开关电源关键元器件

TI大学计划

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Inductors

- Passive elements that stores energy in a magnetic field and resists changes in electric current

$$V = L * \frac{dI}{dT}$$

- Switch-mode power supplies rely on the **Steady-State Inductor Principle** for power conversion
- Common inductor considerations are
  - Inductance
  - DC Current Rating
  - Saturation Current Rating
  - DCR
  - Core loss
  - Saturation profile

Capacitors

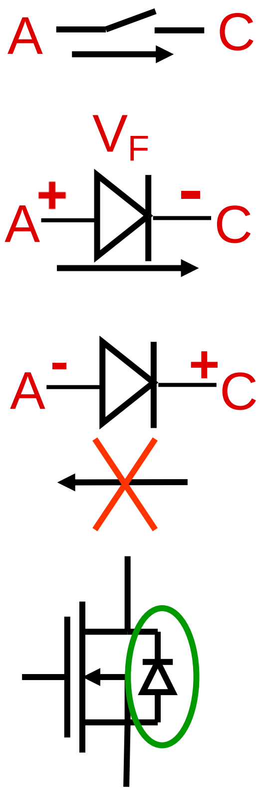
- Passive elements that stores energy in an electric field and resists changes in voltage

$$I = C * \frac{dV}{dT}$$

- Capacitors provide AC current filtering plus voltage hold-up in power supply applications
- Common capacitor considerations are
  - DC Voltage Rating
  - DC Bias
  - ESR
  - ESL
  - RMS Current Rating
  - Dielectric material
  - Lifetime

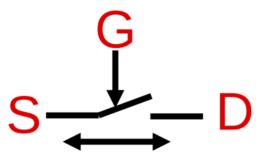
Diodes

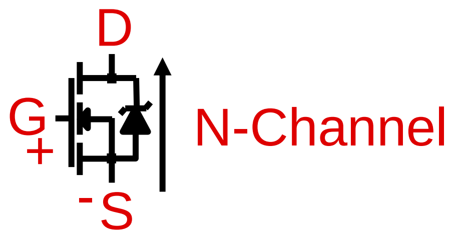
- A Diode is a passive electrical switch.
- Two Terminals – Anode, Cathode.
- The Switch is Closed by applying a Current into the Anode (Forward Bias).
  - This causes a Voltage drop of 0.3V to 1.2V from Anode to Cathode called the Forward Voltage (VF).
  - Charge is stored in the junction.
- The switch is opened by applying a Positive Voltage from Cathode to (Reverse Bias).
  - Stored Charge is dissipated (Reverse Recovery)
- Within the structure of a MOSFET, there is a “Body” Diode from Source to Drain.

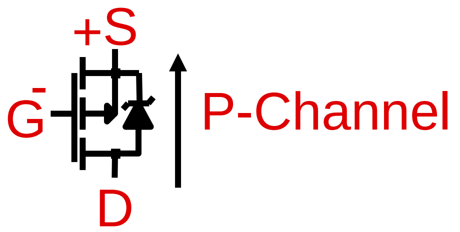


MOSFETs

- A MOSFET (Metal Oxide Semiconductor Field Effect Transistor) is an Active, Bidirectional Switch.
- Three Terminals – Gate, Drain, Source.
- Two Types
  - N-Channel – Positive Voltage from Gate to Source connects Drain to Source.
  - P-Channel – Negative Voltage from Gate to Source connects Drain to Source.
- The On-State characteristic is Resistive.
- The Gate needs to be charged and discharged for the MOSFET to be turned on and off.
- An internal Diode bypasses the switch in one direction.
- Tradeoffs
  - Price
  - Size
  - Performance (definition depends on application)



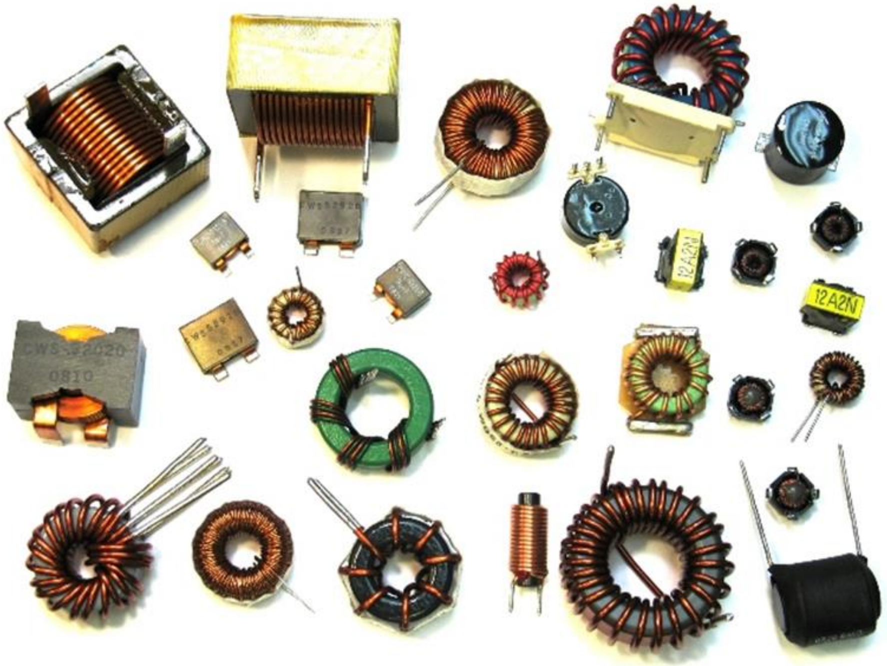




Inductor Selection

Inductor Overview

- Inductors are formed by a wire wound around a ferromagnetic core
- The type of core and the number of turns determines the inductance value
- Other characteristics are also determined by how the turns are wound, the thickness (gauge) of the wire used, the physical size of the inductor etc.



Inductor Overview – Specifications

Part number1	Inductance2 ±20% (µH)	DCR max3 (Ohms)	SRF typ4 (MHz)	Isat5 (A)	Irms6 (A)
LPO3010-102NL_	1.0 ±30%	0.140	200	1.7	1.4
LPO3010-122NL_	1.2 ±30%	0.160	190	1.6	1.4
LPO3010-152NL_	1.5 ±30%	0.200	150	1.3	1.0
LPO3010-222NL_	2.2 ±30%	0.265	140	1.2	0.90
LPO3010-332NL_	3.3 ±30%	0.335	100	0.96	0.60

2 Inductance tested at 100 kHz, 0.1 Vrms, 0 Adc.
3 DCR measured on a micro-ohmmeter.
4 SRF measured using an Agilent/HP 4191A or equivalent.
5 Isat: DC current at which the inductance drops 10% (typ.) from its value without current.
6 Irms: Average current for a of 40°C rise above 25°C ambient.
7 Operating and storage temperature range -40°C to +85°C.
8 Electrical specifications at 25°C.

Inductor Overview – Terminology

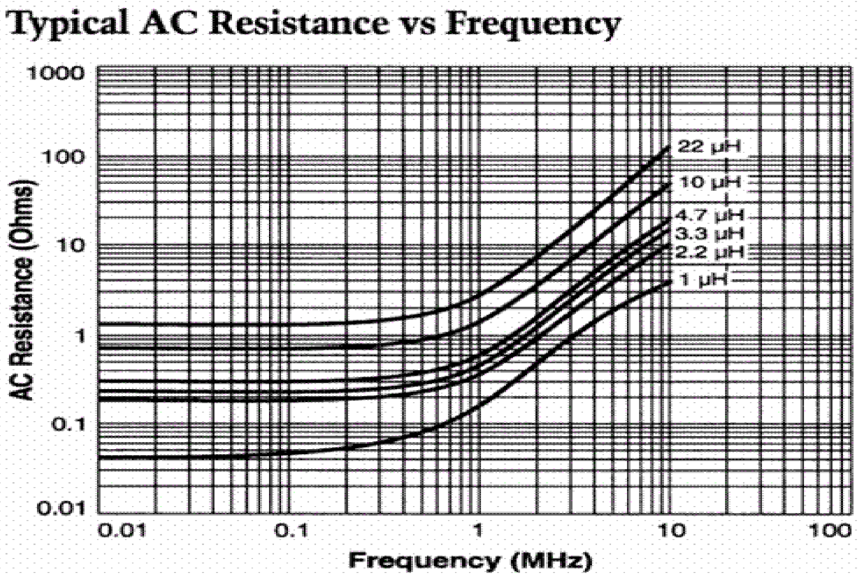
- **L – Inductance**
  - The property of an electric circuit by which an electromotive force is induced in it as the result of a changing magnetic flux.

$$v_L = L \times \frac{\mathrm{di}}{\mathrm{dt}}$$

  - This is the value that is calculated by converter design equations to determine the inductors ability to handle the desired output power and control ripple current.

Inductor Overview – Terminology

- **DCR – DC Resistance**
  - The resistance in a component due to the length and diameter of the winding wire used. Effects the efficiency of a power supple design.
- **ACR – AC Resistance**
  - The AC resistance of the wire due to the skin effect is not usually the primary AC loss but can be important at very high frequencies. The primary AC loss comes from losses in the core as the magnetic field transitions. This includes hysteresis and eddie current losses.



Inductor Overview – Terminology

- **SRF – Self Resonant Frequency**
  - The frequency at which the inductance of an inductor winding resonates naturally with the distributed capacitance characteristic of that winding.
- **I_{sat} – Saturation Current**
  - The amount of current flowing through an inductor that causes the inductance to drop due to core saturation.

