Electeng 311

Electronics Systems Design

MOSFETs

Seho Kim

Contents

- What is a switch?
- Why MOSFETs?
- MOSFETs overview
- Different MOSFET types
- Characteristic curves
- Breakdown voltage
- Conduction loss
- Switching loss
- Safe operating area
- MOSFET drivers

Learning outcomes

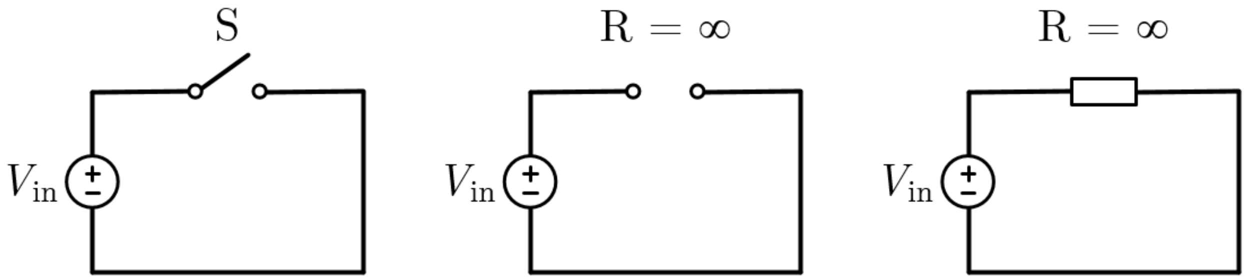
- Understand the operation of an ideal switch.
- Recognise different MOSFET types.
- Understand and be able to explain how MOSFETs turns on and off.
- Understand a MOSFET body diode.
- Able to explain different MOSFET operation regions.
- Calculate simple power loss in a MOSFET and understand absolute temperature ratings.
- Able to interpret a MOSFET datasheet for application requirements.
- Understand the need for a MOSFET driver.

Switches

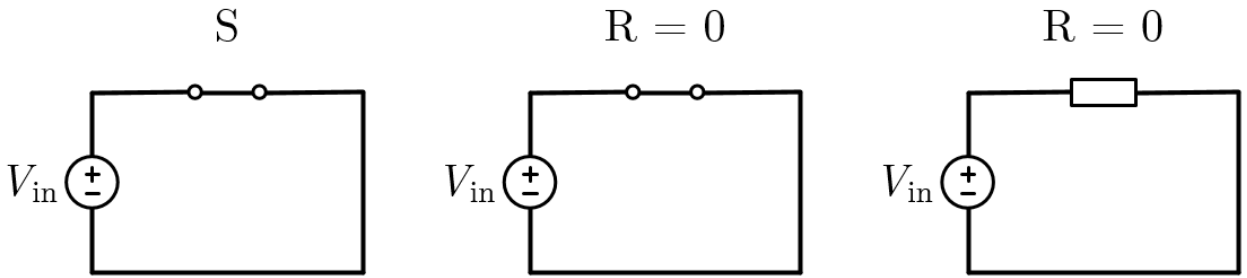
What is a switch?

Ideal switch

- Electrical engineering relies on the ability to control the flow of current.
- A switch can ‘turn on’ to let the current flow.
- A switch can ‘turn off’ to stop the current flow.



- An opened ideal switch acts as an infinite impedance.

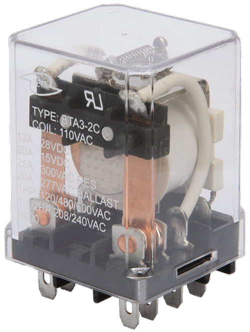


- A closed ideal switch acts as a zero impedance.

Different types of switches

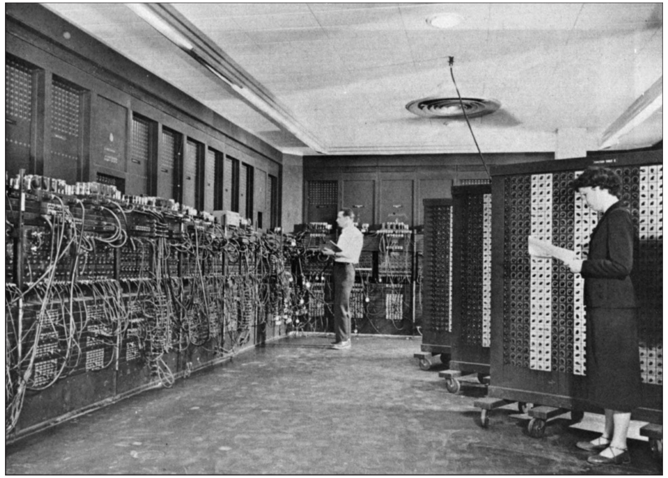
- Switches are used everywhere from light switches to microcontrollers.
- Oldest forms of switches were activated physically.
- Relays energise an electro-magnet to activate.
- Vacuum tubes were regularly used in early to mid 1900s.
- Large, expensive or short lifetime.

- Blade switch [1]



- Relay [2]

- Vacuum tube [3]

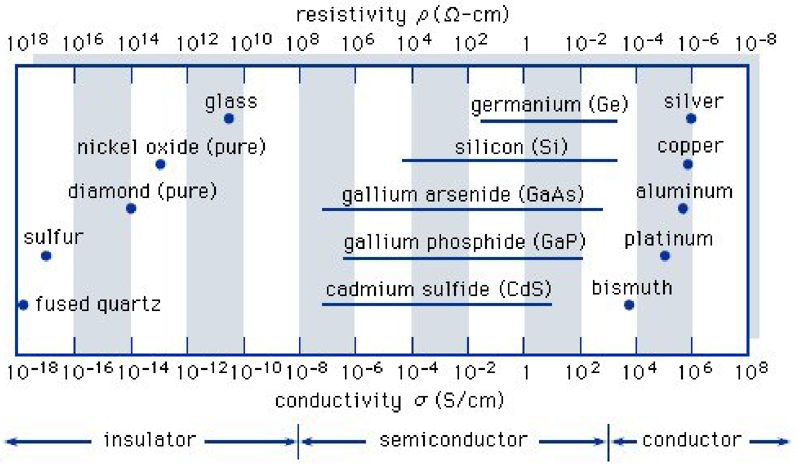


- ENIAC, the first fully electronic general-purpose programmable computer [4]

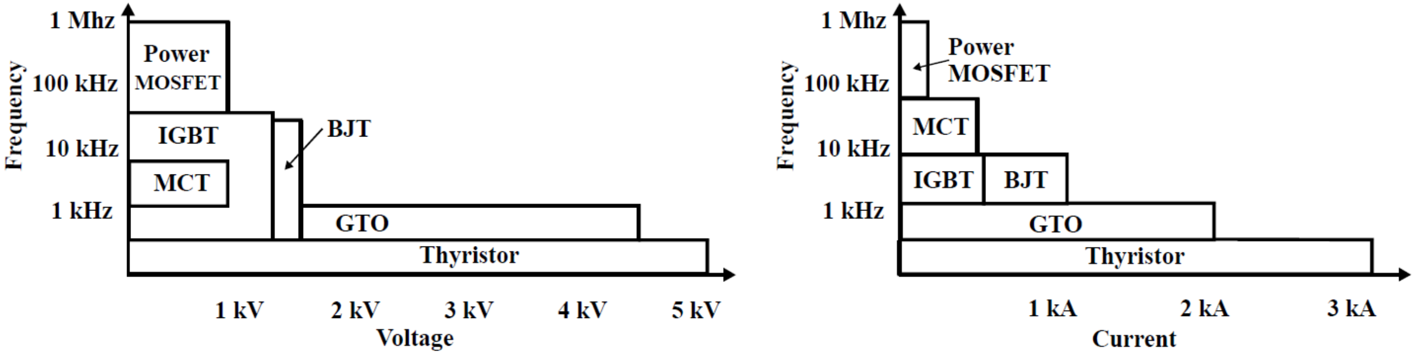
[1] https://electronics.stackexchange.com/questions/199389/knife-blade-on-off-switch-for-an-a-c-circuit
[2] https://www.beta.com.tw/products_detail/54.htm
[3] https://www.tubesandmore.com/products/vacuum-tube-7025-wa-tube-amp-doctor-high-grade-premium-selected
[4] M. Guarnieri, "The Age of Vacuum Tubes: Merging with Digital Computing [Historical]," in *IEEE Industrial Electronics Magazine*, vol. 6, no. 3, pp. 52-55, Sept. 2012, doi: 10.1109/MIE.2012.2207830.

