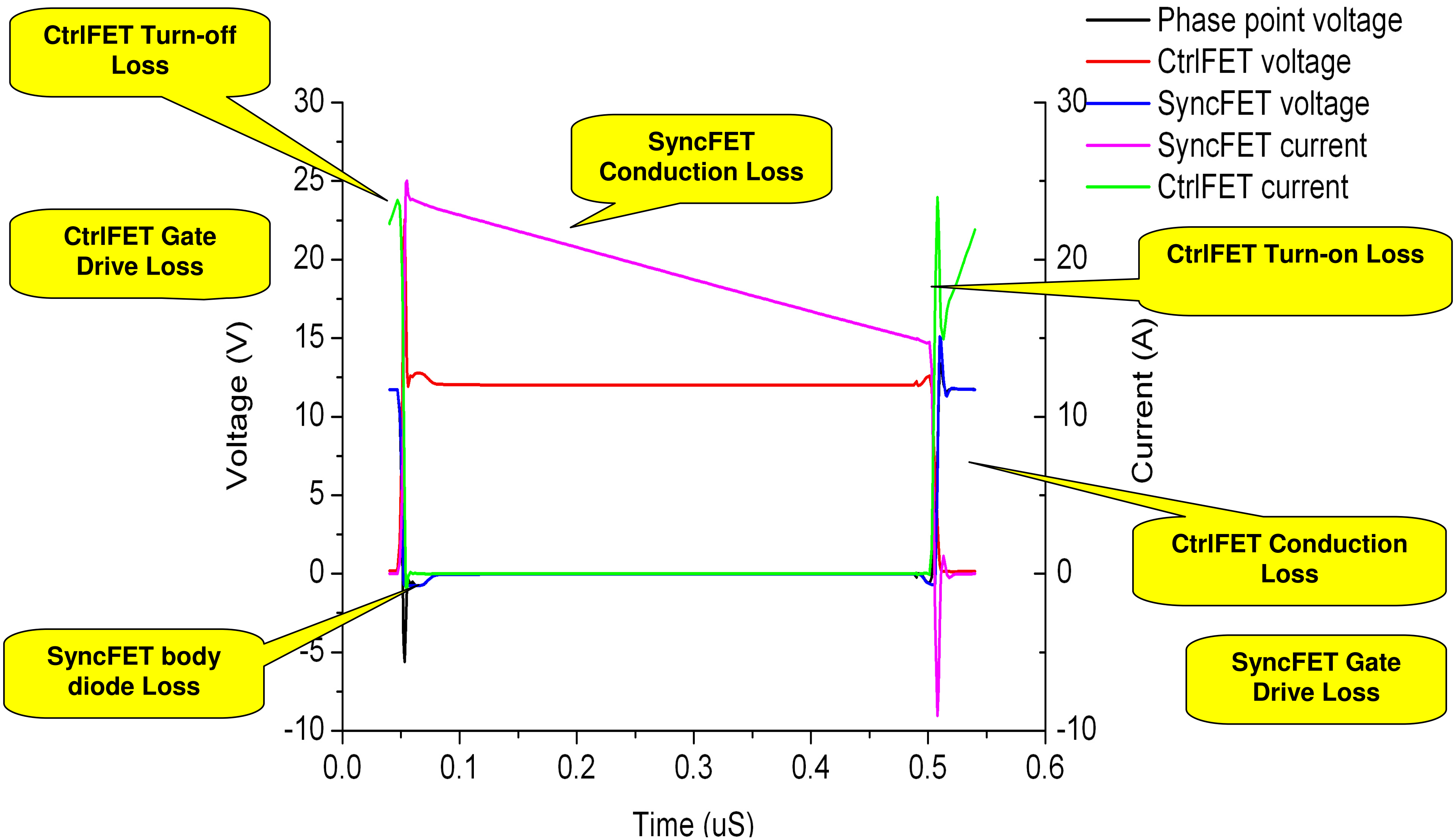
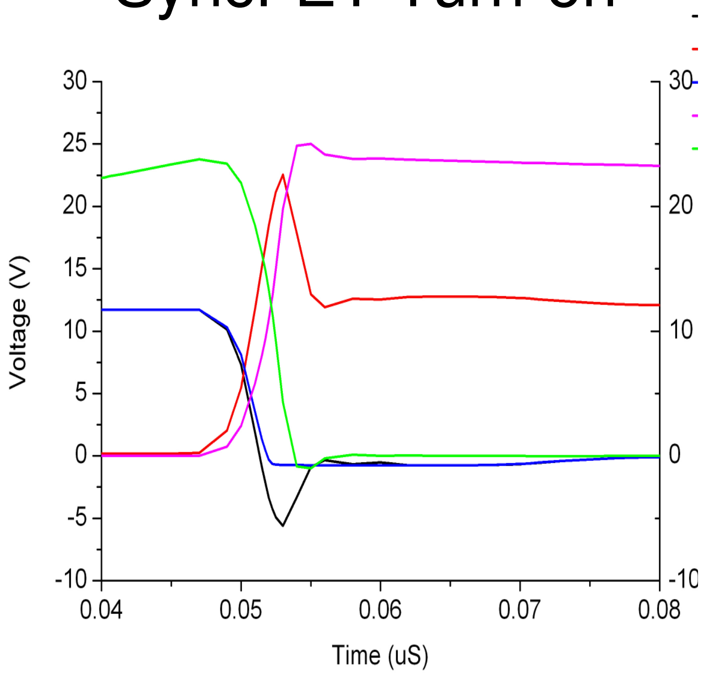
MOSFET Power Loss Terms