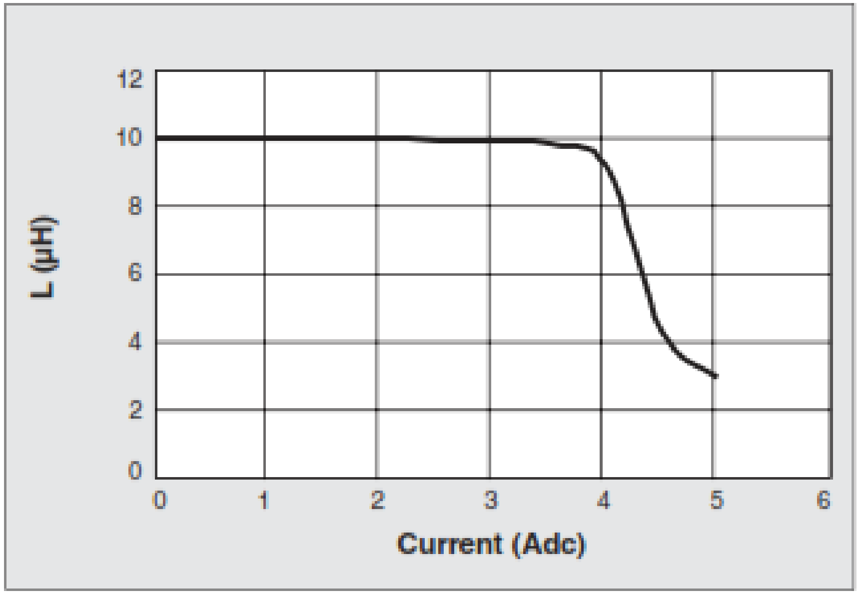
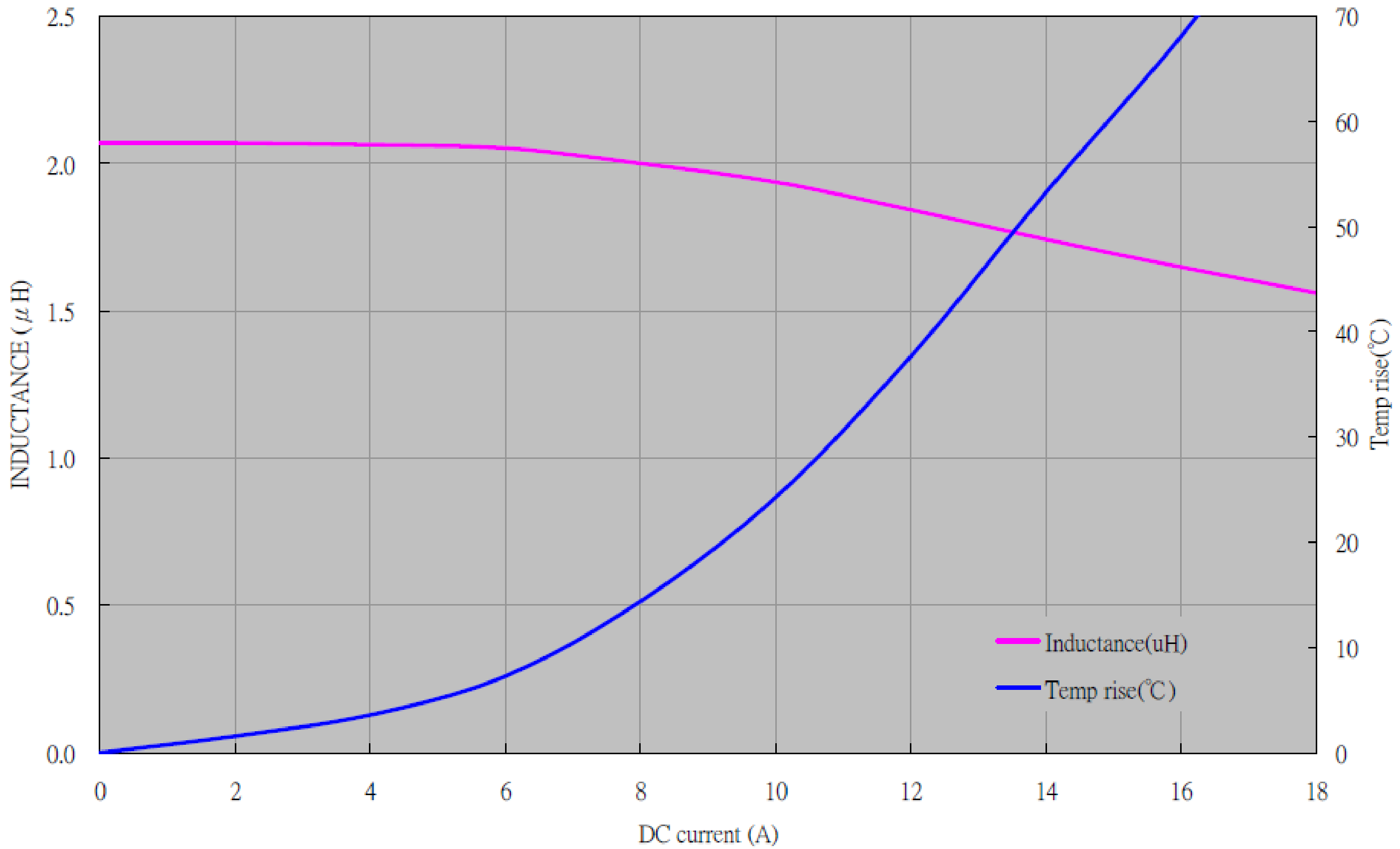


Figure 7. L vs DC Bias Current for Coilcraft DO3316P-103

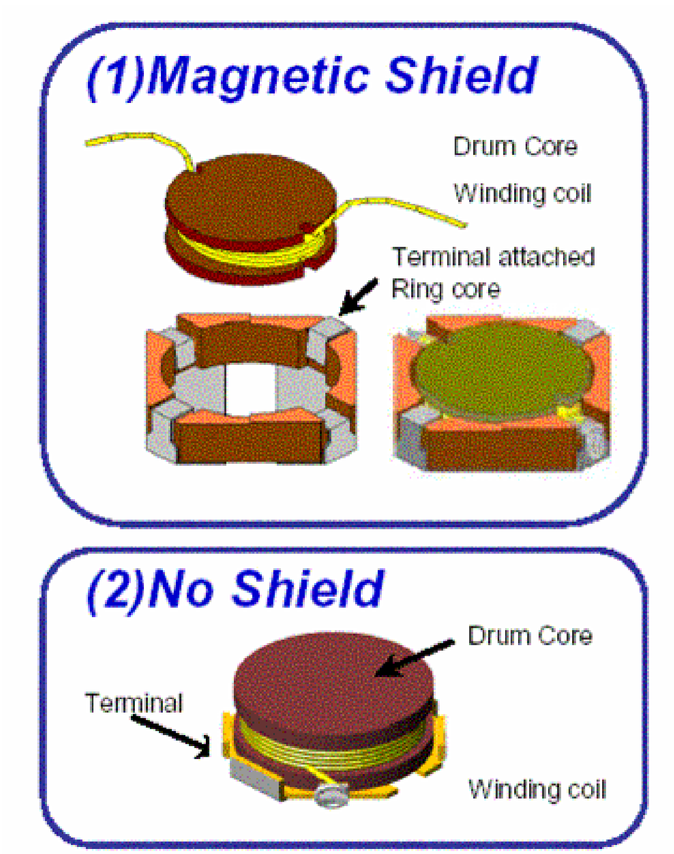
Inductor Overview – Terminology

- **I_{rms} – RMS Current**
  - The amount of continuous current flowing through an inductor that causes the maximum allowable temperature to rise

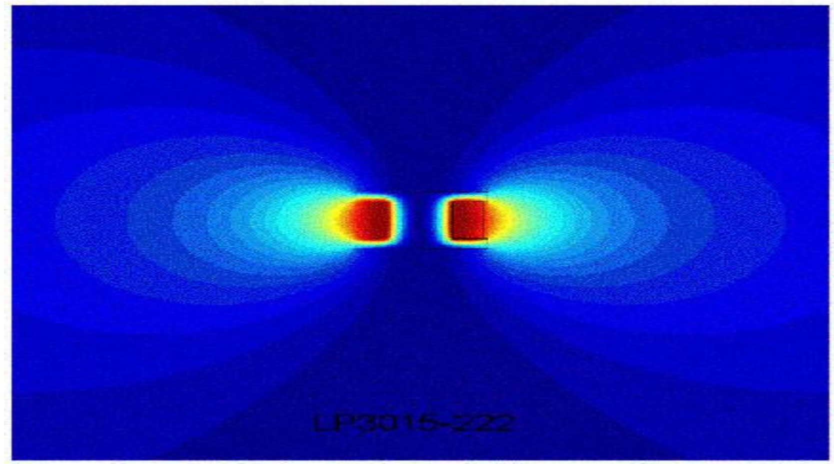


Inductor Terminology - Shielding

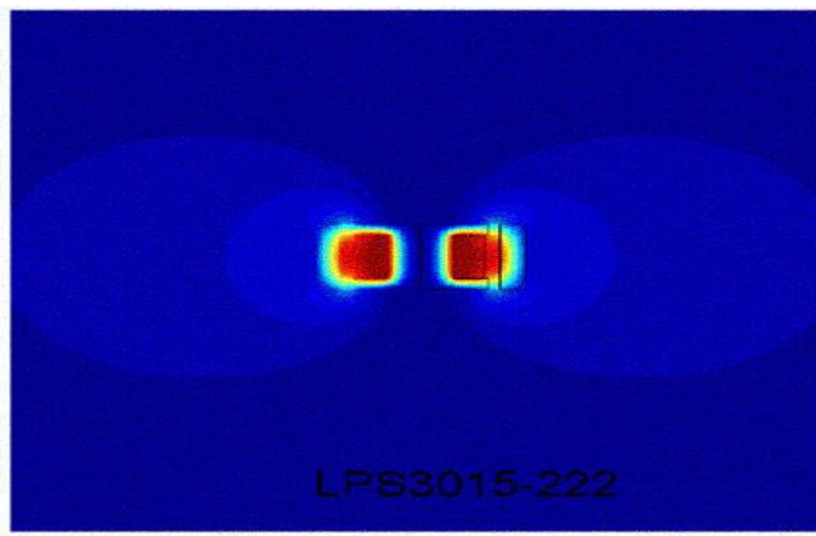
The picture shows the difference between the construction of a shielded and unshielded inductor



Unshielded Inductor Flux:



Shielded Inductor Flux:

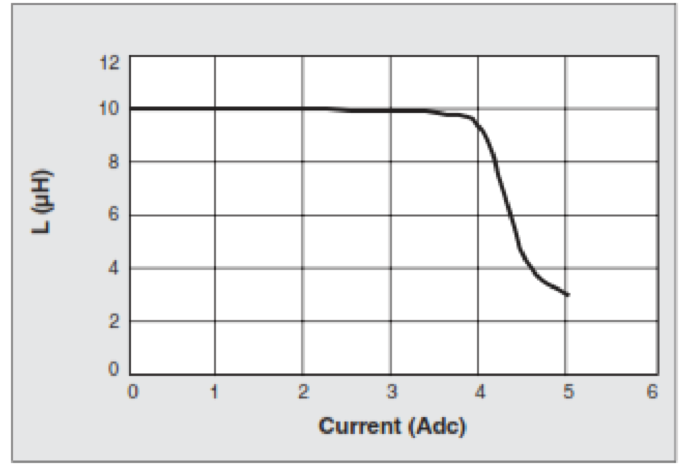


Inductor Terminology – Core Material

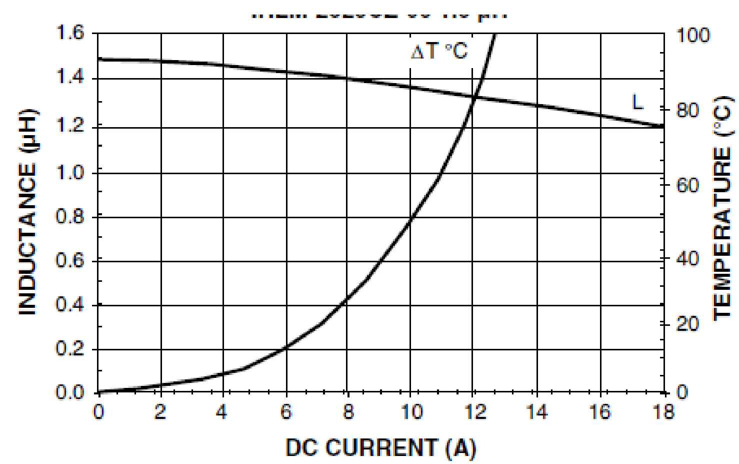
1) Ferrite cores
   a) Come in a variety of shapes
   b) Operate at high switching frequencies
   c) Have fairly steep saturation of inductance.

