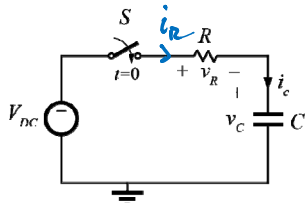




## M<sub>2</sub> Energy Loss

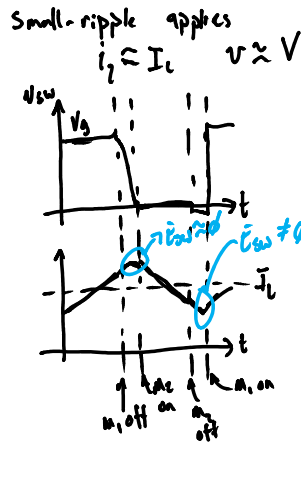
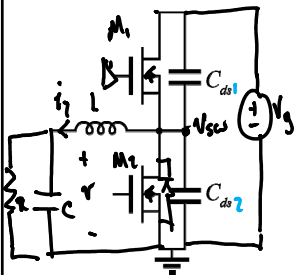


$$\begin{aligned}
 E_R &= \int_0^{\infty} i_c^2 R dt \\
 &= \int_0^{\infty} i_c (V_{dc} - v_c) dt \\
 &= \int_0^{\infty} C \frac{dv_c}{dt} (V_{dc} - v_c) dt \\
 E_R &= \int_0^{V_{dc}} C (V_{dc} - v_c) dv_c = -\int_0^{V_{dc}} C v_c dv_c + \int_0^{V_{dc}} V_{dc} C dv_c \\
 E_R &= V_{dc}^2 C_{eq} - \frac{1}{2} C_{eq} V_{dc}^2 \\
 &\text{Energy supplied from } V_{dc} \quad \text{Energy supplied to } C
 \end{aligned}$$

$$\begin{aligned}
 E_{in} &= \int_0^{\infty} i_c V_{dc} dt = V_{dc} \int_0^{\infty} i_c dt \\
 &= V_{dc} Q \\
 &= V_{dc}^2 C_{eq} \\
 E_{sw} &= V_{dc}^2 C_{eq}
 \end{aligned}$$



## Example: Switching Losses in a Buck



$$\begin{aligned}
 E_{sw} &= E_1 + E_2 \\
 &= \frac{1}{2} C_{d1} E_1 V_g^2 + V_g^2 C_{d2} - \frac{1}{2} C_{d2} E_2 V_g^2 \\
 &\text{if } C_{d1} \& C_{d2} \text{ are identical:} \\
 E_{sw} &= V_g^2 C_{eq} \theta
 \end{aligned}$$

Analytical  $E_{sw}$  for ideal Silicon DMOS

$$C_{ds} = \frac{C_{j0} A}{\sqrt{1 + \frac{v_{ds}}{V_F}}}, \quad C_{j0} = \sqrt{\frac{\epsilon^2 E_{crit}^2}{4 V_{BV} V_F}}$$

on this week's HW  $\rightarrow V_F = 1$

$$C_{ds} = \frac{C_{j0} A}{\sqrt{1 + V_{ds}}}$$

$$C_{eq,Q} = \frac{1}{V_g} \int_0^{V_g} C_{ds} dv = \frac{1}{V_g} \int_0^{V_g} \frac{C_{j0} A}{\sqrt{1+v}} dv$$

$$= \frac{C_{j0} A}{V_g} 2\sqrt{1+v} \Big|_{v=0}^{v=V_g} = \frac{2 C_{j0} A}{V_g} (\sqrt{1+V_g} - 1)$$

$$E_{sw} = 2 V_g C_{j0} A (\sqrt{1+V_g} - 1)$$

$\hookrightarrow$  Note: still linearly proportional to A (device area)

**infineon** IPB60R385CP

13 Typ. capacitances  $C = f(V_{DS}); V_{GS} = 0 V; f = 1 MHz$

14 Typ. Coss stored energy  $E_{Coss} = f(V_{DS})$

The left graph shows capacitance (C [pF]) on a logarithmic scale (from 10<sup>0</sup> to 10<sup>5</sup>) versus drain-source voltage (V<sub>DS</sub> [V]) on a linear scale (from 0 to 500). Three curves are shown: C<sub>iss</sub> (input capacitance), C<sub>oss</sub> (output capacitance), and C<sub>rss</sub> (reverse transfer capacitance). C<sub>oss</sub> starts at approximately 10<sup>4</sup> pF at 0 V and decreases to about 10<sup>1</sup> pF at 500 V. A red arrow points to the start of the C<sub>oss</sub> curve at V<sub>DS</sub> = 0.