Semiconductors

- The search for cheaper, smaller, efficient switches continued in mid-1900s.
- Semiconductors have conductivity somewhere between a conductor (e.g. copper) and an insulator (e.g. glass).
- Semiconductor switches are considered to be solid-state with no moving parts.
- Different semiconductor devices are suitable for different switching applications – breakdown voltage, switching time and efficiency.
- Bipolar junction transistors quite popular several decades ago.



- Conductivity of semiconductors [5]



- Power semiconductor operating regions [6]

- A piece of silicon [7]

- A transistor [8]

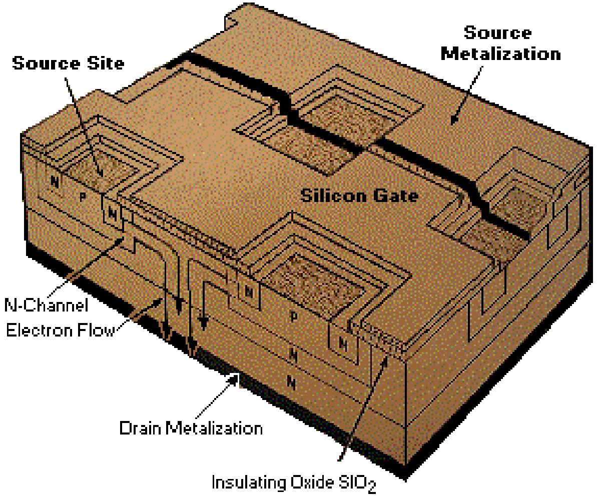
[5] https://www.britannica.com/science/semiconductor
[6] https://en.wikipedia.org/wiki/Silicon
[7] Rashid, M. H. (Ed.). (2001). Power electronics handbook.
[8] https://www.jaycar.co.nz/pn100-npn-multi-replacement-transistor/p/ZT2283

MOSFETs

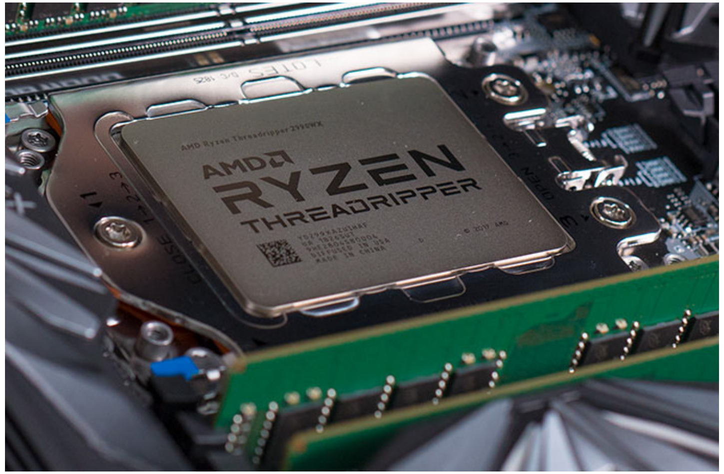
Overview

MOSFETs – Metal-Oxide-Semiconductor Field-Effect Transistor

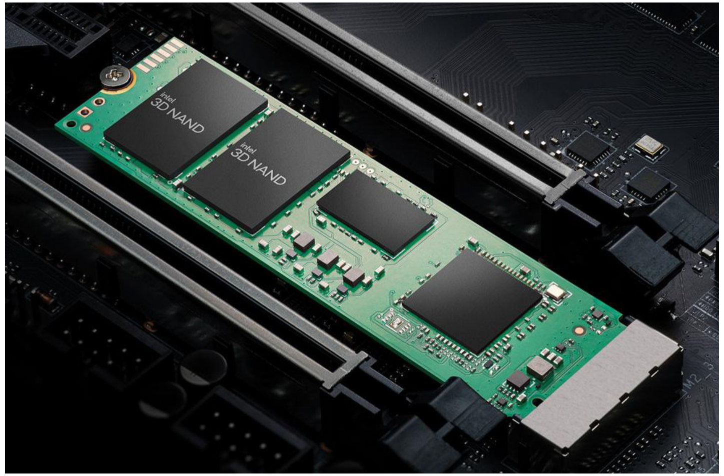
- Commonly used in electronics from CPUs to inverters.
- Micro metres (um) long. Most MOSFET devices are arrays of tiny MOSFET cells.
- Fast switching.
- Easily controllable.
- Relatively high voltage and current ratings.



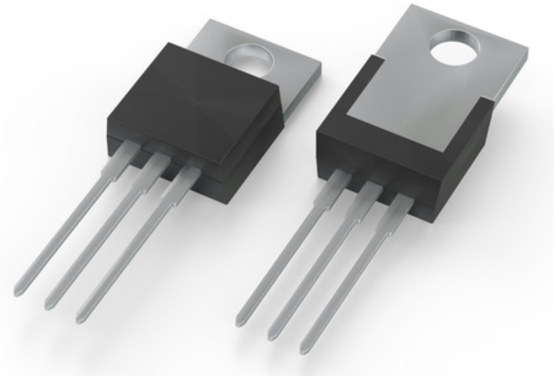
- Array of MOSFET cells [9]



- CPU [10]



- NAND flash drive [11]

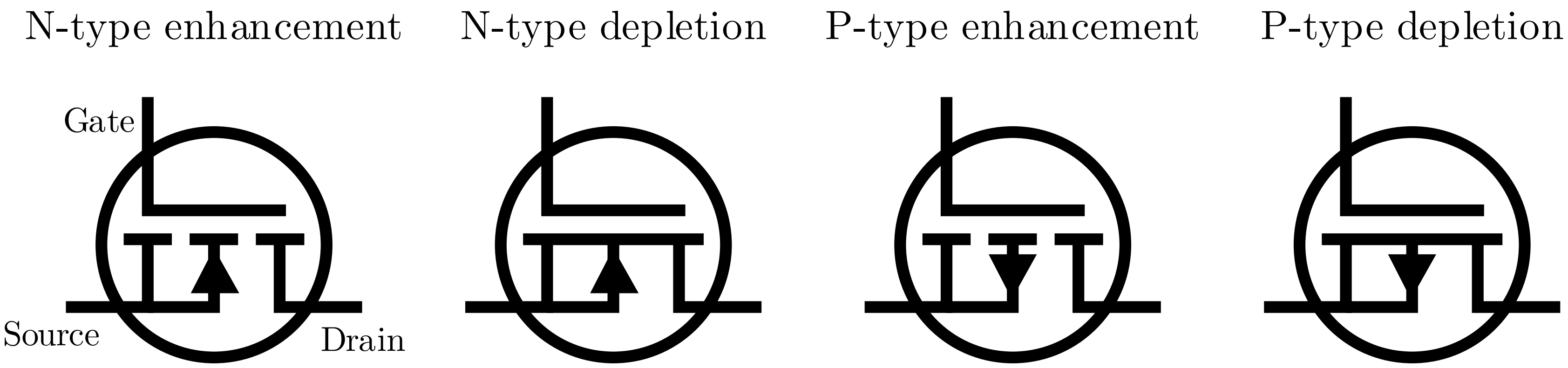


- Off the shelf MOSFETs [12]