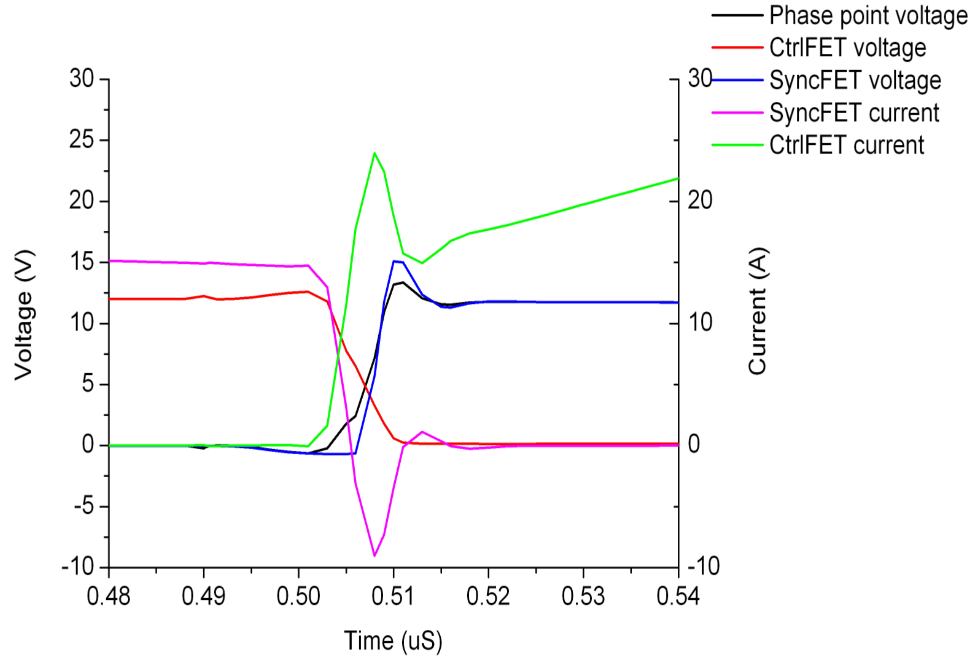


Simulated Buck Converter Waveforms

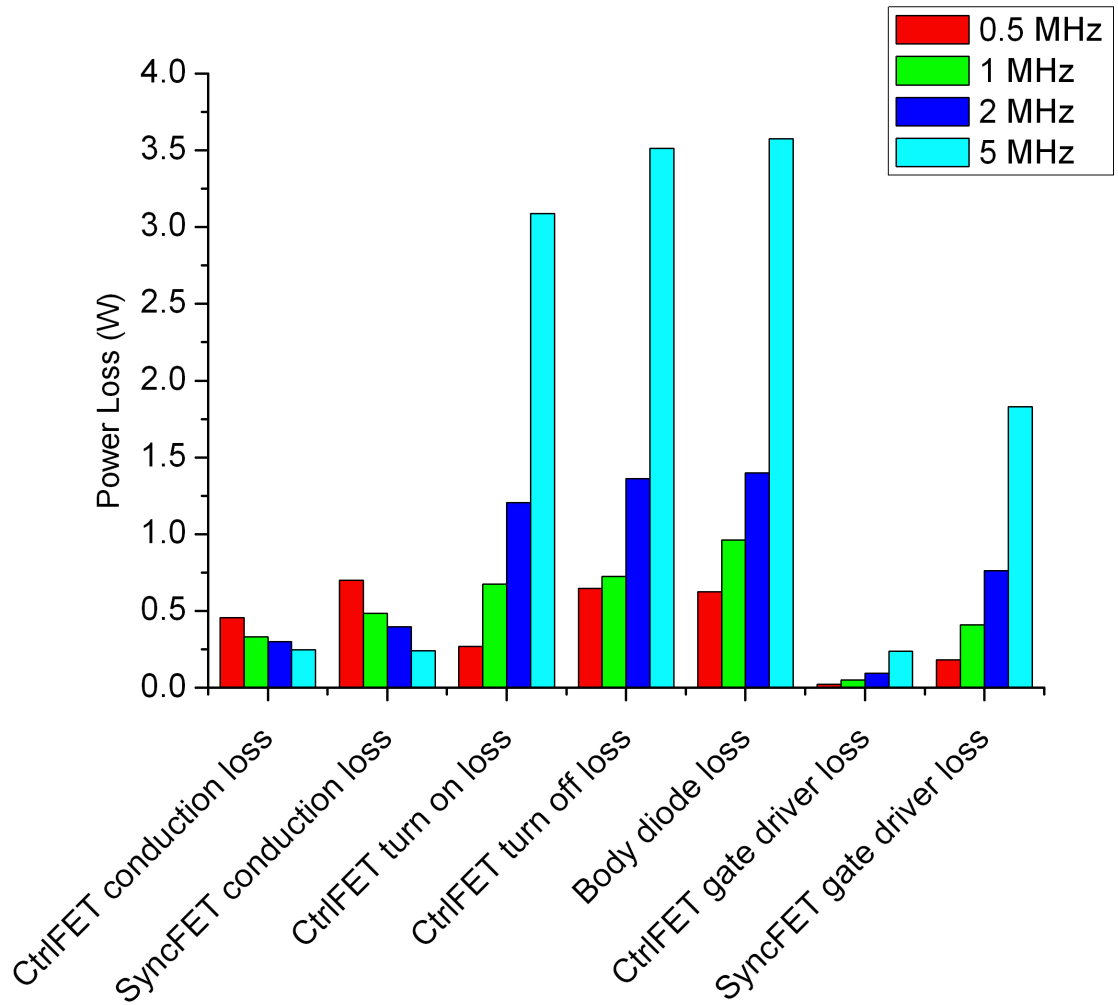
SyncFET Turn-on



CtrlFET Turn-on

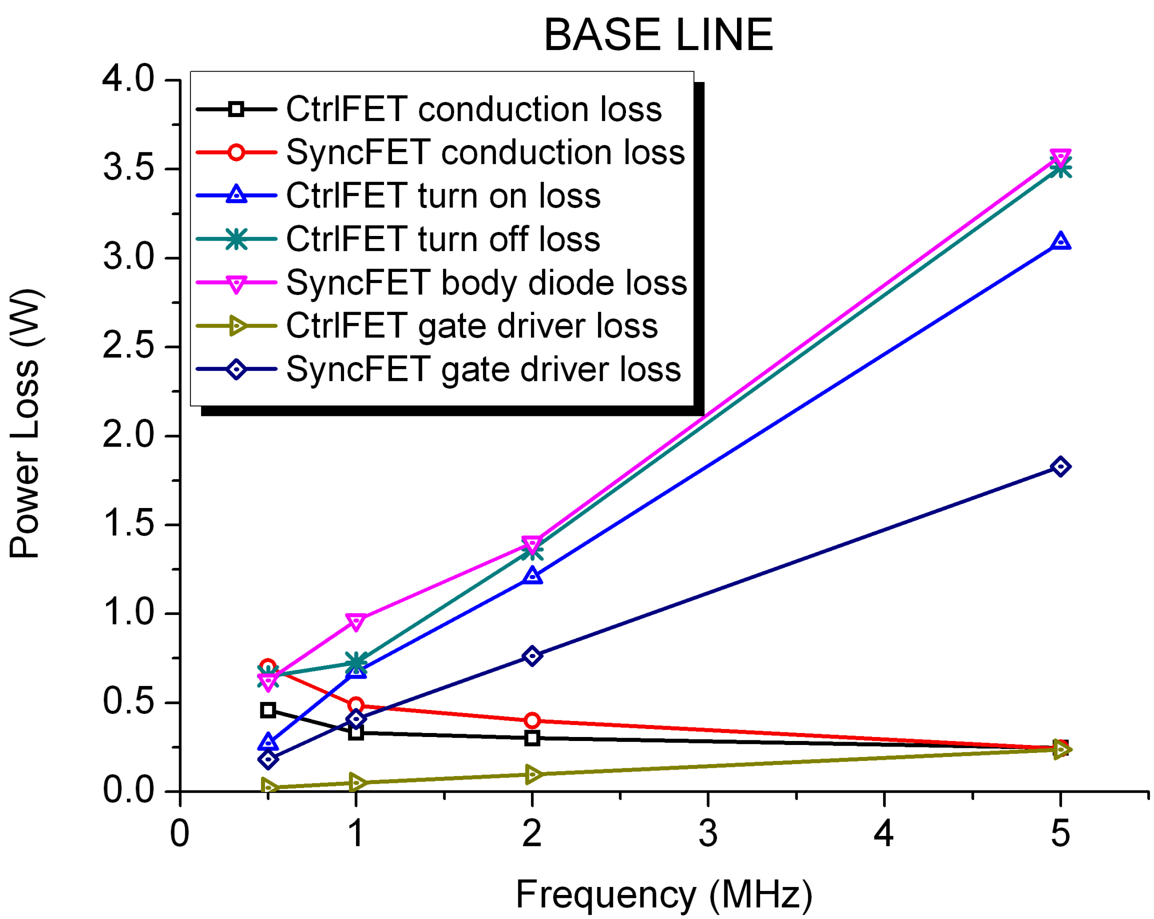


MOSFET Power Loss Contributions



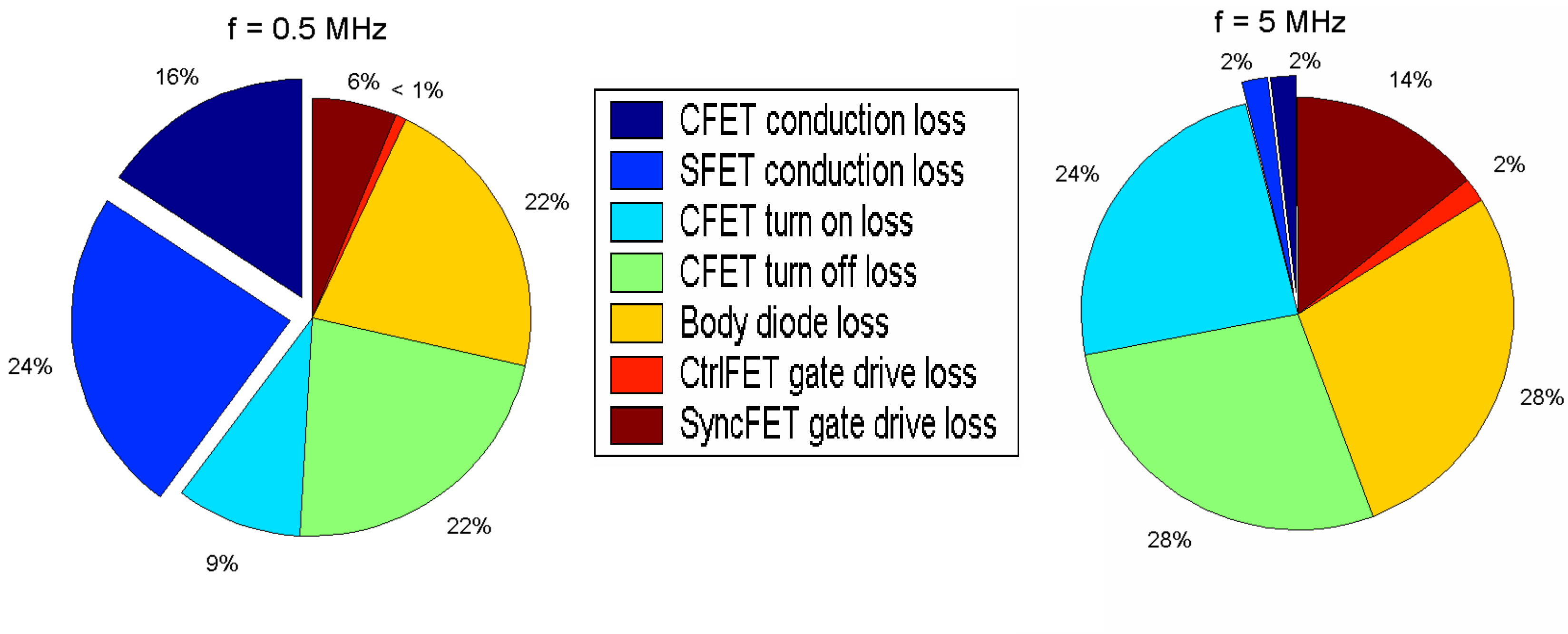