The right graph shows stored energy (E<sub>oss</sub> [uJ]) on a linear scale (from 0 to 6) versus V<sub>DS</sub> [V] on a linear scale (from 0 to 600). The curve shows that stored energy increases quadratically with V<sub>DS</sub>. A handwritten red formula is present:  $E = \int_0^V C(v) v dv$ .

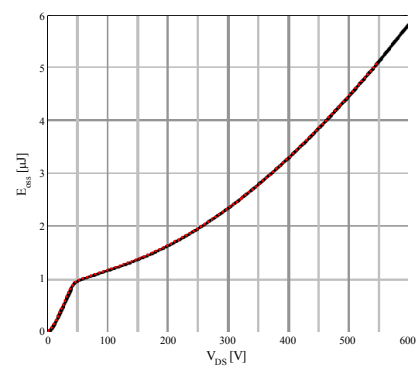
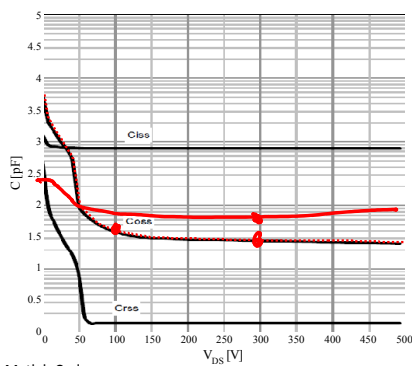


## Nonlinear Capacitance Extraction

- <http://web.eecs.utk.edu/~dcostine/personal/PowerDeviceLib/DigiTest/index.html>



## Energy Equivalent



Matlab Code:

```
Vdc = 550;
```

```
Vds = [0 5 10 40 50 75 100 150 200 300 400 500 600];
Coss = [5500 2500 1900 550 95 50 38 30 29 27 25 24]*1e-12;
```

```
vx = 0.01:0.01:Vdc;
```

```
Cx = 10.^interp1(Vdc,log10(Coss),vx,'linear');
```

```
E = cumtrapz(vx, Cx.*vx);
```

```
Ceq_e = 2*(E)./vx.^2;
```



## Datasheet Reported Capacitance

### Dynamic characteristics

|  |              |  |   |           |   |    |
|--|--------------|--|---|-----------|---|----|
| Input capacitance  | $C_{iss}$    | $V_{GS}=0\text{ V}, V_{DS}=100\text{ V},$<br>$f=1\text{ MHz}$                          | - | 790       | - | pF |
| Output capacitance   | $C_{oss}$    |  | - | <u>38</u> | - |    |
| Effective output capacitance, energy related <sup>6)</sup> | $C_{o(er)}$  | $V_{GS}=0\text{ V}, V_{DS}=0\text{ V}$<br>to 480 V                                     | - | <u>36</u> | - | ns |
| Effective output capacitance, time related <sup>7)</sup>   | $C_{o(tr)}$  |  | - | <u>96</u> | - |    |
| Turn-on delay time   | $t_{d(on)}$  |  | - | 10        | - |    |
| Rise time  | $t_r$        | $V_{DD}=400\text{ V},$<br>$V_{GS}=10\text{ V}, I_D=5.2\text{ A},$<br>$R_G=3.3\ \Omega$ | - | 5         | - |    |
| Turn-off delay time  | $t_{d(off)}$ |  | - | 40        | - |    |
| Fall time  | $t_f$        |  | - | 5         | - |    |

<sup>6)</sup>  $C_{o(er)}$  is a fixed capacitance that gives the same stored energy as  $C_{oss}$  while  $V_{DS}$  is rising from 0 to 80%  $V_{DSS}$ .

<sup>7)</sup>  $C_{o(tr)}$  is a fixed capacitance that gives the same charging time as  $C_{oss}$  while  $V_{DS}$  is rising from 0 to 80%  $V_{DSS}$ .