[9] https://www.learningelectronics.net/VA3AVR/tutorial/xtor/xtor9/xtor9.html
[10] https://www.amd.com/en/products/ryzen-threadripper
[11] https://www.intel.com/content/www/us/en/newsroom/news/ssd-everyday-computing-mainstream-gaming.html#gs.2v8gcp
[12] https://www.jaycar.co.nz/pn100-npn-multi-replacement-transistor/p/ZT2283

MOSFETs – different types

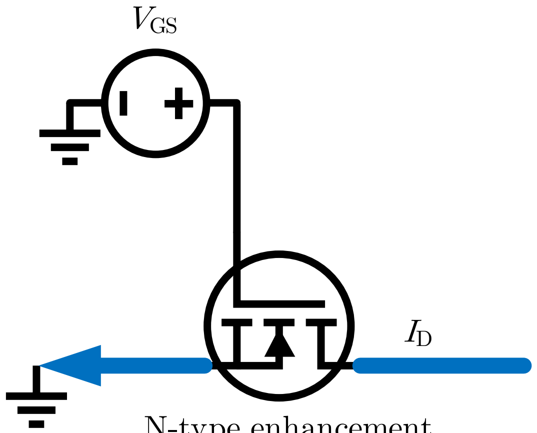
- Arrow pointing up for N-type. Down for P-type.
- N-type enhancement is often used for switching applications.



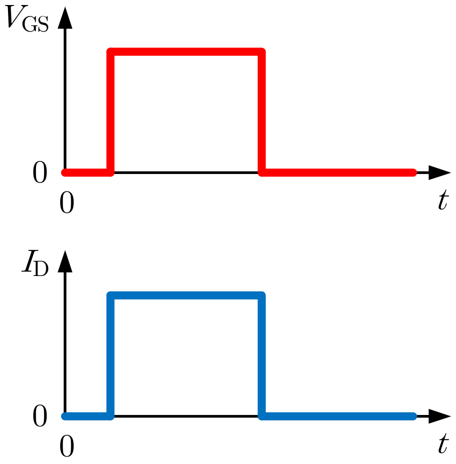
MOSFET type	**Positive V_{GS}**	**V_{GS} = 0V**	**Negative V_{GS}**
N-type enhancement	ON	OFF	OFF
N-type depletion	ON	ON	OFF
P-type enhancement	OFF	OFF	ON
P-type depletion	OFF	ON	ON

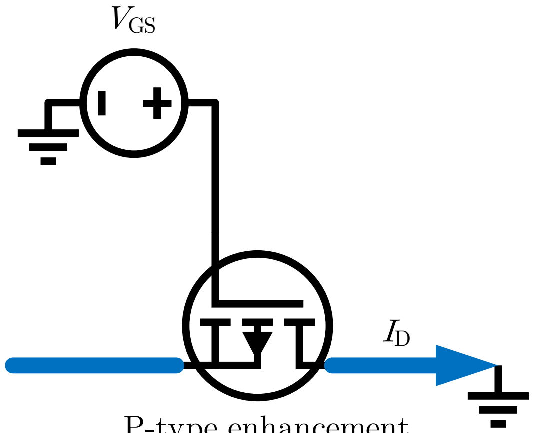
MOSFETs – enhancement mode

- Two modes of MOSFETS: enhancement and depletion modes.
- Enhancement is the most common.
- Enhancement MOSFETs are nominally turned off. (Naturally turned off when no voltage is applied to the gate)
- N-type enhancement mode **<u>turns on</u>** with **<u>positive voltage</u>** at the gate.
- P-type enhancement mode **<u>turns on</u>** with **<u>negative voltage</u>** at the gate.