- Turn-on and turn-off switching losses of CtrlFET and body diode loss of SyncFET dominate the total power loss at MHz switching frequency
- Sync-FET gate drive loss is also significant

Power losses vs. PWM Frequency



- Turn-on and turn-off switching losses of CtrlFET and body diode loss and gate drive loss of SyncFET increase with switching frequency

TrenchFET Power Loss Contributions



From 500kHz to 5MHz:

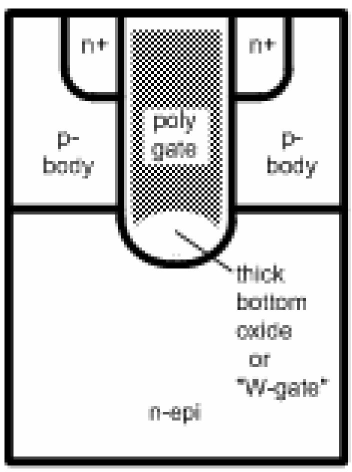
- Conduction Loss Contribution: **40% → 4%**
- Switching Loss Contribution: **60% → 96%**

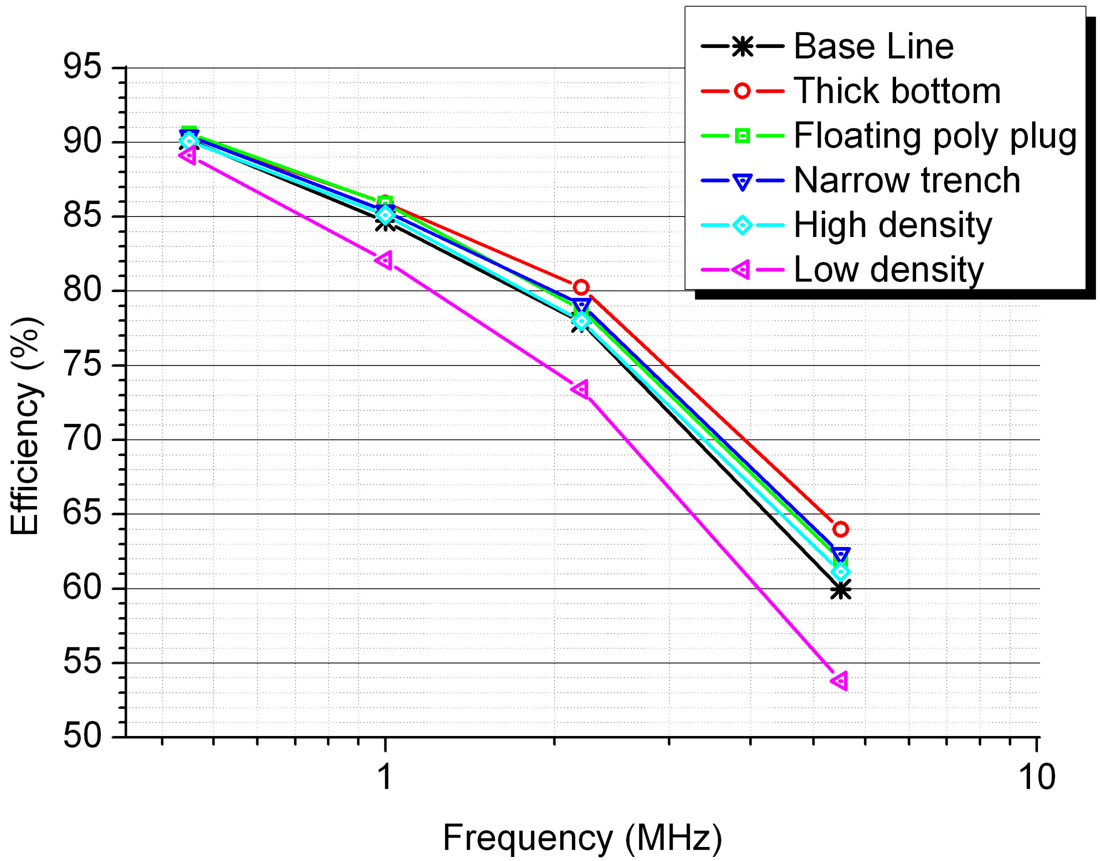
Comparison of Trench Power MOSFET Technologies