2) Iron Powder cores
   a) Molded into a standard slug shape
   b) Higher core losses make it unsuitable for high switching frequencies
   c) Shallow saturation of inductance makes it very useful for high current low ripple designs.

Typical Saturation Curve for Ferrite

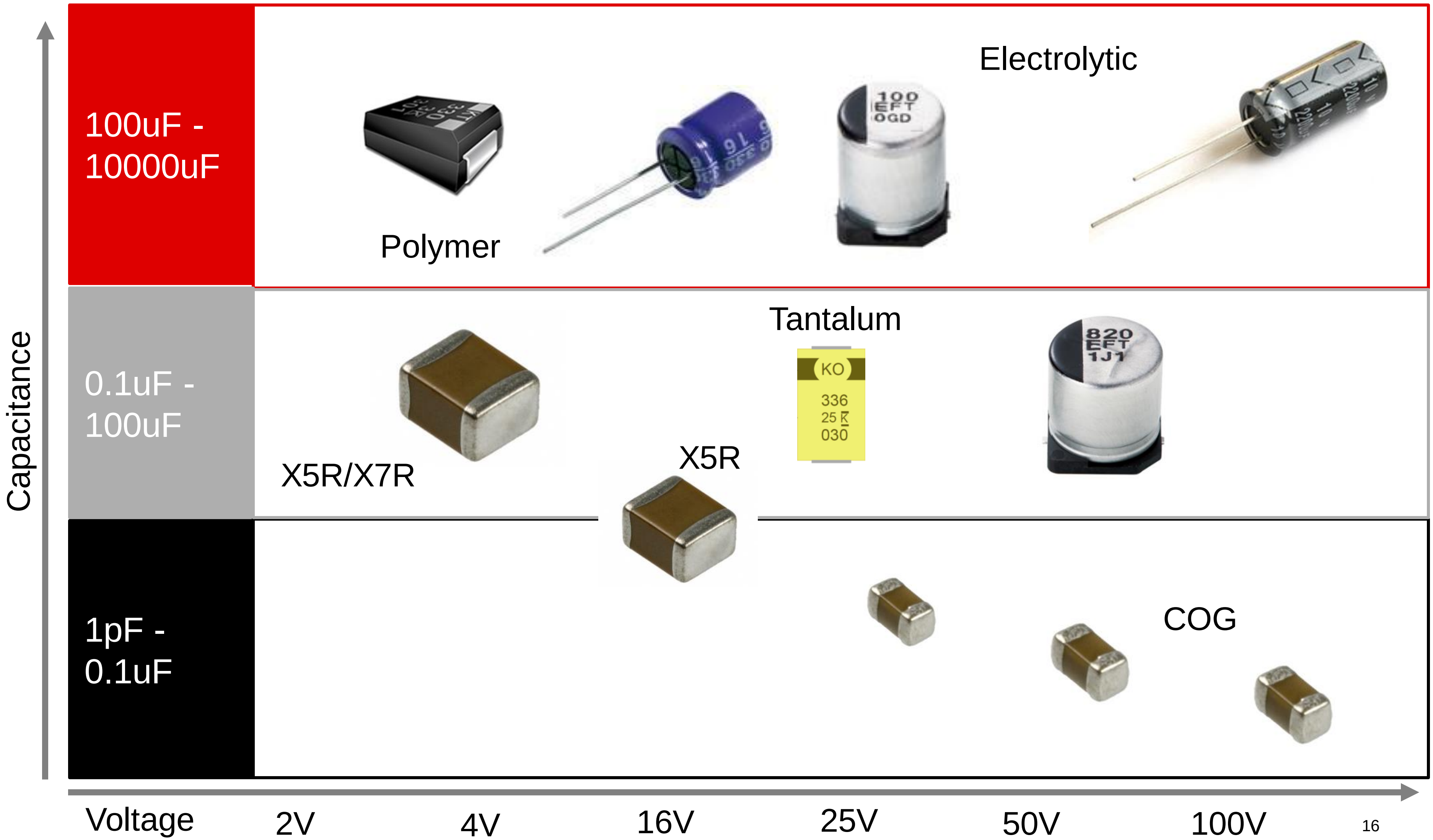


Typical Saturation Curve for Iron Powder



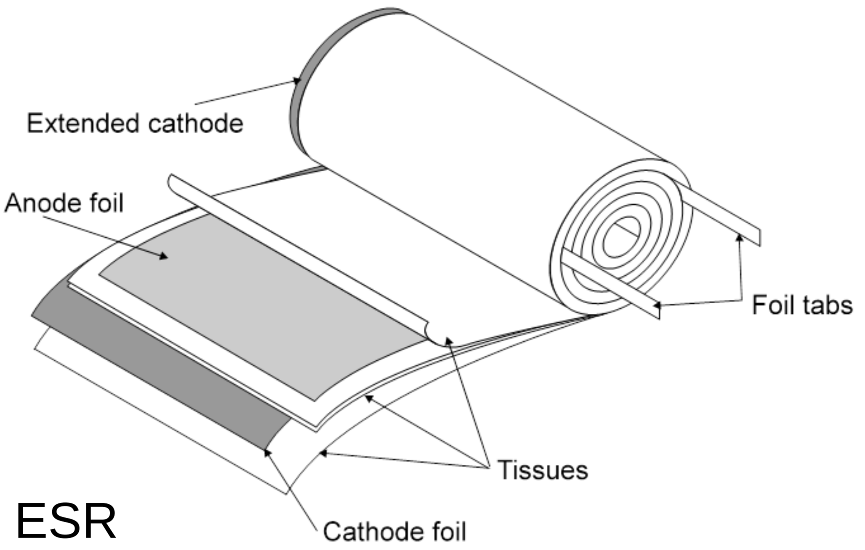
Capacitors

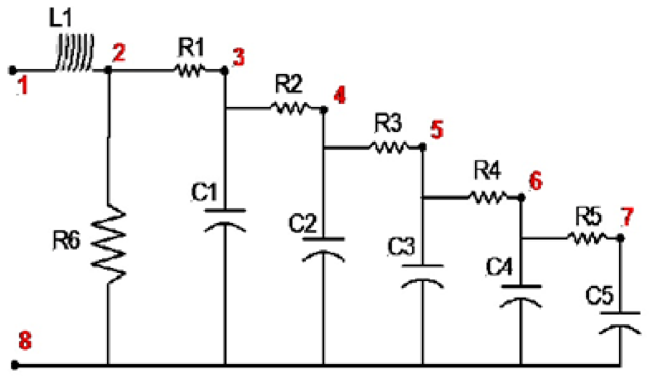
Capacitor Chemistry: Value and Voltage rating



Aluminum Electrolytics: Overview

- **Least Expensive** Capacitors for Bulk Capacitance
  - Multiple vendors
  - Small size, surface mountable
- How is it made?
  - Etched foil with liquid Electrolyte
  - Placed in a can with a seal/vent
- **Highest ESR**
- Low Frequency Cap roll off due to higher ESR
- Wear Out Mechanism – **Limited lifetime**
  - Liquid electrolyte – with a vent
  - Cap changes over time with Voltage and Temp
  - ESR changes over time
- Mounting
  - High shock and vibration can cause failure





Aluminum Electrolytics: Packaging

- Through hole versions, usually in a round can
  - Large ones have screw terminals or solder lugs
  - Radial or axial leads
  - Non SMT may have higher inductance because of long leads
- Surface mountable versions, are modified from radial leaded versions
  - SMT versions usually have the capacitor value visibly printed on can
  - SMT versions may use letter codes instead of numeric rating

Aluminum Electrolytics

Advantages	Disadvantages

- Low Cost
  - Mature technology with low cost materials
- Long History
  - (Industry started in the 1930's)
- Many Manufacturers to choose from.
- High capacitance values available.
- Only choice for SMPS that need high voltage and high capacitance.

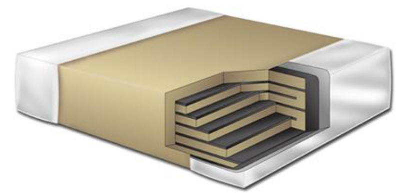
Aluminum Electrolytics

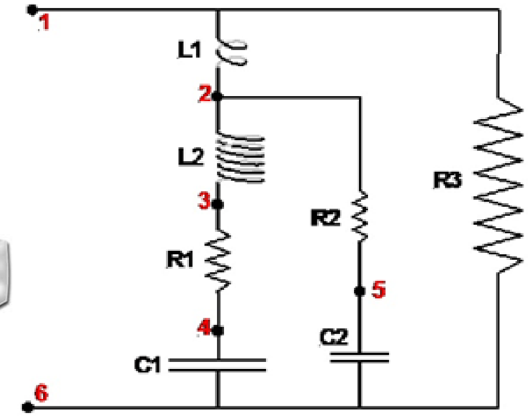
Advantages	Disadvantages

- Large Parasitics
  - High ESR (Effective Series Resistance)
  - High ESL – (Effective Series Inductance).
- Electrolytic capacitors eventually degrade over the life of the product.
  - The electrolyte eventually dries out.
  - Long term storage may cause Aluminum oxide barrier layer to de-form.
    - Capacitance drops
    - ESR increases.
      - Higher ESR causes more internal heat causing it to dry out even faster.
      - This effect is worse at high temperatures.
  - (Lesson: Don't use "old stock" aluminum capacitors in your product.)
- Needs a ceramic in parallel for switch mode applications.
  - High ESR and ESL can cause SMPS malfunction.
- Have measurable dc leakage current.
  - Probably not an issue in power circuits;
    - Leakage current can be a problem in timing circuits.