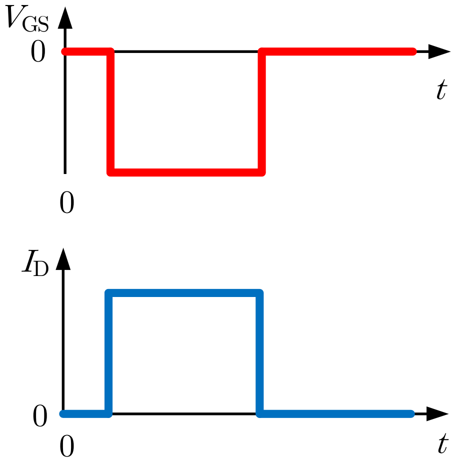


N-type enhancement



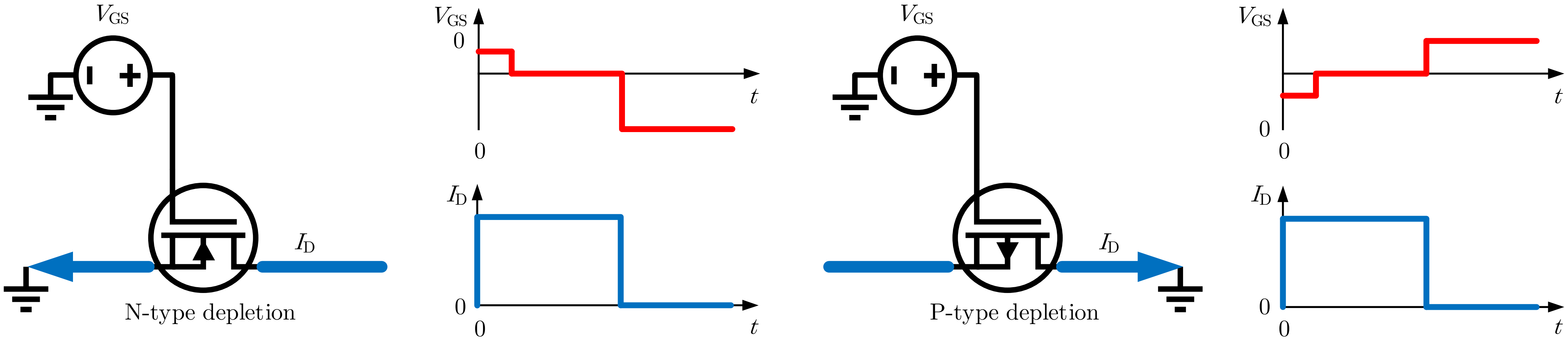


P-type enhancement



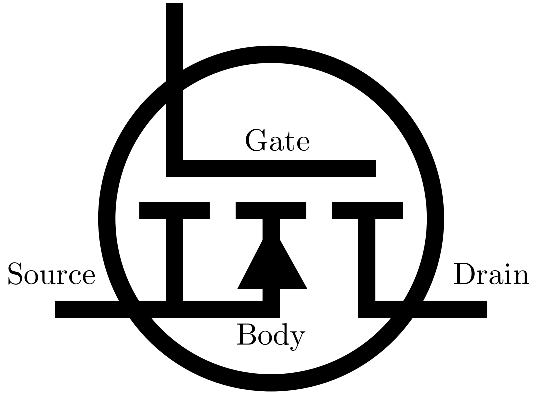
MOSFETs – depletion mode

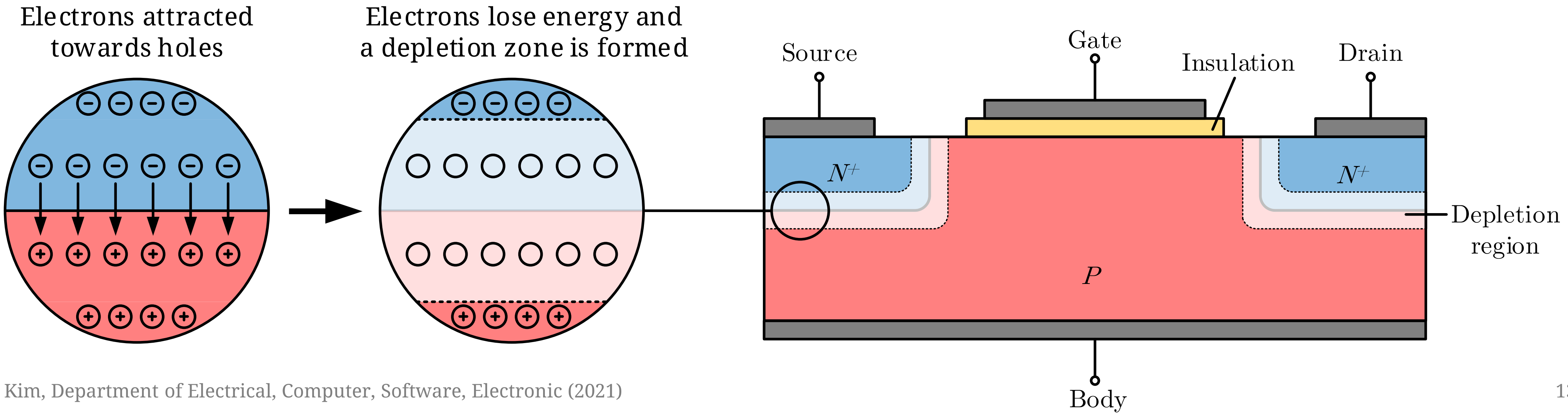
- Depletion MOSFETs are nominally turned on.
- Note that depletion mode MOSFETs can also go into enhancement mode.
- A depletion MOSFET turns on if no voltage applied at the gate or enhancement condition is met.
- N-type depletion mode **<u>turns on</u>** with **<u>positive voltage or no voltage</u>** at the gate.
- P-type depletion mode **<u>turns on</u>** with **<u>negative voltage or no voltage</u>** at the gate.



MOSFETs – N-type enhancement structure

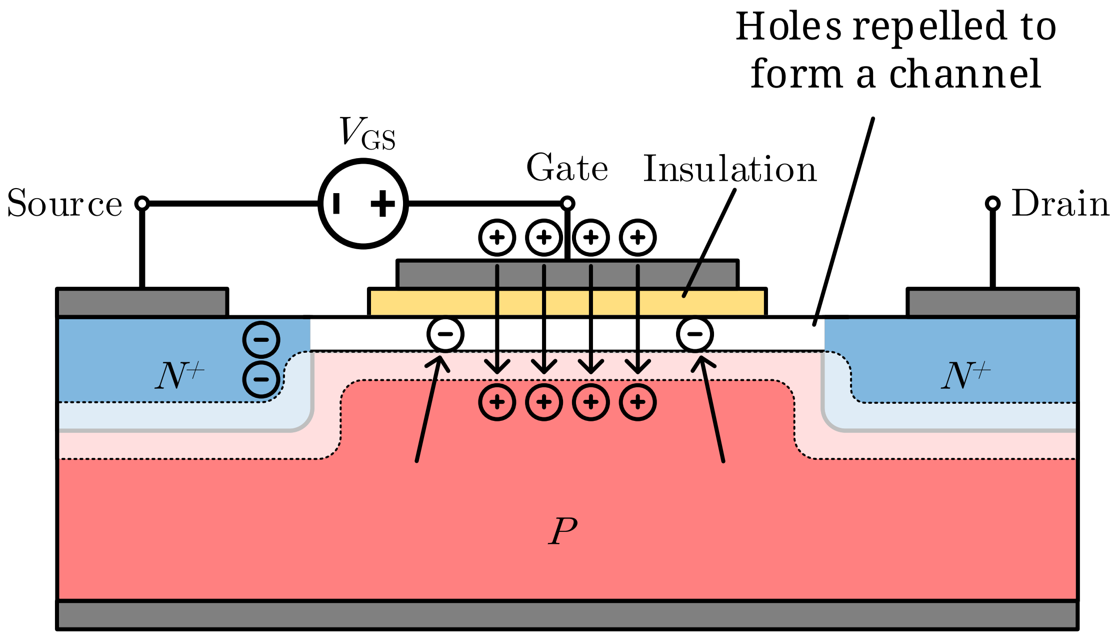
- N-type enhancement MOSFET has two N regions at the source and drain with a P region in between.
- P-N junctions: lots of electrons on one side and lots of holes on the other side.
- Electrons are naturally attracted to holes.
- Once electrons reach the holes in a P-N junction, their energy to move is ‘depleted’.
- This forms depletion zones in the middle of P-N junctions.
- At rest, no electron can flow from the source to drain of the MOSFET.

