Diode Stored Charge

The diode equation:

\[ q(t) = Q_0 \left( e^{\lambda v(t)} - 1 \right) \]

Charge control equation:

\[ \frac{dq(t)}{dt} = i(t) - \frac{q(t)}{\tau_L} \]

With:

\[ \lambda = 1/(26 \text{ mV}) \text{ at } 300 \text{ K} \]

\[ \tau_L = \text{minority carrier lifetime} \]

(above equations don’t include current that charges depletion region capacitance)

In equilibrium: \( dq/dt = 0 \), and hence

\[ i(t) = \frac{q(t)}{\tau_L} = \frac{Q_0}{\tau_L} \left( e^{\lambda v(t)} - 1 \right) = I_0 \left( e^{\lambda v(t)} - 1 \right) \]

Fundamentals of Power Electronics

Diode Turn-On

Depletion region, reverse-biased
Diode Turn-Off

Diode Reverse Recovery
Diode Switching Waveforms

Datasheet RR Characteristics

Fig. 9 - Typical Reverse Recovery Time vs. \( dl/dt \)

Fig. 10 - Typical Stored Charge vs. \( dl/dt \)
Including Switching Loss in Avg. Equivalent Circuit

- Switching losses can be included with little modification
- Simply sketch waveforms with (non-ideal) switching transitions, then average as normal
- Steady-state averaging holds as normal:
  \[-\langle v_L \rangle = 0, \langle i_C \rangle = 0, \langle i_g \rangle = I_g\]
- Use resulting equations to construct equivalent circuit model

Buck Converter Example

- All elements ideal except for reverse recovery \((Q_r\text{ and } t_r)\) of diode
Predicted Efficiency vs Duty Cycle

- Switching frequency 100 kHz
- Input voltage 24 V
- Load resistance 15 Ω
- Recovered charge 0.75 μCoul
- Reverse recovery time 75 nsec

- (no attempt is made here to model how the reverse recovery process varies with inductor current)

- Substantial degradation of efficiency
- Poor efficiency at low duty cycle
Paralleling Diodes

Attempts to parallel diodes, and share the current so that $i_1 = i_2 = i/2$, generally don’t work.

*Reason:* thermal instability caused by temperature dependence of the diode equation.

Increased temperature leads to increased current, or reduced voltage.

One diode will hog the current.

To get the diodes to share the current, heroic measures are required:

- Select matched devices
- Package on common thermal substrate
- Build external circuitry that forces the currents to balance

Types of Power Diodes

*Standard recovery*
Reverse recovery time not specified, intended for 50/60Hz

*Fast recovery and ultra-fast recovery*
Reverse recovery time and recovered charge specified
Intended for converter applications

*Schottky diode*
A majority carrier device
Essentially no recovered charge
Model with equilibrium $i-v$ characteristic, in parallel with depletion region capacitance
Restricted to low voltage (few devices can block 100V or more)
Schottky Diode

<table>
<thead>
<tr>
<th>$L$</th>
<th>$C_{out}$</th>
<th>$f_s$</th>
<th>Diode</th>
<th>$\eta$ (Sim)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22uH</td>
<td>22uF</td>
<td>200k</td>
<td>Si (FR)</td>
<td>93.9%</td>
</tr>
<tr>
<td>22uH</td>
<td>22uF</td>
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<td>96.9%</td>
</tr>
</tbody>
</table>

Simulation Waveforms

[Simulation Waveforms Diagram]
Switching Transition

Power MOSFET