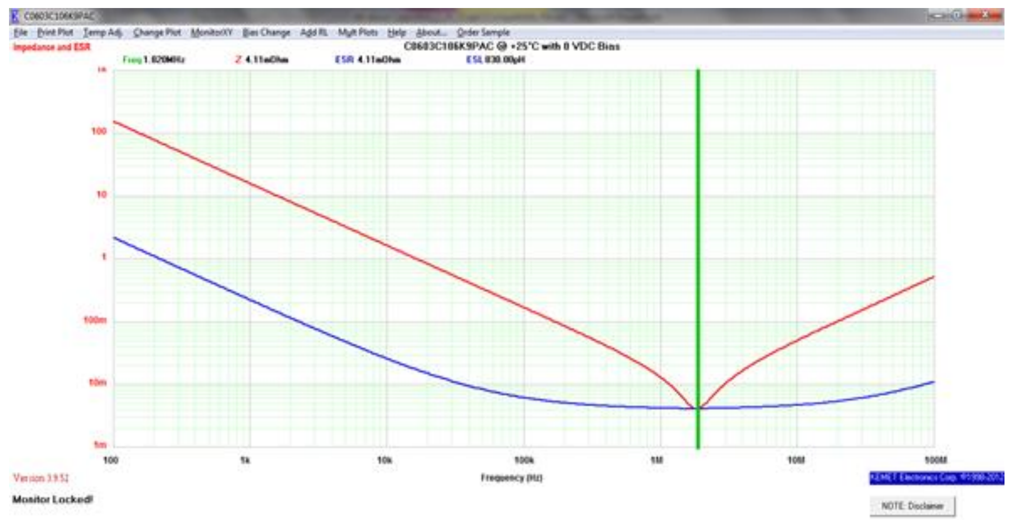
Ceramics: Overview

- Lowest Cost devices
  - Primarily for decoupling and bypass applications
  - Multiple vendors, sizes
  - Surface mountable
- How is it made?
  - Alternating layers of electrodes and ceramic dielectric materials





- Significant effects for Class 2 Dielectrics i.e. X5R, X7R
  - Voltage bias effect
  - Temperature effects
  - Ageing
    - 2%/decade hour for X7R
    - 5%/decade hour for X5R
    - Starts decay after soldering
  - High Q
    - Frequency selective



Ceramic Dielectric: 3 Character Codes

Class 1 (Best Performance)

- Temperature Coefficient Decoder

ppm/°C	
C	0.0
B	0.3
L	0.8
A	0.9
M	1.0
P	1.5
R	2.2
S	3.3
T	4.7
V	5.6
U	7.5

Multiplier	
0	-1
1	-10
2	-100
3	-1000
4	+1
6	+10
7	+100
8	+1000

Tolerance in ppm/°C (25-85 °C)	
G	±30
H	±60
J	±120
K	±250
L	±500
M	±1000
N	±2500

- Typical Values:
  - NP0,C0G, values up to 100,000pF

Class 2 (Higher Capacitance)

- Temperature and Capacitance Tolerance Decoder

Minimum temperature	
X	-55 °C
Y	-30 °C
Z	+10 °C

Maximum temperature	
4	+65 °C
5	+85 °C
6	+105 °C
7	+125 °C
8	+150 °C
9	+200 °C

Capacitance change permitted	
A	±1.0%
B	±1.5%
C	±2.2%
D	±3.3%
E	±4.7%
F	±7.5%
L	+15% / -40%
P	±10%
R	±15%
S	±22%
T	+22% / -33%
U	+22% / -56%
V	+22% / -82% [1]

- Typical Values:
  - X5R,X7R, values up to 150uF

Ceramic Capacitors

Advantages	Disadvantages

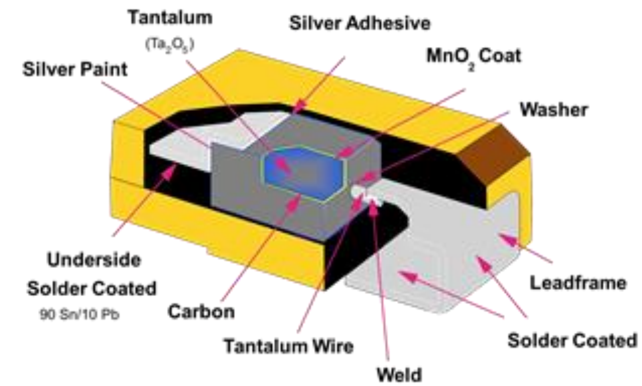
- Low Cost
  - Mature technology with low cost materials
- Many Manufacturers to choose from.
- Reliable and rugged
  - Extremely tolerant of over voltage surges
- Best Choice for local bypassing
- Not Polarized
- Lowest effective series resistance (Low ESR)
  - several milliohms
  - Leads to high RMS current rating
- Low effective series inductance (Low ESL)
  - < 3nH

Ceramic Capacitors

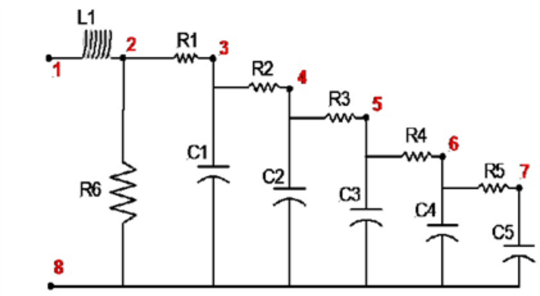
Advantages	Disadvantages

- Capacitance limited to around 150 uF / 6.3V
- Large body sizes prone to cracking with PCB flexing. Several small units in parallel may be a better choice.
- Have both a voltage and temperature coefficient that reduces capacitance value.
- Some large package size units exhibit piezo-electric audible “singing”.
  - Difficult to control. (Ceramic speaker effect.)
  - More noticeable with Class 2 dielectrics
- Incomplete data sheets!!
  - ESR, ESL, SRF and Ripple Current rating often missing from data sheets
  - Contact the manufacturer for ripple current
- Capacitance value not printed on SMT device package.
  - Impossible to visually inspect for value once mounted on the PCB.
- Some power supply circuits are not stable with ceramic output capacitors.
  - Usually LDO’s and parts using COT control

Tantalum: Overview (MnO2 based)



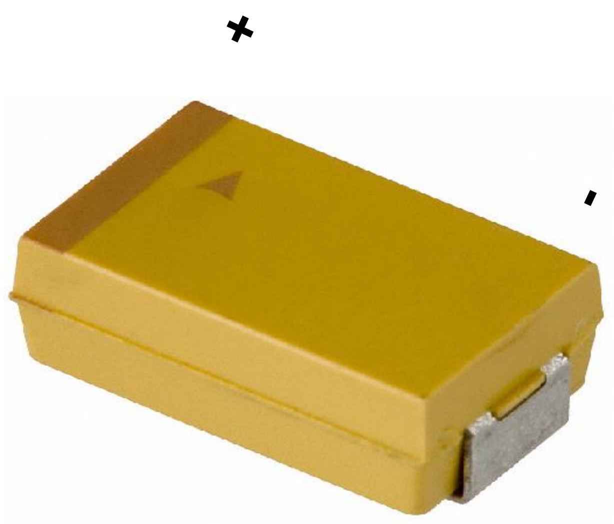
- High Capacitance per unit Volume Technology
  - Small package sizes available
    - Thin devices are available
- How is it made?
  - Tantalum Anode pressed around a tantalum wire
  - Oxide grown on surface
  - Cathode formed by dipping and heat conversion Mn→MnO_2
  - Epoxy encapsulated
- Old technology
  - Requires 50% Voltage derating
    - PPM failure rates increase exponentially above 50% voltage derating
  - Can fail **explosively**
  - High ESR compared to Polymer types
  - Fairly low cap roll off vs. frequency

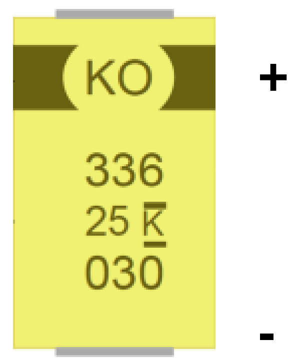


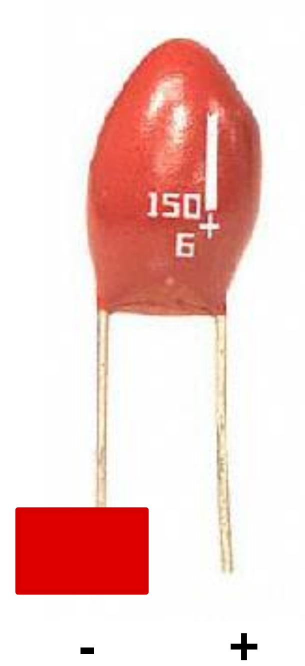
Tantalum Model

Solid Tantalum Capacitors: Packaging

- Usually rectangular Surface Mount Technology – SMT machine mountable
- Capacitance ratings for 1uF to 1000uF







Solid Tantalum Capacitors

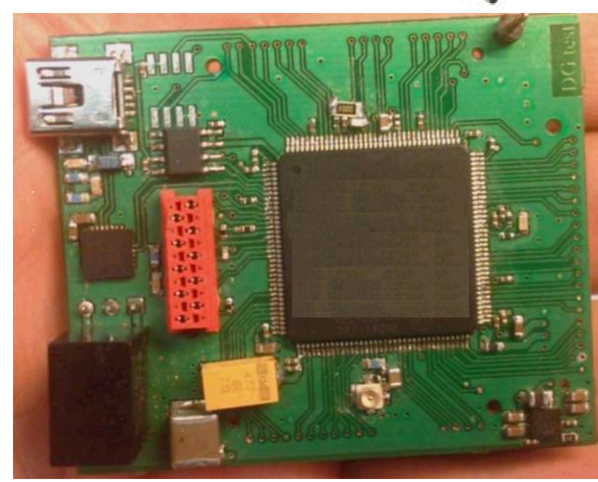
Advantages | **Disadvantages**

- Lots of capacitance in a small package.
  - 1uF to 1000uF max
- Medium-high effective series resistance (Low ESR)
  - 10 to 500 milliohms
  - Medium level of RMS current
- Low effective series inductance (Low ESL)
  - < 3nH
- Numerous manufacturers
- Good datasheet vs. electrolytic

Solid Tantalum Capacitors

Advantages	Disadvantages

- Limited voltage range 50V rating max
  - Therefore for circuit voltages less than 25 or 35VDC
- Fairly high in cost
  - Historically Tantalum has had supply shortages
- Limited inrush surge current capability
  - Do not use tantalum for hot pluggable input capacitors!

