Light Load Operation
Light Load – Diode Operation

- Gate driver equation: $i(t) \approx i$
- $V_{ds}(t)$
- $C_{ds,eq} = 45$ pF
- $R_{on} = 0.15 \Omega$
- $t_{rr} = 40$ ns
- $Q_{rr} = 60$ nC
- $2C_{d,eq} - C_{d,eq} = 22$ pF
- $V_D = 1.5$ V

Hard-switched Si devices

- $di/dt = 200$ A/μs
- $C_{ds,eq} = 45$ pF
- $R_{on} = 0.15 \Omega$
- $t_{rr} = 40$ ns
- $Q_{rr} = 60$ nC
- $2C_{d,eq} - C_{d,eq} = 22$ pF
- $V_D = 1.5$ V

MOSFET

Si diode

RL = 0.5 Ω

fs = 1 MHz
**Loss breakdown: Si Boost**

- $f_s = 100\ kHz$
  - $P_{loss} = 10.6\ W$, $\eta = 96.6\%$

- $f_s = 1\ MHz$
  - $P_{loss} = 84.7\ W$, $\eta = 78.0\%$

Reverse-recovery: 54% of the total loss

Conduction losses: RL, Ron, VD
Switching losses:
  - "RR" reverse recovery,
  - "Cap" $C_{sw}$ discharge

Experiment*: $\eta = 81.2\%$

*Pulsed measurement, continuous operation not feasible due to thermal runaway

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**Efficiency: hard-switched Si Boost**

$\eta [\%]$

Switching frequency $f_s$

Practice,
ZVS with Si diode

- ZVS turn-ON
  - Eliminated losses due to $C_{sw}$ discharge during turn-ON transient
  - Eliminated losses due to MOSFET $di/dt$ during turn-ON transient
- Diode reverse recovery still impacts the waveforms and losses
- Increased current ripple
  - Increased conduction losses (by >30%)
  - Increased $dv_{ds}/dt$ upon turn-OFF, MOSFET turn-OFF speed is more important

Loss Breakdown: Soft-Switched Si Boost

- $f_s = 100$ kHz
  - $P_{loss} = 5.7$ W, $\eta = 98.1\%$
  - Reverse-recovery: 21% of the total loss

- $f_s = 1$ MHz
  - $P_{loss} = 17.7$ W, $\eta = 94.4\%$
  - Experiment: $\eta = 95.1\%$
  - Reverse-recovery: 68% of the total loss
Efficiency: soft-switched Si Boost

Hard-Switched SiC Schottky Diode

SiC diode, standard “hard-switched” operation

MOSFET
- $\frac{di}{dt} = 200 \text{ A/}\mu\text{s}$
- $C_{ds,eq} = 45 \text{ pF}$
- $R_{on} = 0.15 \text{ Ω}$

SiC diode
- $t_r = 0, Q_o = 0$
- $2C_{d,eq} = 64 \text{ pF}$
- $V_D = 1.8 \text{ V}$
Loss Breakdown: hard-switched SiC diode

- $f_s = 100 \text{ kHz}$
  - $P_{\text{loss}} = 5 \text{ W}$, $\eta = 98.4\%$
- $f_s = 1 \text{ MHz}$
  - $P_{\text{loss}} = 15.7 \text{ W}$, $\eta = 95.0\%$

Experiment: $\eta = 94.7\%$

C_{\text{sw}} \text{ discharge loss now dominates}$

Efficiency comparison

- $\eta$ [%]
- $f_s = 10 \text{ kHz}$
- $f_s = 100 \text{ kHz}$
- $f_s = 1 \text{ MHz}$

- Hard-switched P-N Si
- Soft-switched P-N Si
- Schottky diode, hard-switched
- Extended practical $f_s$ range
**Soft-switched SiC Schottky diode**

- **MOSFET**
  - \( \frac{di}{dt} = 200 \text{ A/\mu s} \)
  - \( C_{ds,eq} = 45 \text{ pF} \)
  - \( R_{on} = 0.15 \text{ \Omega} \)

- **SiC diode**
  - \( t_r = 0, Q_{rr} = 0 \)
  - \( 2C_{d,eq} - C_{d,eq} = 64 \text{ pF} \)
  - \( V_D = 1.8 \text{ V} \)

**SiC diode, soft-switched operation**

\( f_s = 1 \text{ MHz} \)

**Soft-switched Boost with SiC diode**

- **Conduction losses only, 2nd-order switching losses not included in the model**

- **100 kHz or 1 MHz**
- **98.5% efficiency**
- **\( P_{loss} = 4.5 \text{ W} \)**

**Experiments:**
- **98.7% at 1 MHz**
- **98.0% at 2 MHz**
Efficiency comparison

\[ \eta \text{ [%]} \]

Switching frequency \( f_s \)

- Hard-switched P-N Si
- Soft-switched P-N Si
- Schottky diode, soft-switched

*2nd-order switching losses not modeled

Limitations: \( t_d / T_S \)
Limitations: 2\textsuperscript{nd} Order Loss Mechanisms

Texas Instruments, "Optimizing MOSFET Characteristics by Adjusting Gate Drive Amplitude"

Limitations: Gate Drive

Texas Instruments, "Selection of External Bootstrap Diode for LM510X Devices"
Limitations: Magnetics Design

Minimum Switching Frequency vs. Core Volume

Limitations: Thermal

Power Density vs. Switching Frequency