Type	Area Factor	Ron (mΩ)	Ciss (pF)	Coss (pF)	Crss (pF)	Qrr (nC)	Qg (nC)	Qgd (nC)	Ron*Qg (mΩ*nC)	Ron*Qgd (mΩ*nC)
Base line	1	9.4	1263	234	144	31.992	13.587	5.0	127.7178	47
Thick bottom	1.04	9.4	1230.8	212.2	109.2	28.14	10.505	4.2	98.747	39.48
Floating poly plug	1.138	9.4	1410.3	227.3	118.9	36.296	11.7	4.5	109.98	42.3
Narrow trench	1.106	9.4	1303	233	106.9	33.097	12.2	5.1	114.68	47.94
High density	0.622	9.4	1546	126	105	18.096	13.685	4.8	128.639	45.12
Low density	1.94	9.4	1318	428	240	57.257	19.24	11.3	180.856	106.22

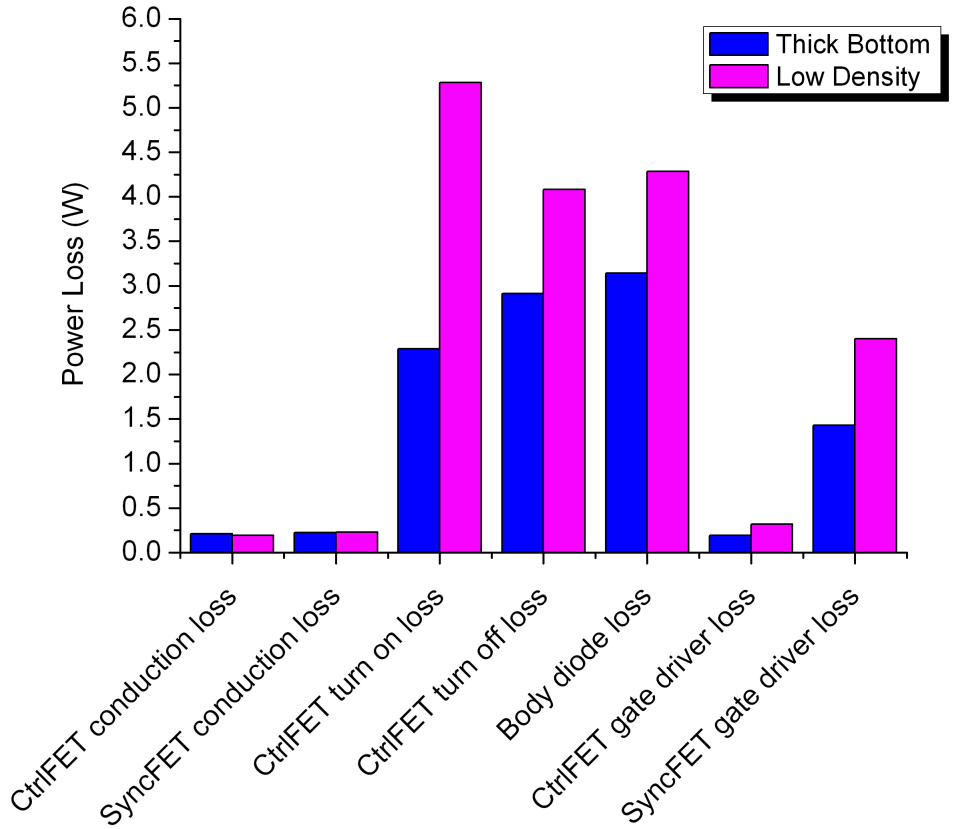
Comparison of Trench Power MOSFET Technologies

- The thick bottom trench MOSFET technology offers the highest efficiency in the MHz frequency range.