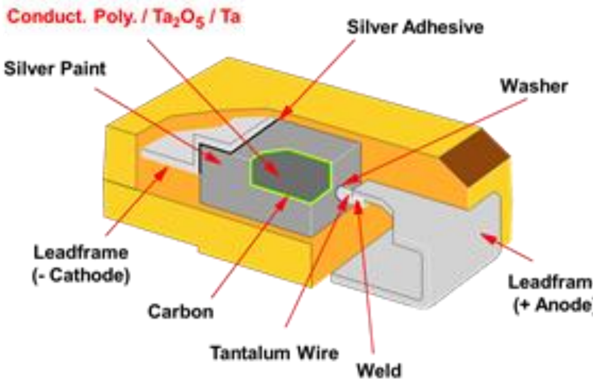


Don’t Hot plug tantalum!

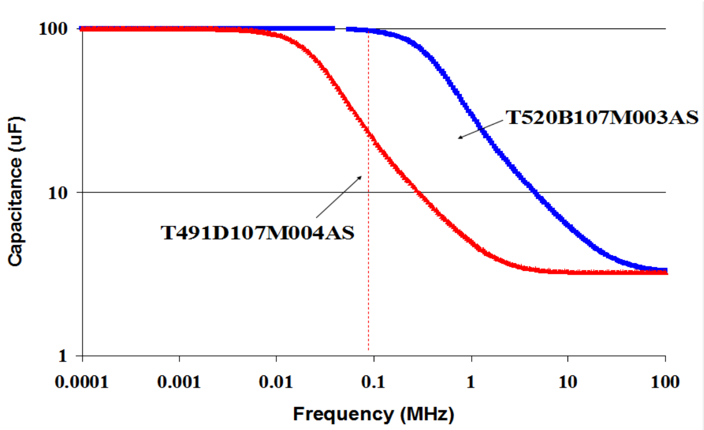
Solid Tantalum Capacitors Application Safety

- ALWAYS
  - Observe voltage polarity
- DO NOT
  - Exceed voltage rating
  - Exceed inrush surge rating
- Potential Outcomes
  - Can fail catastrophically if misapplied
  - Can fail open or short

Polymer - Overview



- Highest Capacitance per unit Volume Technology
  - Small package sizes available
- How is it made?
  - Tantalum Anode pressed around a tantalum wire
  - Oxide grown on surface
  - Cathode formed by dipping into Monomer and cured at room temperature
  - Epoxy encapsulated
- Lower ESR vs MnO2 based Tantalums
  - Higher frequency operation – over a Mhz…still looks like a cap!
  - Lower power dissipation
    - Higher ripple current capabi
    - May need less capacitance



Polymer & Organic Capacitors: Packaging

- SMT Block style similar to tantalum.
- Round / Radial versions in SMT and through-hole.
- Types
  – Tantalum polymer / Aluminum polymer / Organic semiconductor

-

+

Kemet Tantalum Polymer

PosCap

+

-

+

OSCON

-

Polymer & Organic Capacitors

Advantages | **Disadvantages**

- Low ESR
  - but not as low as equivalent ceramic.
- Low ESL
  - depending on construction method
- New technology
  - Designed for SMPS.
- Can be very low profile.
- High capacitance per unit volume.
  - Much better performance than aluminum electrolytic and much smaller in size.
- No voltage coefficient.
- Viable alternative to solid tantalum.

Polymer & Organic Capacitors

Advantages	Disadvantages

- High cost
- Voltage surges capability depends on chemistry.
  – Oscon very intolerant of voltage surges
- Tend to be from a single supplier.
  – May have availability issues.

Polymer & Organic Capacitors Failure Mode

- Tantalum Polymer
  - Less prone to catastrophic failure than solid tantalum but will still vent and emit smoke.
- Organic (OSCON)
  - Emits noxious smoke.

QUICK COMPARISON CHARTS

Capacitor Chemistry: Quick Comparison

	Al-Elect	Ta	Ceram	Al-Poly	Film
ESR	5	4	1	3	2
ESL	5	3	1	3	3
DCL	5	3	1	4	2
Self-Healing	Yes (Reform)	Yes	No	Yes	Yes
Wear-Out	Yes	No	Aging	No	No
Shelf Decay	Yes	No	No	No	No
Volumetric Eff.	4	1	3	2	5
Over-Volt Capability	3	5	1	2	4
Cost	2	3	1	3	5
Pb-Free	No	Yes	Yes	Yes	Yes
Failure Mode	Open/Short	Short	Short	Short	Open/Short
Piezoelectric	No	No	Yes	No	No

Numerical Rankings from 1 (Best) to 5 (Worst)

Capacitor Chemistry: General Parameters

Characteristic	PET (MKT)	PEN (MKN)	PPS (MKI)	PP MKP/KP	COG (NPO)	X7R	X8R	Tantalum MnO2	Tantalum Polymer	Aluminum Polymer	Aluminum Electrolytic
Operating Temperature Range (°C)	-55° to 125°	-55° to 125°	-55° to 140°	-55° to 105°	-55° to 125°	-55° to 125°	-55° to 150°	-55° to 125°	-55° to 105° -55° to 125°	-55° to 105° -55° to 125°	-55° to 105°
Temperature characteristic (C/C)	±5%	±5%	±1.5%	±1.5%	0±30ppm	±15%	±10%	±10%	±10%	±10%	25 to -30%
DC Voltage Coefficient (%) at Vr	Negligible	Negligible	Negligible	Negligible	Negligible	-20%	±15%	Negligible	Negligible	Negligible	10 to -15%
Aging Rate (%hr/Decade)	Negligible	Negligible	Negligible	Negligible	Negligible	2%	1%	N.A.	N.A.	N.A.	N.A.
Dissipation Factor (%) 1 KHz		0.8	0.2	0.05	0.1	2.5	3.5	8	8	8	5
10 KHz	1.5	1.5	0.25	0.5	0.1						20
100 KHz	3.0	3.0	0.5	1							
ESR	low	low	very low	very low	low	Moderate to high	Moderate to high	high	Low to Moderate	Low to Moderate	high
Insulation Resistance (MΩxµF) 25°C	10,000	10,000	10,000	10,000	10,000	1,000	1,000	100	10	17	500
85°C	1,000	1,000	1,000	1,000	1,000	500	200	10	1	1.7	5
Dielectric absorption (DA) (%)	0.5	1	0.2	0.05	0.6	2.5	1	0.5	0.5	0.5	N.A.
Capacitance Range	1000pF to 10µF	1000pF to 6.8µF	100pF to 1µF	100pF to 10µF	0.5pF to 1µF	100pF to 4.7µF	100pF to 1µF	0.1µF to 1500µF	10µF to 1500µF	6.8µF to 470µF	0.1µF to 100µF
Capacitance Tolerances (±%)	5; 10	5; 10	2.5; 5	5; 10; 20	5; 10	10; 20	5; 10; 20	5;10; 20	20	20	-20 +50
Failure Mode Self Healing	Open Yes	Open Yes	Open Limited	Open Yes	Short No	Short No	Short No	Short Limited	Short Limited	Short Limited	Short Limited
Reliability	High	High	High	High	High	Moderate	Moderate	High	High	High	Low
Piezoelectric effect	No	No	No	No	No	Yes	Yes	No	No	No	
Resistance to thermal and mechanical shock	High	High	High	High	Low	Moderate to Low	Low	High	High	High	
Non-Linear distortion (3rd harmonic)	Very Low	Very Low	Very Low	Very Low	Low	High	High	N.A.	N.A.	N.A.	High
Polar	No	No	No	No	No	No	No	Yes	Yes	Yes	Yes
260°C Pb-Free Capable	Not Yet	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	No

MOSFETs

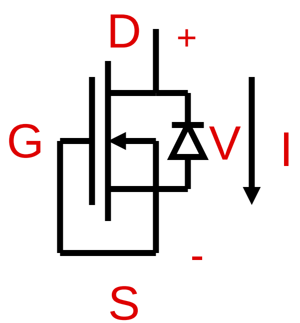
MOSFET Parameters

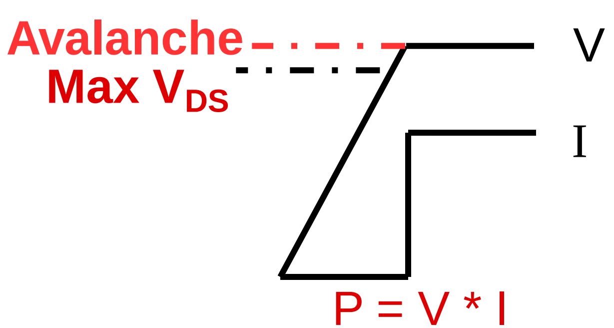
- Configuration
- Maximum Drain to Source Voltage (V_{DS})
- Maximum Gate to Source Voltage (V_{GS})
- Gate Threshold ($V_{GS(TH)}$)
- Drain to Source on State Resistance (R_{DSON})
- Gate Charge (Q_G, Q_{RGSR}, Q_{GD})
- Series Gate Resistance (R_G)
- Output Charge (Q_{OSS})
- Source to Drain Diode Forward Voltage (V_{SD})
- Source to Drain Diode Reverse Recovery Charge (Q_{RR})

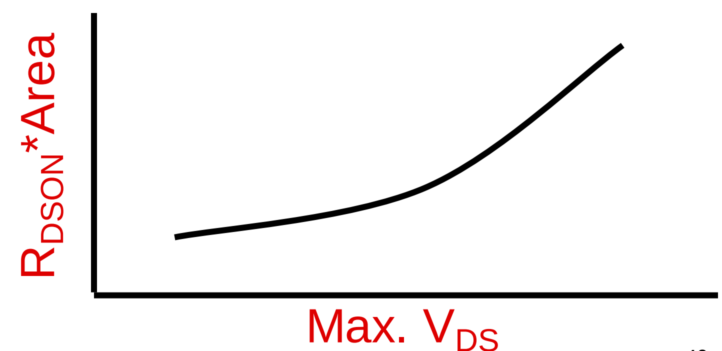
Maximum Drain to Source Breakdown Voltage $V_{DS(Max)}$, BV_{DSS}

- Maximum V_{DS} is the highest drain to source voltage a MOSFET can block .
- As the voltage on the drain (relative to the source) rises, it is blocked until the Maximum V_{DS} rating is exceeded, then Avalanche occurs.
- Maximum V_{DS} is the first consideration in designing in a MOSFET.
- MOSFETs with a lower Drain to Source Breakdown Voltage have a lower specific R_{DSON}, (R_{DSON} per Area) and are more efficient, and Lowest possible Drain to Source Breakdown voltage is always the first step in MOSFET selection.
- Exceeding the $V_{DS(Max)}$ may cause Avalanche Breakdown from Drain to Source.
  - When $V_{DS(Max)}$ is exceeded Avalanche limitations may not be exceeded.