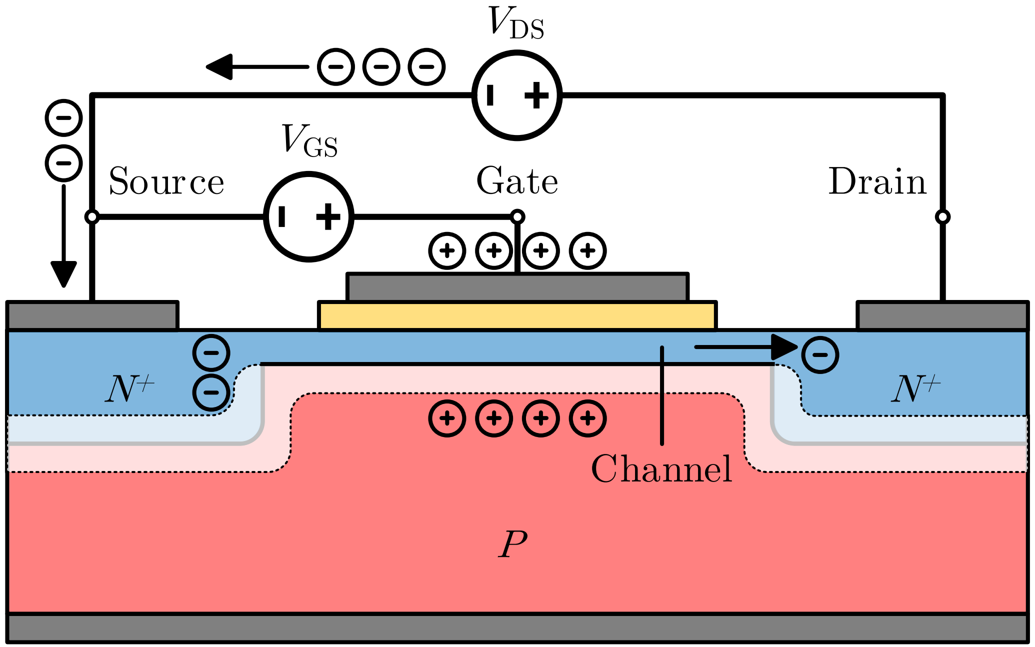




MOSFETs – N-type enhancement structure

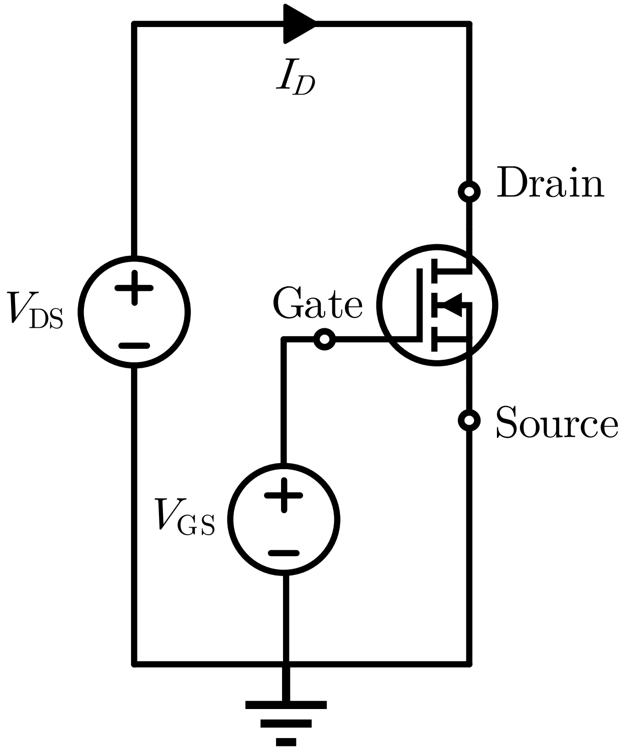
- Positive voltage applied to the gate 'repels' the holes near the gate, while electrons move towards the gate.
- This forms a channel between the source and the drain.
- When an external voltage source is applied, electrons can freely flow from the source to the drain through the channel.
- Note that <u>**conventional current flows from the drain to the source**</u>.





MOSFETs – overview

- Today, MOSFETs are predominantly used to process information and power.
- N-type and P-type MOSFETs.
- Enhancement and depletion modes.
- Electrons always move towards holes.
- P-N junctions and depletion zone.
- N-type enhancement most commonly used for switching purposes.
- Positive voltage to the gate to turn on the N-type MOSFET.



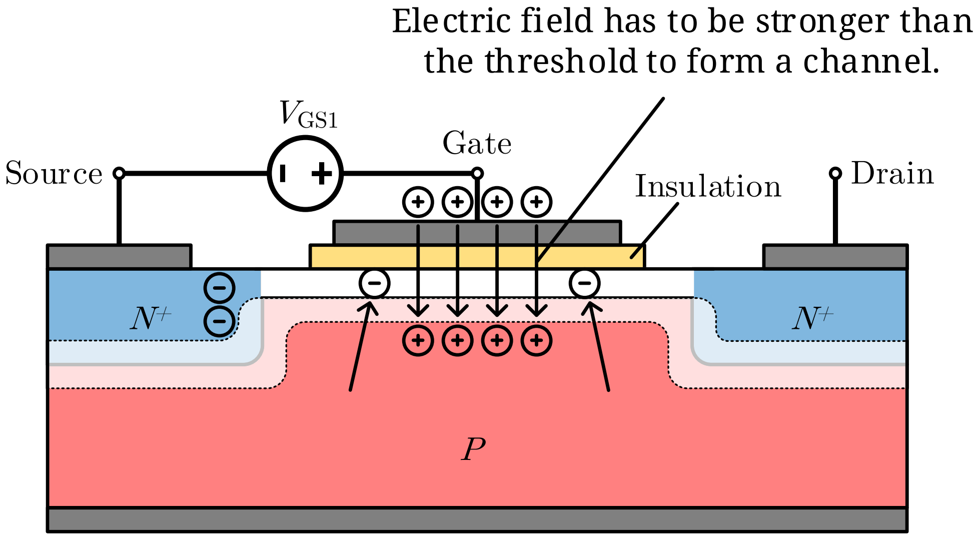
- An example N-type enhancement MOSFET circuit

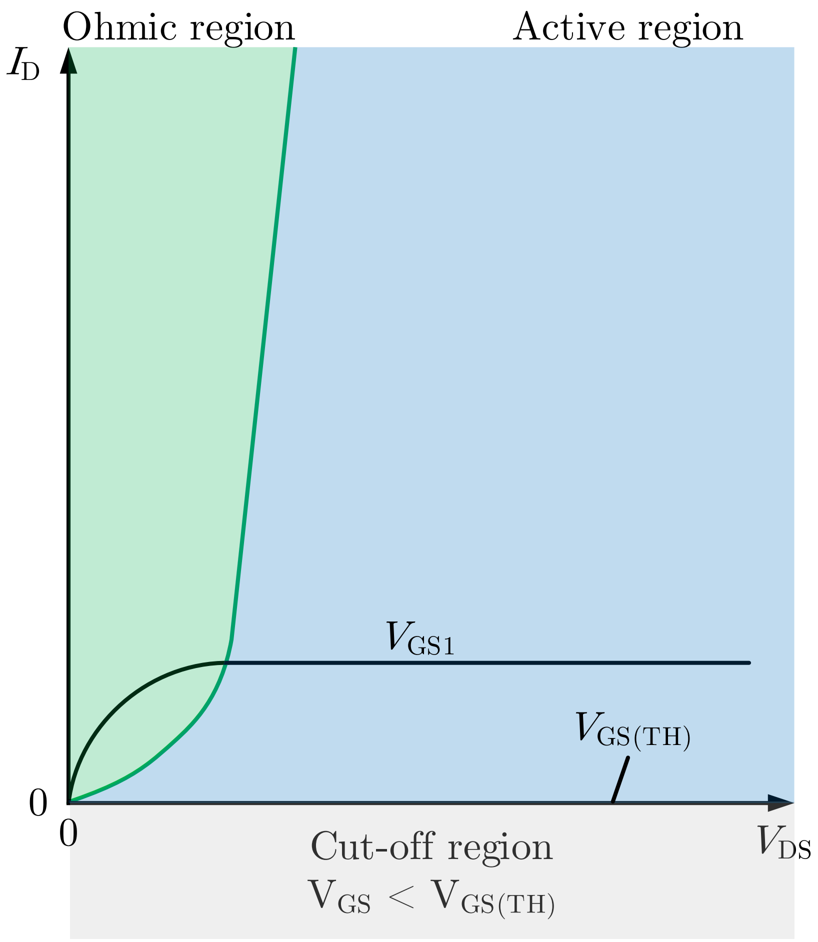
MOSFETs

Characteristics

MOSFETs – operating regions

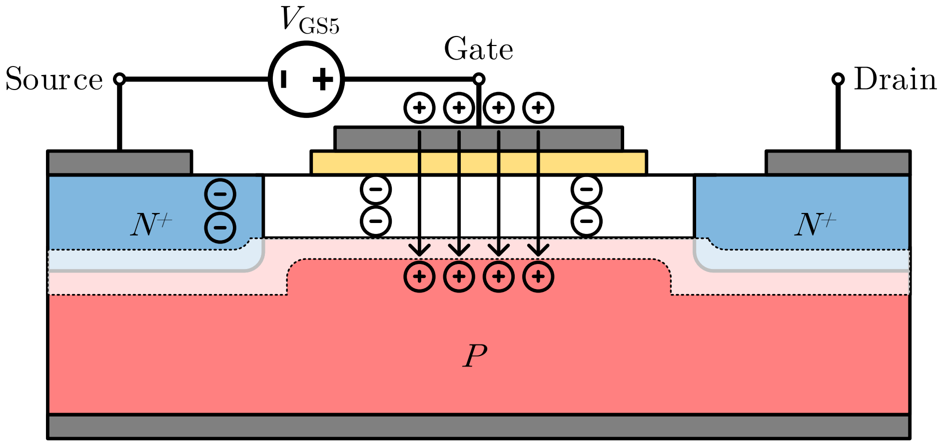
- A sufficient amount of charge is needed at the gate to form a channel between the source and drain.
- Gate threshold voltage ($V_{GS(TH)}$) is the minimum voltage required to turn the MOSFET on.
- Cut-off region when $V_{GS} \leq V_{GS(TH)}$.
- Ohmic region when V_{DS} increases proportionally to I_D.
- Active region when I_D and V_{DS} are independent of each other.