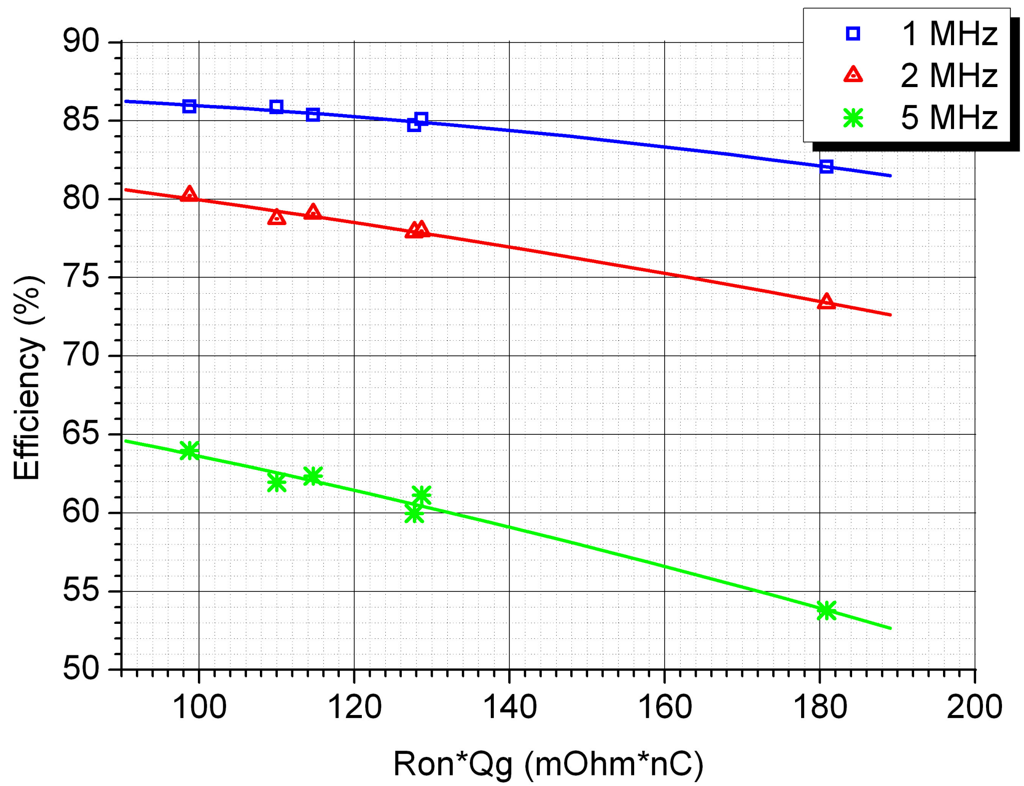


Comparison of Trench Power MOSFET Technologies



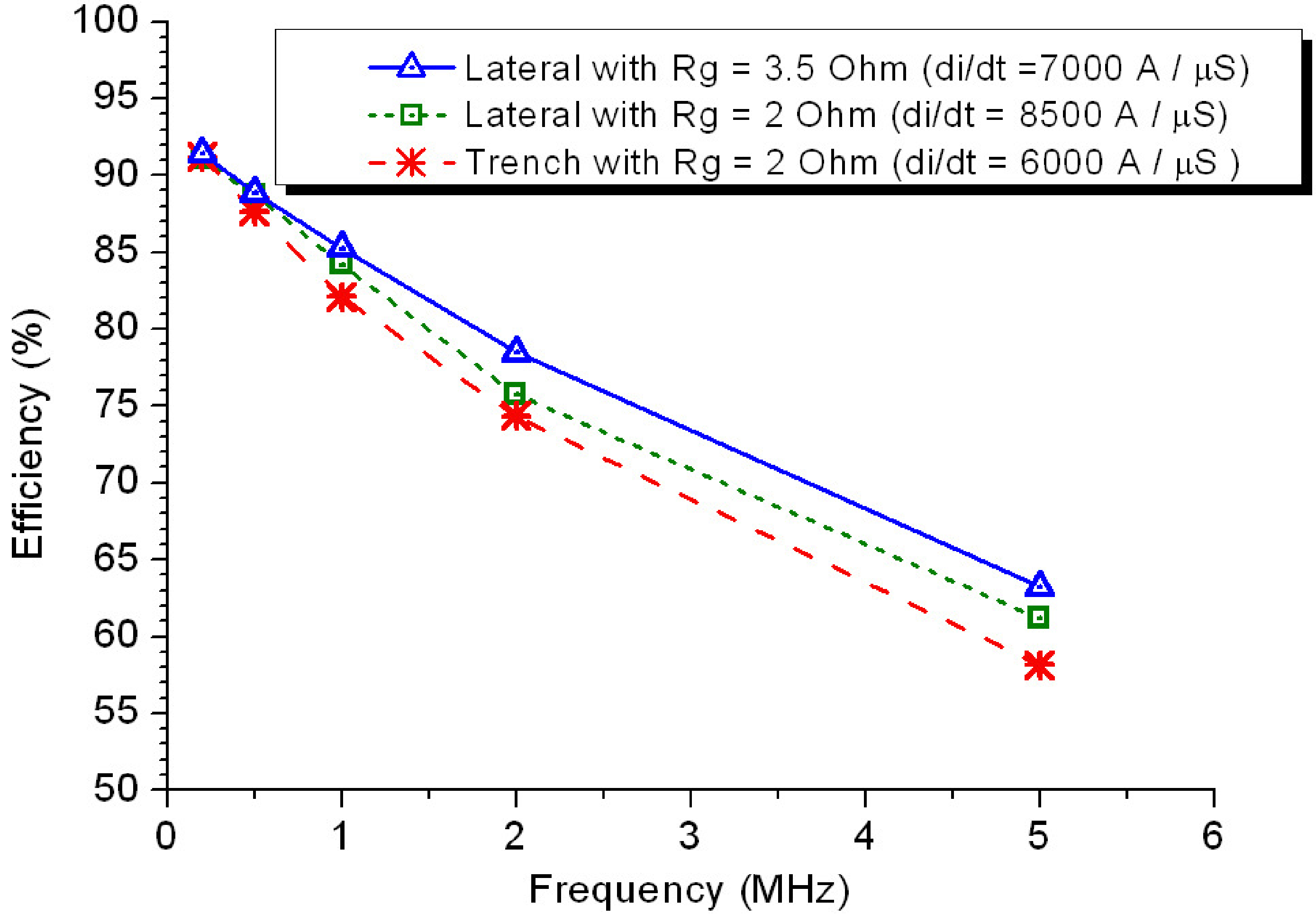
	Ron Ctrl/Sync (mΩ)	*Qrr* (nC)	*Qg* (nC)	*Qgd* (nC)
Base line	9.4/2.2	31.992	13.587	5.0
Thick Bottom	9.4/2.2	28.14	10.505	4.2
Floating Poly Plug	9.4/2.2	36.296	11.7	4.5
Narrow Trench	9.4/2.2	33.097	12.2	5.1
High Density	9.4/2.2	18.096	13.685	4.8
Low Density	9.4/2.2	57.257	19.24	11.3