Abs Max	V_{DS}	Drain to Source Voltage		20			V
Char	BV_{DSS}	Drain to Source Voltage	$V_{GS} = 0V$, $I_D = 250\mu A$	20	—	—	V





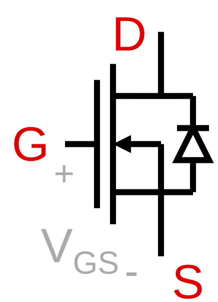


Maximum Gate to Source Voltage $V_{GS(Max)}$

- Maximum V_{GS} is the highest Gate to Source voltage that can be Reliably applied to a MOSFET.
  - It may or may not be symmetrical for positive and negative voltages.
- Maximum V_{GS} can be traded off with V_{GSTH}, and the V_{GS} where R_{DSON} can be specified.
  - Higher $V_{GS(MAX)}$ gives Higher V_{GSTH} and higher V_{GS} where R_{DSON} can be specified.

Abs Max

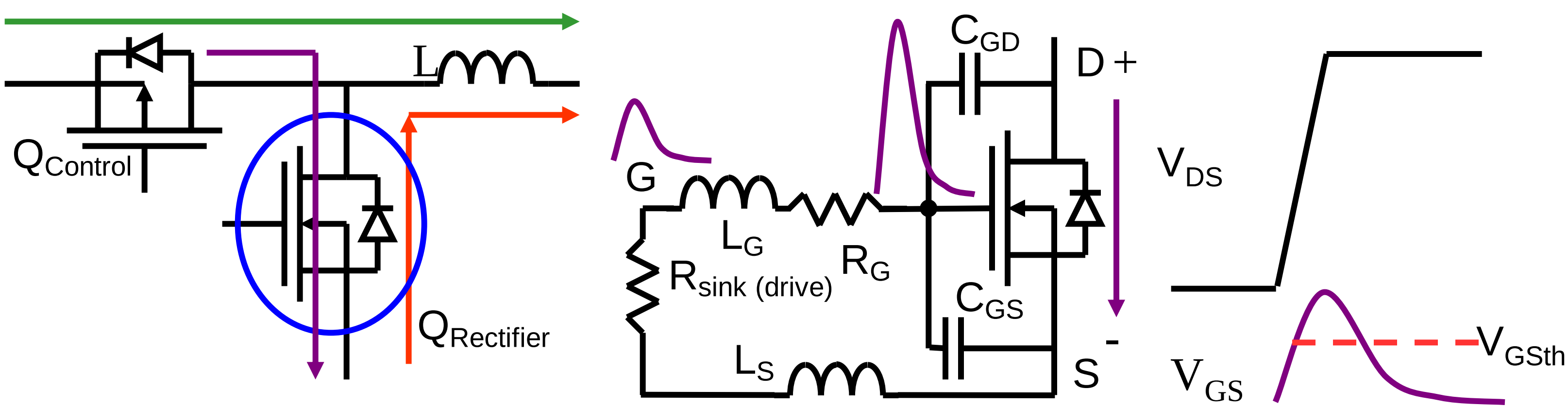
V_{GS}	Gate to Source Voltage	±12	V



Gate to Source Threshold Voltage $V_{GS(TH)}$

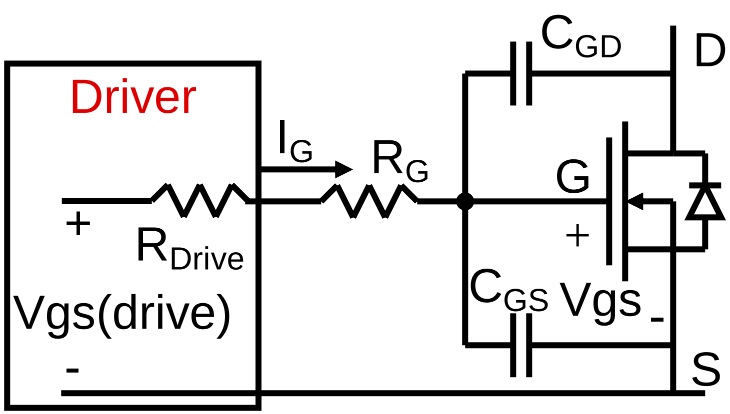
- V_{GS} Threshold ($V_{GS(TH)}$) is where the MOSFET is no longer fully off.
  - $V_{GS(TH)}$ is specified at $I_D = 250\mu A$.
- It is important that V_{GS} does not exceed $V_{GS(TH)}$ during a dV/dt event to assure that cross conduction does not occur in a Rectifier Switch.
  - The dV/dt is coupled into the gate via the Capacitive Divider of C_{GD} and C_{GS}.
  - The V_{GS} spike measured outside of the package is much smaller than the V_{GS} spike in the MOSFET due to internal Gate Inductance and Gate Resistance.

$V_{GS(th)}$	Gate to Source Threshold Voltage	$V_{DS} = V_{GS}$, $I_D = 250\mu A$	—	2.3	—	V

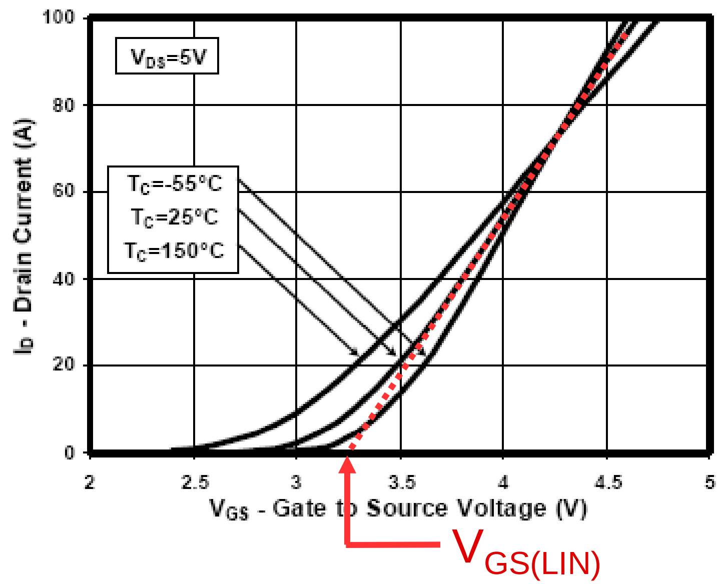


Gate to Source Linear Threshold Voltage $V_{GS(TH)}$, $V_{GS(LIN)}$

- Linear Threshold ($V_{GS(LIN)}$) is where the Linear Region of the Transfer Characteristics Curve is extended to I_D = 0V.
  - $V_{GS(LIN)}$ is used to approximate Gate Charging Current during the switching event.



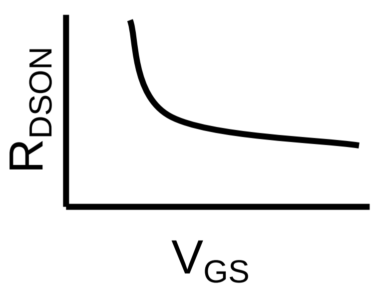
$$I_G = \frac{V_{GS(Drive)} - V_{GS}}{R_G + R_{Drive}}$$

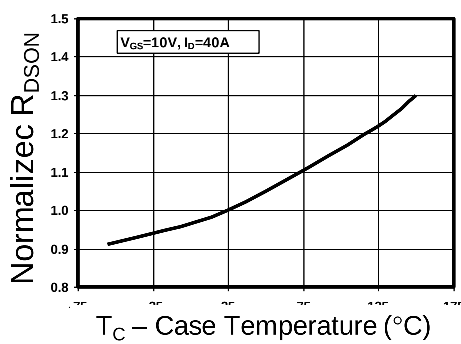


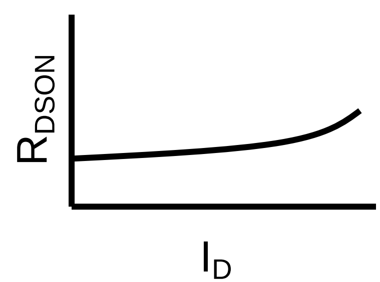
Drain to Source On-State Resistance R_{DSON}

- R_{DSON} is the Resistance through the MOSFET when it is on.
  - When on, the MOSFET is symmetrical – R_{DSON} is the same in both directions
- R_{DSON} is important because it determines the:
  - Voltage drop across the MOSFET at a particular Current: $V = I * R_{DSON}$.
  - Power dissipated (heat generated) by the MOSFET in the on state: $P = I^2 * R_{DSON}$.
- R_{DSON} is dependent on Gate to Source Voltage (V_{GS}), Junction Temperature (T_J), and Drain Current (I_D).
  - R_{DSON} is specified as typical and maximum at several Gate to source voltages.
  - R_{DSON} is specified at T_J = 25°C. It increases roughly 1.4 to 1.7 times from 25°C to 150°C.