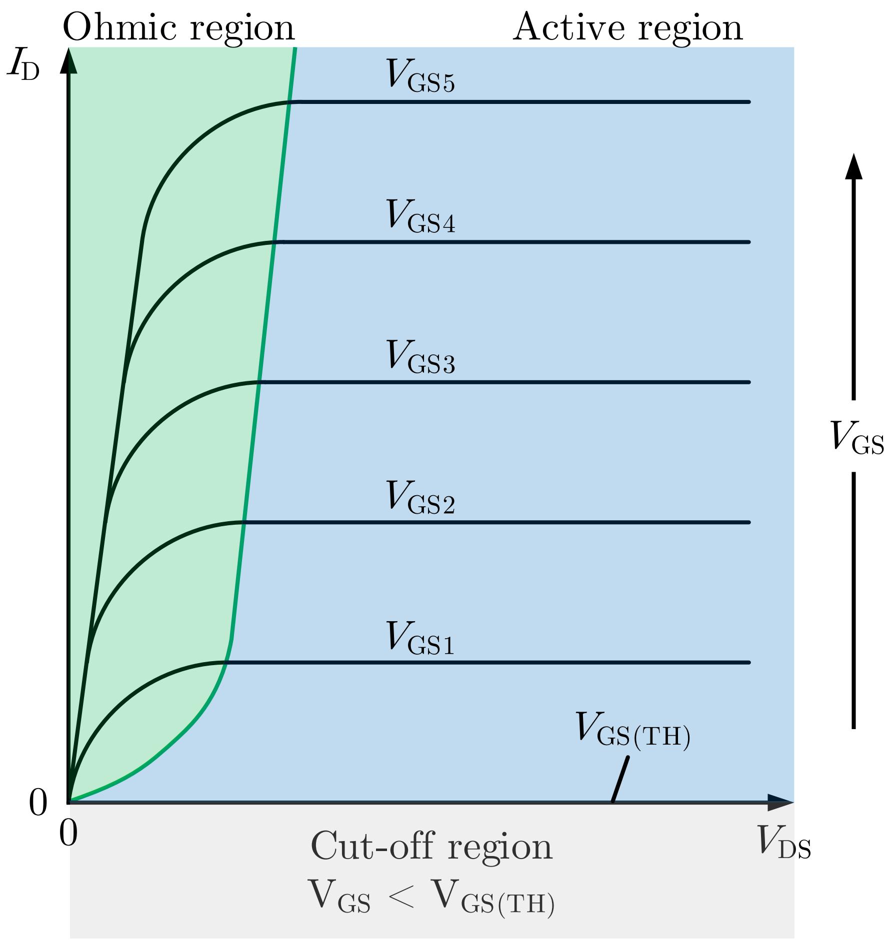




MOSFETs – operating regions

- As a switch, the MOSFET should pass as much current as possible when turned on.
- Larger V_{GS} results in more charge accumulating at the gate to generate a stronger electric field.
- The stronger the electric field, the larger the channel.
- Large channels allow for higher current to flow within the switch (I_D).
- The control of current flow using the electric field is called “field-effect”.





MOSFET – FQP13N10

- The MOSFET used in this project is **FQP13N10**.
- The datasheet can be referred to find the $V_{GS(TH)}$ and different operating regions of the MOSFET.
- In this MOSFET, the maximum current (I_D) of 12.8A flows when V_{GS} is at least 15V.
- For a short amount of time, a much higher I_D can be pulsed.
- Note the operating regions are drawn in log scale.

Absolute Maximum Ratings T_C = 25°C unless otherwise noted.

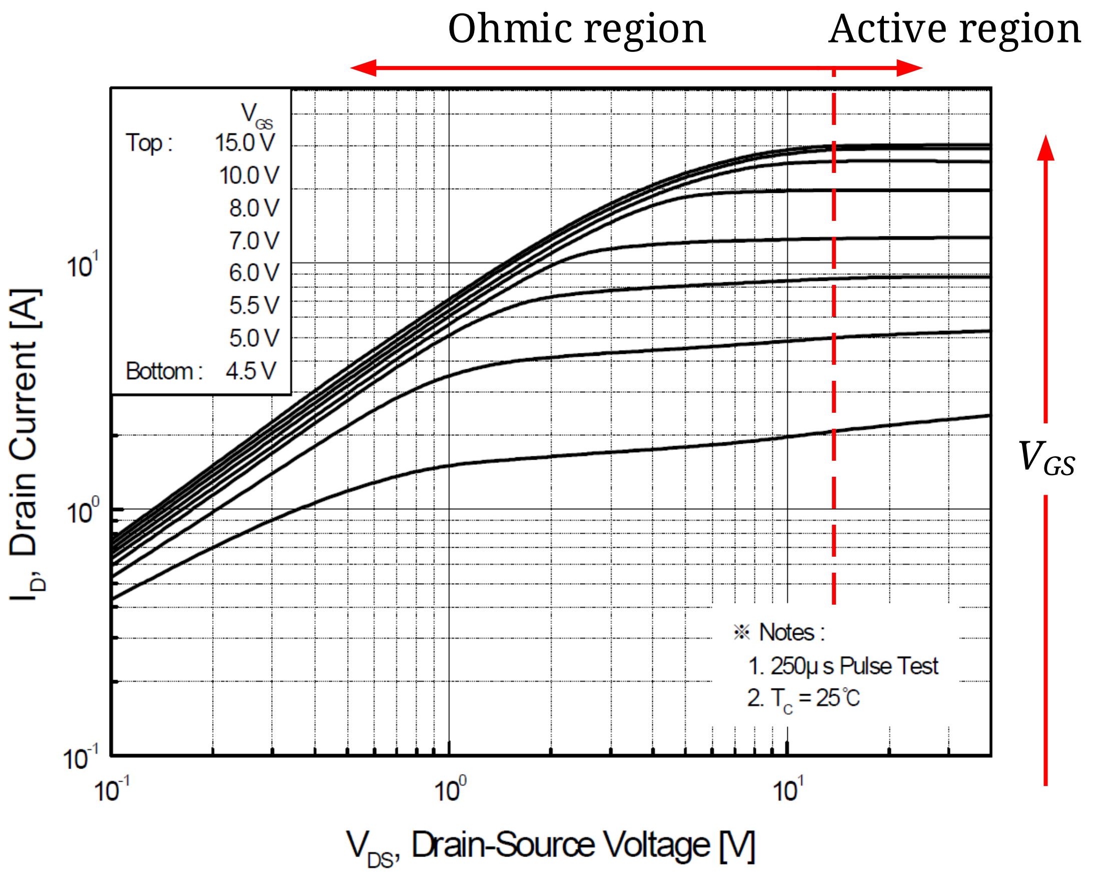
Symbol	Parameter			FQP13N10	Unit
I_D	Drain Current	- Continuous (T_C = 25°C)		12.8	A
		- Continuous (T_C = 100°C)		9.05	A
I_{DM}	Drain Current	- Pulsed	(Note 1)	51.2	A
V_{GSS}	Gate-Source Voltage			± 25	V

Electrical Characteristics T_C = 25°C unless otherwise noted.