FOM of Trench Power MOSFETs

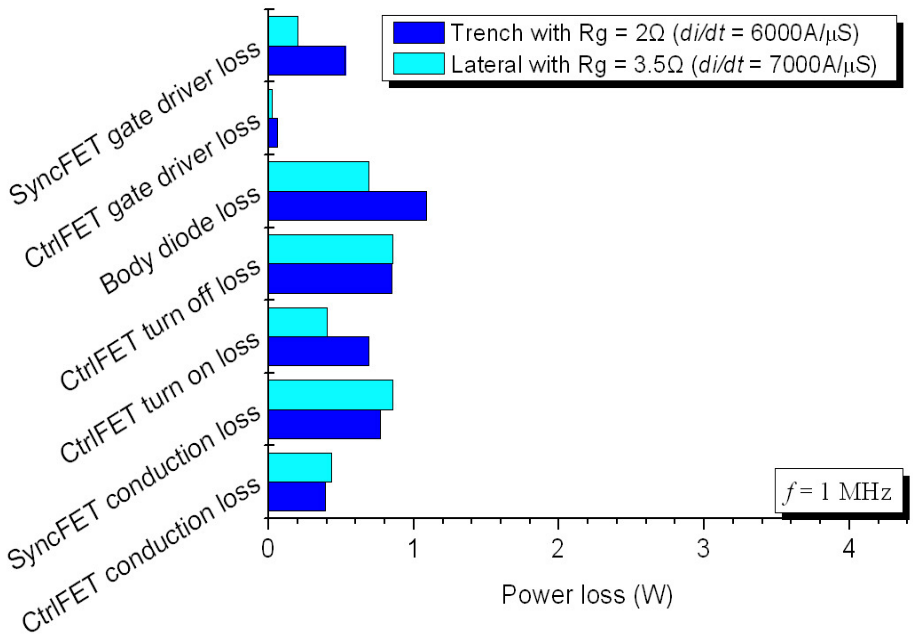


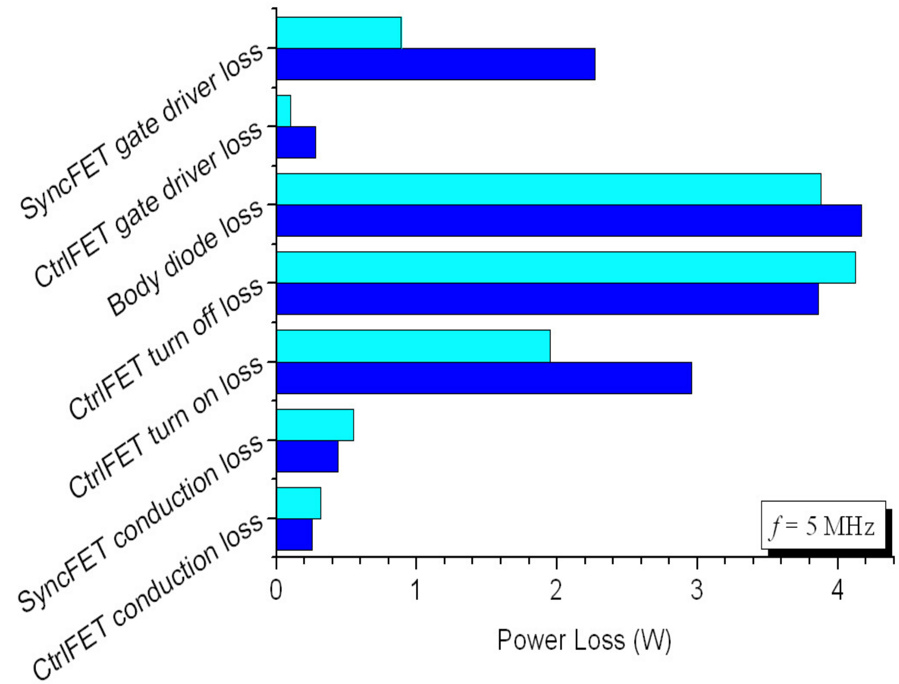
The Rdson•Qg FOM seems to be a good indicator of converter efficiency even into the MHz frequency range.