$R_{DS(on)}$	Drain to Source On Resistance	V_{GS} = 4.5V, I_D = 35A	–	1.4	TBD	mΩ
		V_{GS} = 10V, I_D = 40A	–	1.2	TBD	mΩ







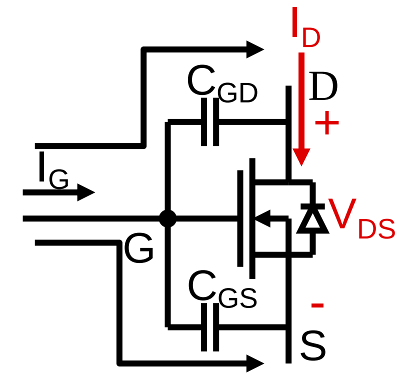
Gate Charge
Q_G, Q_{GS}, Q_{GD}

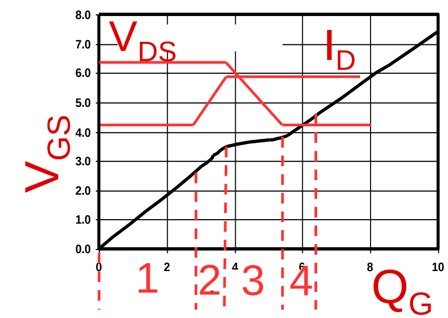
- Gate Charge is the amount of charge required to be put into or taken out of the Gate to Drain and Gate to Source Capacitances to Switch the MOSFET.
- Gate Charge can be split into:
  1. Gate to Source Charge (Q_{GS}), Pre Conduction – From 0V to the gate voltage where current begins to rise on the Transfer Characteristics curve – Nothing really happens.
  2. Q_{GS}, Switching (~1/4 Q_{GS}) – Current rises along transfer characteristics curve to the Drain current while V_{DS} remains high.
  3. Gate to Drain (Miller) Charge (Q_{GD}), - While Current is high, V_{DS} collapses.
  4. Overdrive Charge – V_{GS} rises to its final value, driving down R_{DSON}.
- Energy required to switch the gate in one cycle (on and off:

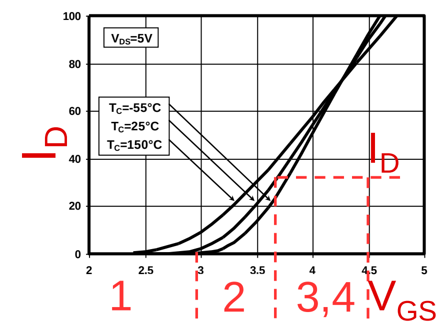
$$E_G = Q_G V_{GS}$$

- Energy dissipated in the switching action in one cycle:

$$E_{SW} = V_{DS} I_D \left(\frac{1}{4} Q_{GS} + Q_{GD} \right) \div I_G$$



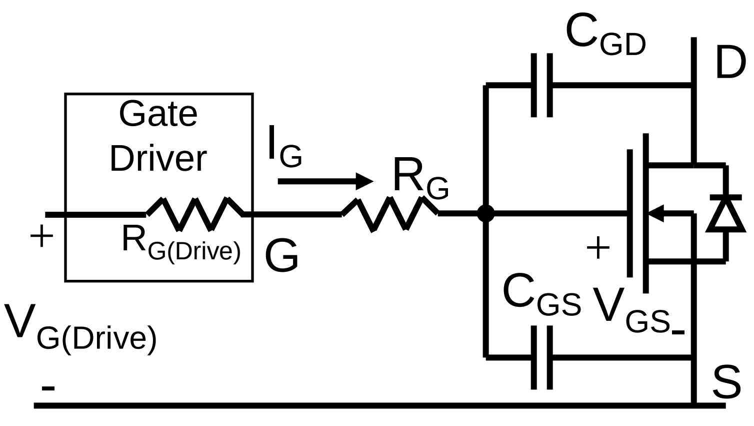


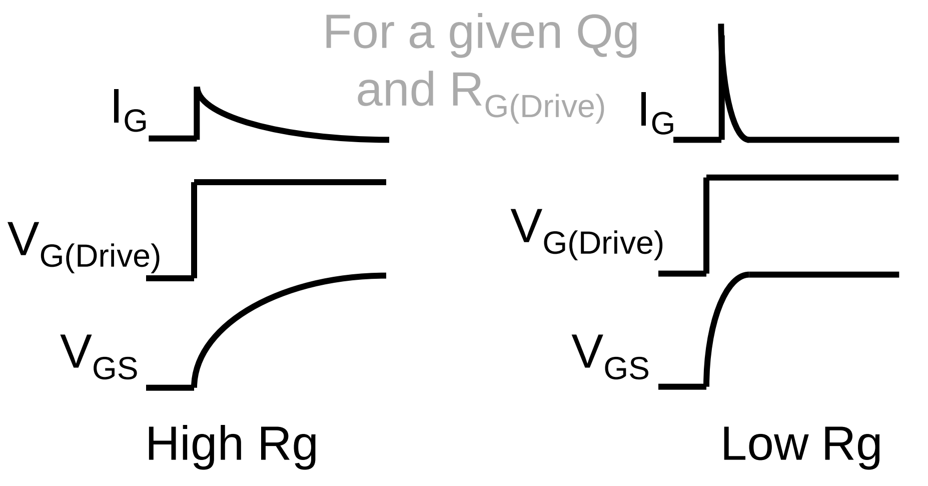


Series Gate Resistance R_G

- Series Gate Resistance is the internal resistance which impedes the flow of Charge into the gate capacitance, slowing the switching transition.
- It is important in High Frequency DC-DC converters.
- It is in Series with the Gate Driver's Resistance.

R_G	Series Gate Resistance	—	—	1.2	TBD	Ω

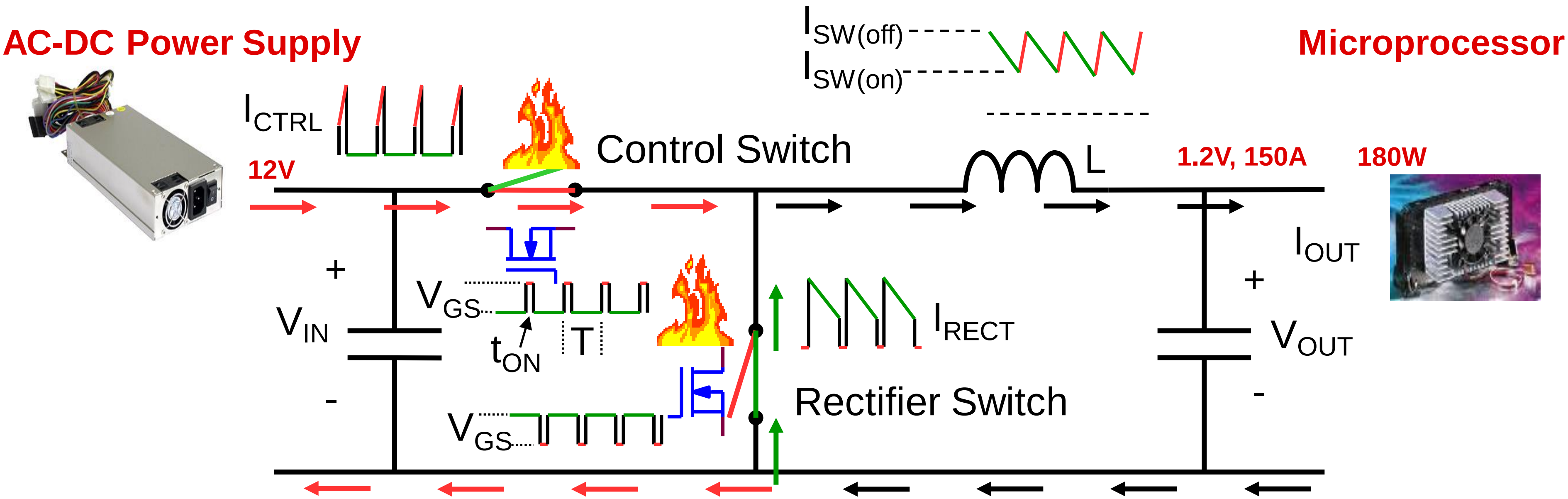




MOSFET Applications

- Non Isolated DC-DC Converter
  - Buck Regulator (AKA Point of Load (POL) Converter and Voltage Regulator Module (VRM), Step Down Converter).
  - Boost Regulator (AKA Step Up Converter)
- Isolated AC-DC Converter or DC-DC Converter (AKA Intermediate Bus Converter (IBC), DC Transformer)
  - Flyback Converter
  - Forward Converter
  - Two Transistor Forward Converter
  - Active Clamp Forward Converter
  - Half Bridge Converter
  - Push-Pull Converter
  - Full Bridge Converter
- Load Switch
- Linear Regulator
- Inrush Protection
- Or-ing

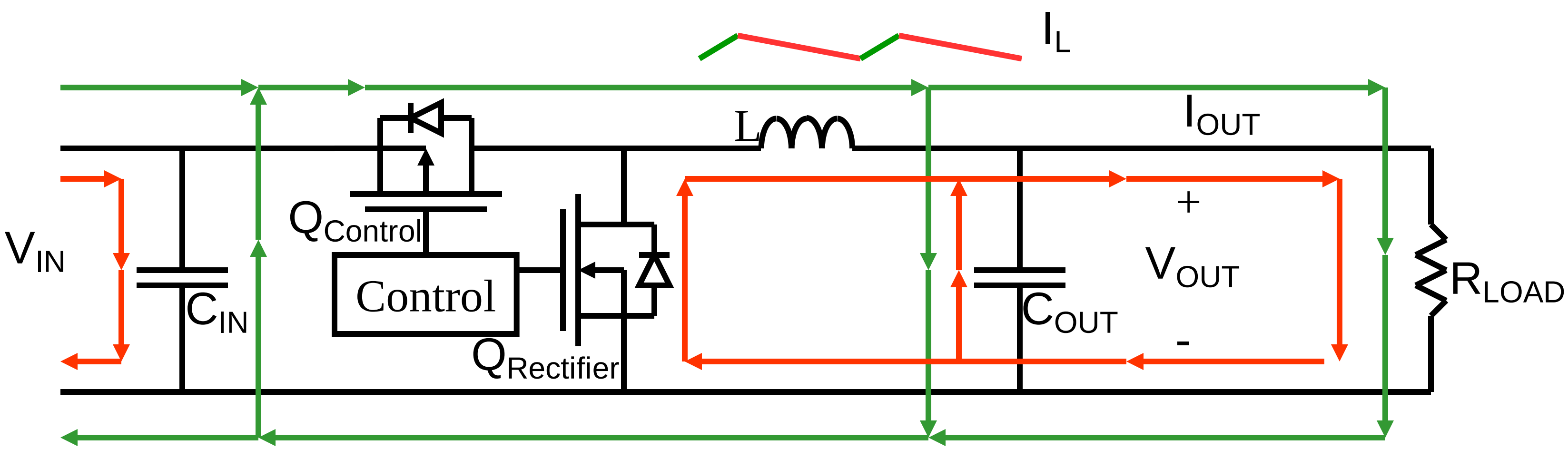
Buck Converter



- A Buck Converter is used to step voltage down.
- V_{IN} is Input Voltage, V_{OUT} is Input Voltage, I_{OUT} is Output Current.
- Frequency (f) = 1/T, Duty Cycle (DC) = t_{ON}/T.
- Inductance (L) determines the slope of the Current.
- $I_{(RMS)}$ is the RMS value of the Current Waveform.
- V_{GS} is the Gate to Source Voltage applied to the Switches by the Gate Drivers.