Symbol	Parameter	Test Conditions	Min	Typ	Max	Unit
On Characteristics						
$V_{GS(th)}$	Gate Threshold Voltage	$V_{DS} = V_{GS}$, I_D = 250 µA	2.0	--	4.0	V

Notes:
1. Repetitive Rating : Pulse width limited by maximum junction temperature.

- I_D and V_{GS} characteristics from FQP13N10 datasheet [13]

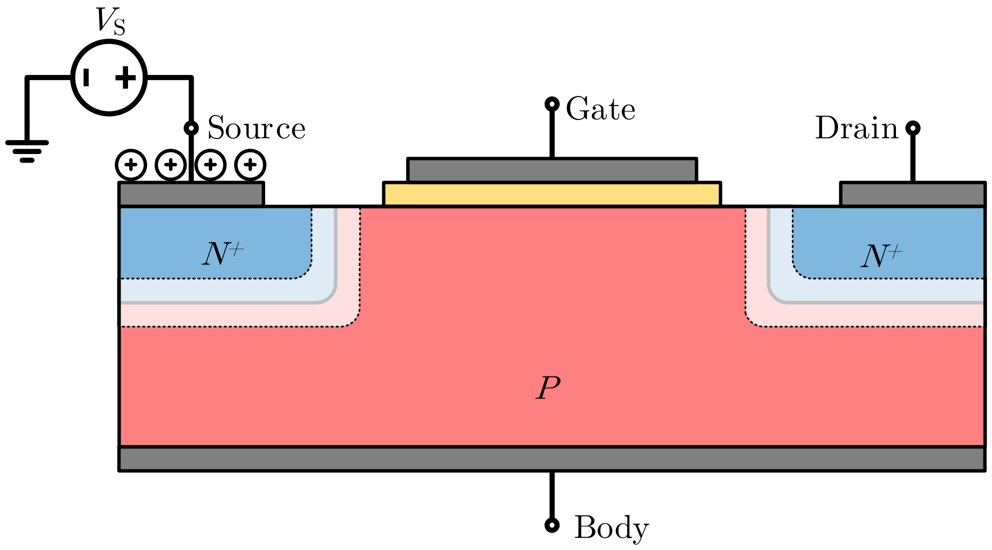


- On-region characteristics from FQP13N10 datasheet [13]

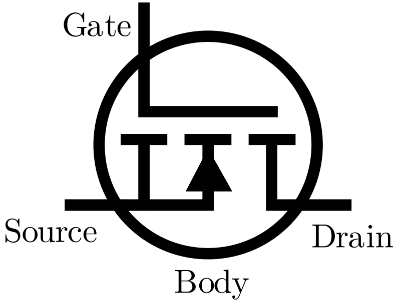
[13] https://www.onsemi.com/pdf/datasheet/fqp13n10-d.pdf

MOSFETs – body and source

- The source and body are tied together for MOSFETS used for switching large currents.
- If voltage potential in the source is higher than the body, the depletion region increases and $V_{GS(TH)}$ increases.
- If the MOSFET operates at a fixed V_{GS}, the maximum current through the drain (I_D) is reduced due to a higher $V_{GS(TH)}$.
- In order to ensure I_D stays at the maximum level, the source and the body are tied together.
- Often the symbols will indicate hat the source and body are tied together so there are only three terminals in the MOSFET instead of four.