Trench vs. Lateral MOSFETs

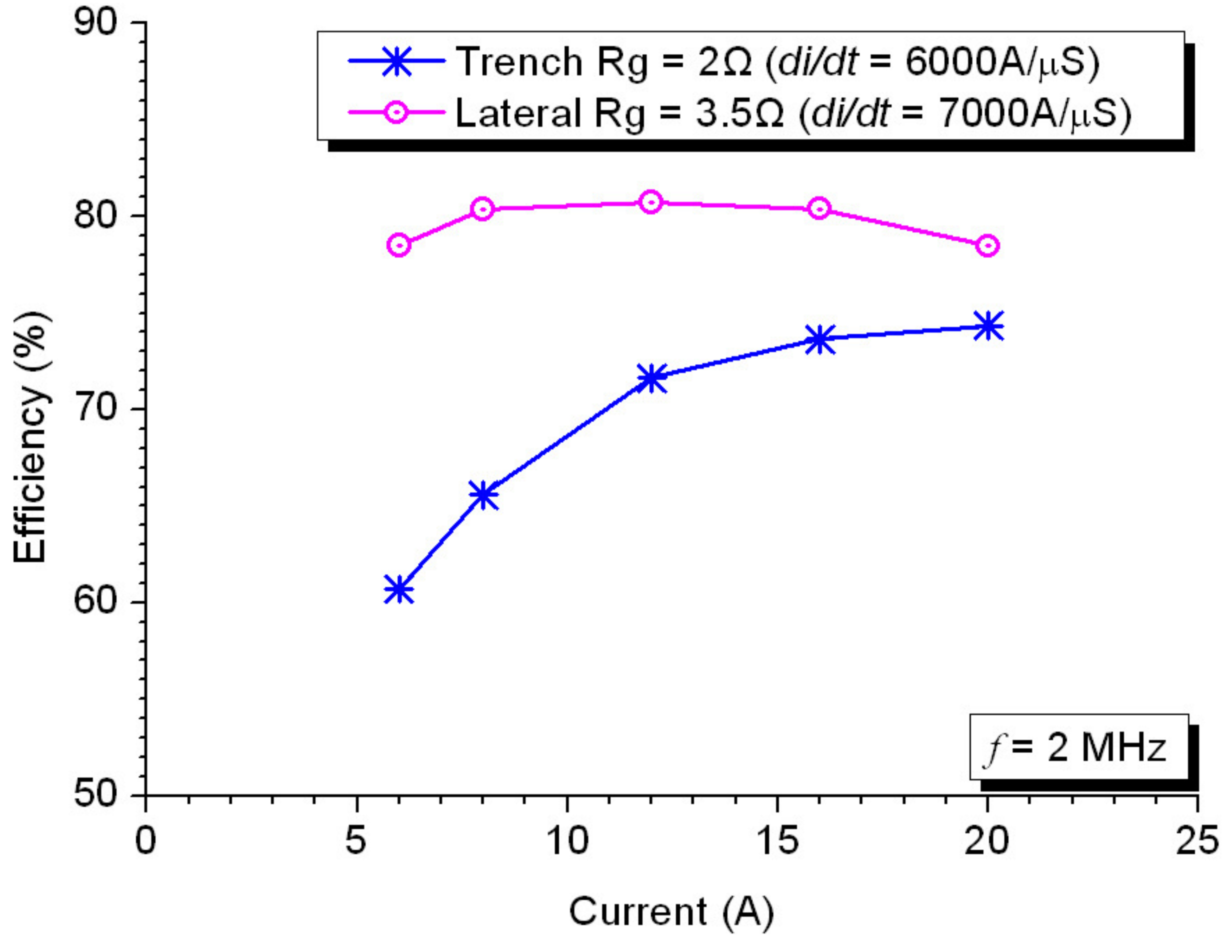


Trench vs. Lateral MOSFETs





Trench vs. Lateral MOSFETs



Summary

- The RDS(ON)×QG Figure of Merit (FOM) still correlate well to buck converter efficiency in the low MHz frequency range
- LDMOS offers significant efficiency improvement (up to 5 percent points at 5 MHz) over trench power MOSFETs in buck converters. The improvement mainly comes from the reduced gate drive power losses and switching times due to low Qg.
- The efficiency of the hard switching buck topology is limited to 80% at 2MHz and 65% at 5MHz even with lateral MOSFETs. CtrlFET switching loss and SyncFET body diode loss predominantly limit the efficiency of hard switching buck converters using either trench or lateral MOSFET chipset.
- Soft switching topology and resonant gate drive technology are needed for even higher MHz ranges. A new MOSFET FOM may be needed for those new circuits.