Buck Converter - Detailed Operation

- When the Control Switch ($Q_{Control}$, N Channel or P Channel) is turned on, Current flows (Green), from the power source and C_{IN} through the Inductor, and into the load and C_{OUT}.
  - Energy is transferred from the source and C_{IN} to L, C_{OUT} , and the load.
- When the Control Switch is turned off, the inductor continues to push current (red) into the load. Current will also flow out of C_{OUT} to the load. This is regardless of whether the Rectifier Switch ($Q_{Rectifier}$, N Channel) is turned on or not.
  - Energy is transferred from L and C_{OUT} to the load.
- Duty Cycle (DC) = Vout/Vin

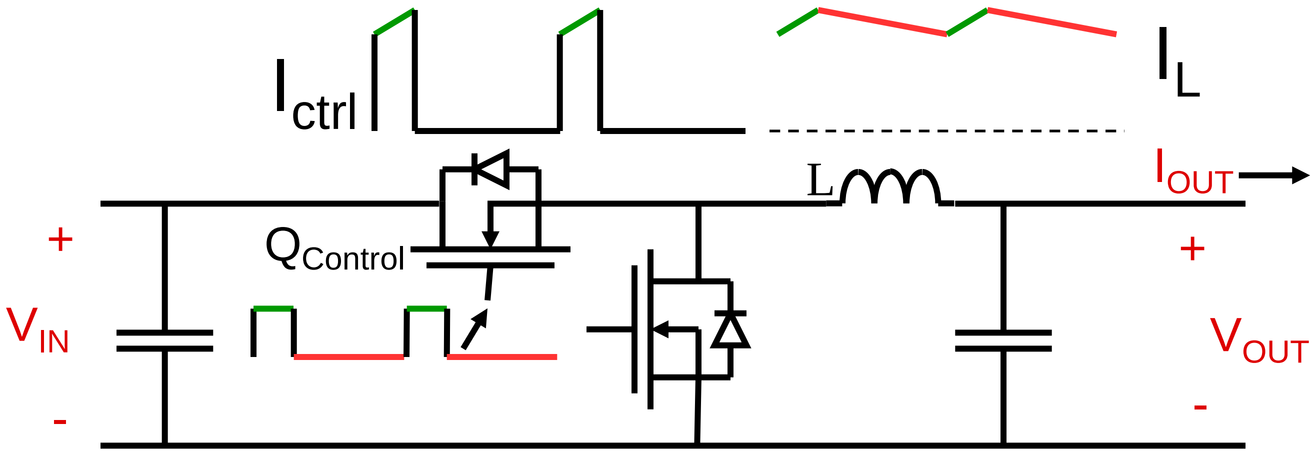


Buck Converter

Buck Control Switch On State Power Dissipation (P_{ON})

$$P_{ON} = I_{RMS(ctrl)}^{\ 2} \times R_{DSON}$$

- R_{DSON} is interpolated between available V_{GS} points and normalized for 100°C.
- $I_{RMS(ctrl)} = f(V_{IN}, V_{OUT}, I_{OUT}, L)$



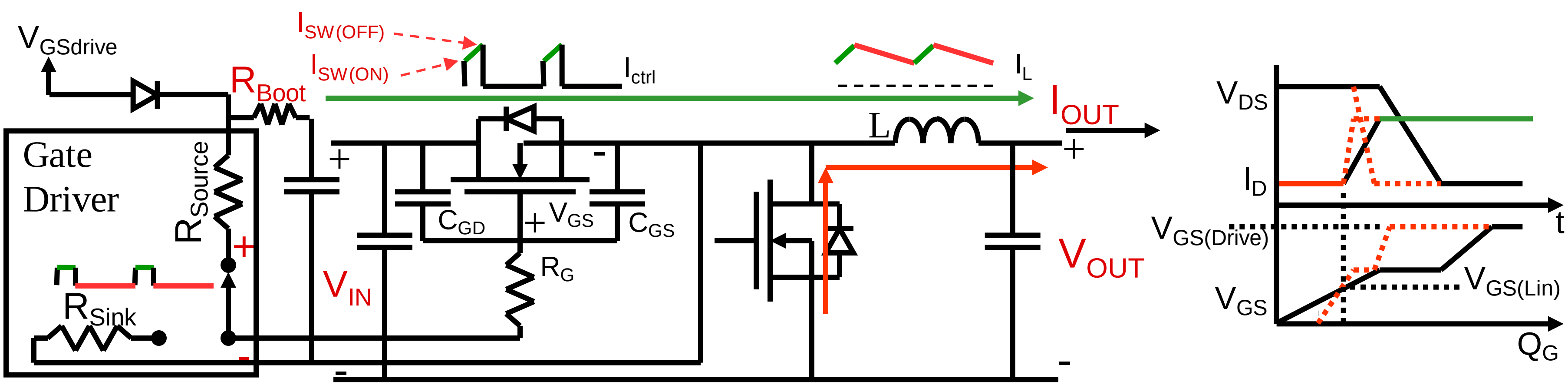
Buck Control Switch Switching Power Dissipation ($P_{SW(ON)}$, $P_{SW(OFF)}$)

$$E_{SW(ON)} = \frac{V_{IN} I_{SW(ON)} \left(\frac{1}{4} Q_{GS} + Q_{GD}\right)\left(R_G + R_{CTRL(SRC)}\right)}{2\left(V_{GS(Drive)} - V_{GS(Lin)}\right)}$$

$$E_{SW(OFF)} = \frac{V_{IN} I_{SW(OFF)} \left(\frac{1}{4} Q_{GS} + Q_{GD}\right)\left(R_G + R_{CTRL(SNK)}\right)}{2\left(V_{GS(Lin)}\right)}$$

$$P_{SW(ON/OFF)} = E_{SW(ON/OFF)} f$$

- Qgd is adjusted for V_{DS}.
- Approximately ¼ of the Q_{GS} is involved in switching Current.
  - $I_{SW(ON)}$, $I_{SW(ON)}$ = f(V_{IN}, V_{OUT}, I_{OUT}, L)
  - $V_{GS(Lin)}$ - the Linear Threshold - V_{GS} where significant current capability begins.
  - Rg - the Internal Series Gate Resistance of the MOSFET.
  - $R_{CTRL(SRC/SNK)}$ - the Source/Sink Impedance of the Gate Driver.
  - f is Switching Frequency.
  - A Bootstrap Resistor can be used to slow turn on without affecting turn off.

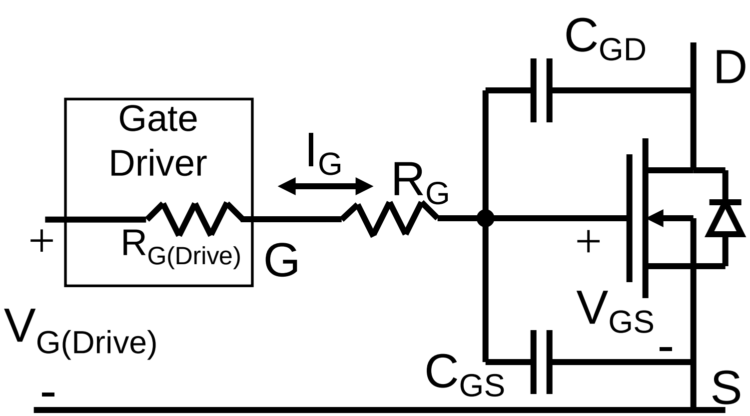


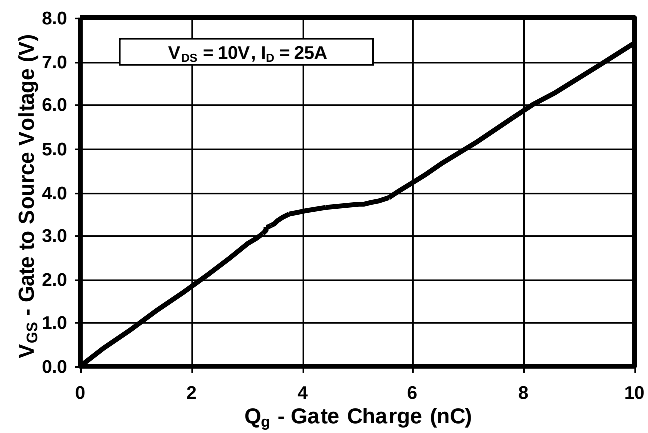
Gate Power Dissipation (P_G)

$$E_{G(ON)} = E_{G(OFF)} = \frac{1}{2} Q_G V_{GS}$$

$$P_G = \left(E_{G(ON)} + E_{G(OFF)}\right) f = Q_G V_{GS}\, f$$

- With each switching cycle, the MOSFET Input Capacitance (C_{GS}+ C_{GD}) is Charged and Discharged with a Total Gate Charge of Qg.
- The amount of Total Charge (Q_G) is interpolated between the known Gate Charges.
- P_G is dissipated in R_G and $R_{G(Drive)}$.
- It is not dependant on load current, so it is more critical for efficiency at light loads.
  - V_{GS} is Gate to Source (Drive) Voltage.
  - f is Switching Frequency.





Efficiency
η

- System Efficiency
  - Compares System Power Out to System Power Lost
  - $P_{IN} = P_{OUT} + P_{Diss(sys)}$ $\eta = P_{OUT} / P_{IN} = P_{OUT} / P_{OUT} + P_{Diss(sys)}$
- Component Efficiency
  - Compares System Power Out to Component Total Power Dissipation.
  - $P_{IN} = P_{OUT} + P_{Tot(comp)}$ $\eta = P_{OUT} / P_{OUT} + P_{Diss(comp)}$