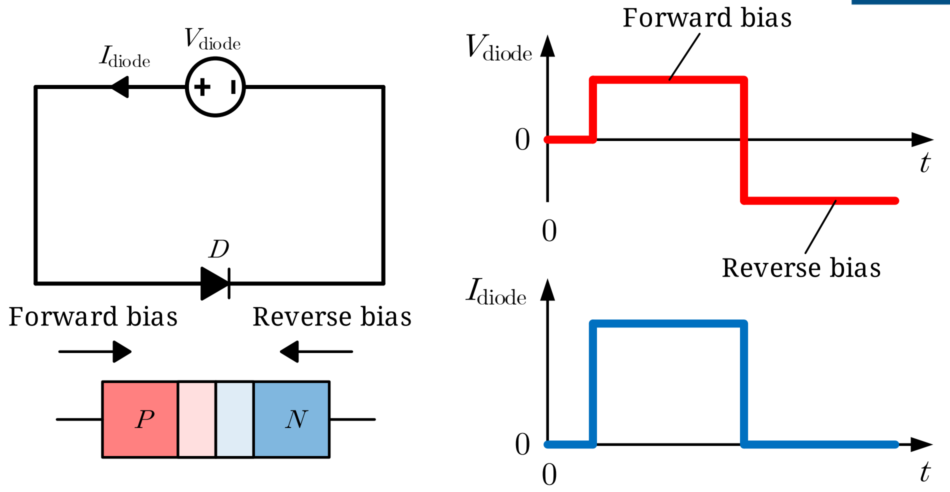


N-type enhancement

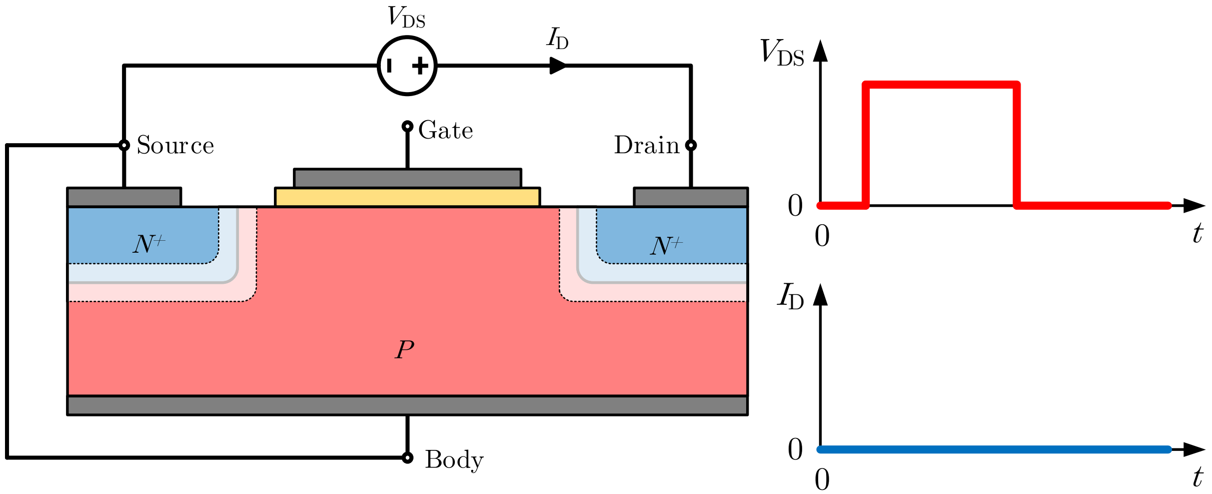


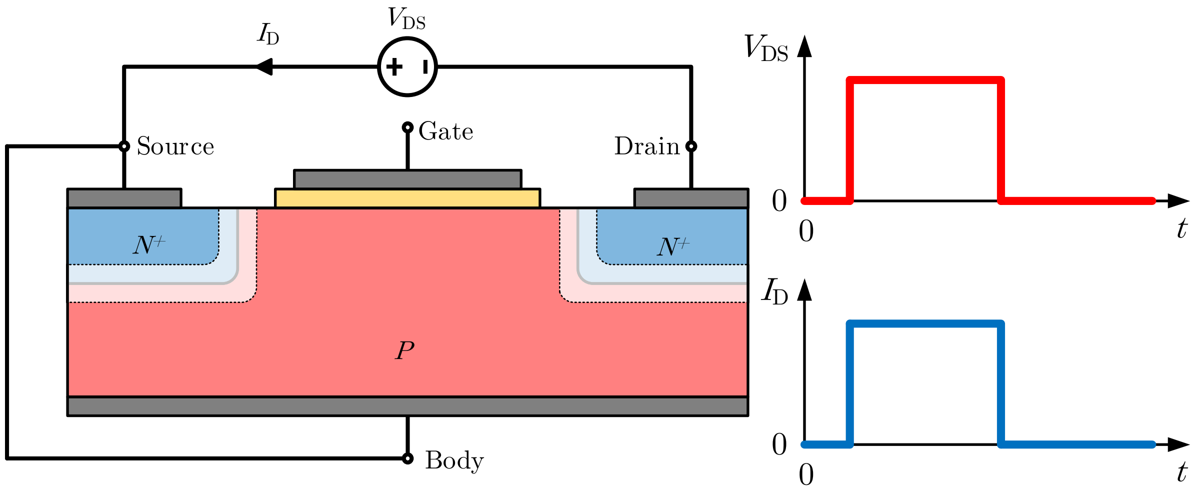
MOSFETs – body diode

- When the MOSFET is forward biased, no current flows without positive voltage on the gate.
- When the MOSFET is reverse biased, current flows without any voltage to the gate.
- This one directional current flow acts like a diode so it is called a ‘body diode’.



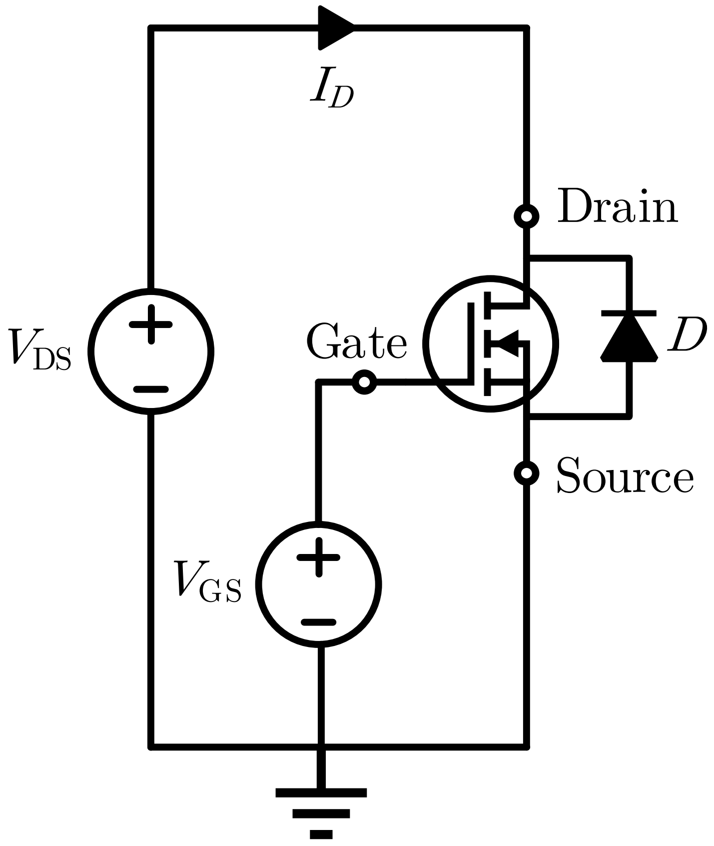
- Operation of a diode





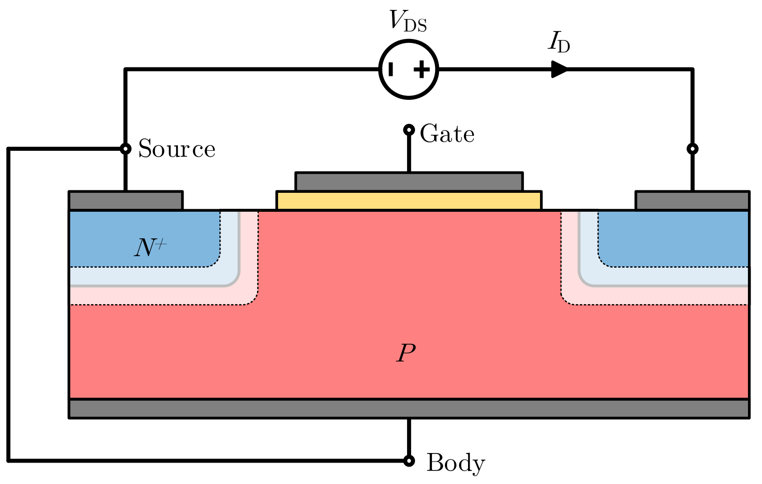
MOSFETs – body diode

- MOSFET body diode is often drawn in the diagrams to include the current flow in the reverse direction.



MOSFETs – breakdown voltages

- The maximum voltage that can be applied to the switch across the drain and source (V_{DSS}) is listed in the absolute maximum ratings as 100V for FQP13N10.
- If $V_{DSS(MAX)} > 100V$, the MOSFET shorts across the drain and source so current flows freely and the MOSFET does not work like a switch.
- The **drain source breakdown voltage** (BV_{DSS}) is also listed in the off-characteristics to show the maximum rating of the switch again.
- Usually, switches are chosen to operate well within the absolute maximum ratings. In actual circuits, transients in the system cause voltage spikes that may exceed the calculated voltages for the switches.
- As a rule of thumb, select switches that has a breakdown voltage at least 30% higher than the maximum voltage stress.



Absolute Maximum Ratings T_C = 25°C unless otherwise noted.

Symbol	Parameter	FQP13N10	Unit
V_{DSS}	Drain-Source Voltage	100	V

Electrical Characteristics T_C = 25°C unless otherwise noted.

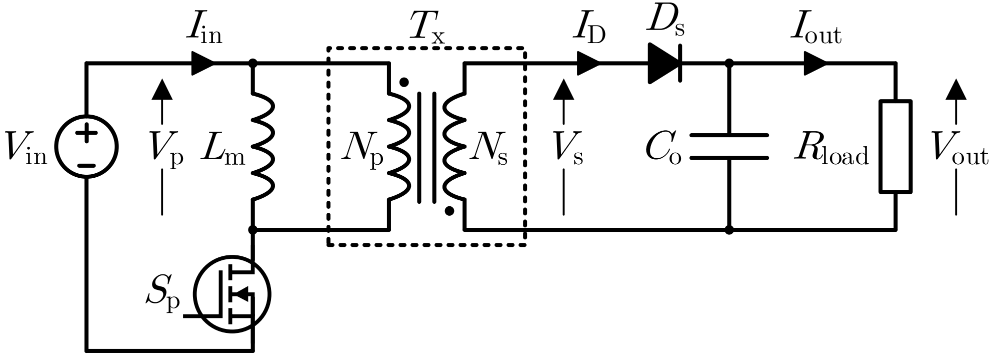
Symbol	Parameter	Test Conditions	Min	Typ	Max	Unit
Off Characteristics						
BV_{DSS}	Drain-Source Breakdown Voltage	V_{GS} = 0 V, I_D = 250 µA	100	--	--	V

- Breakdown voltages from FQP13N10 datasheet [13]

[13] https://www.onsemi.com/pdf/datasheet/fqp13n10-d.pdf

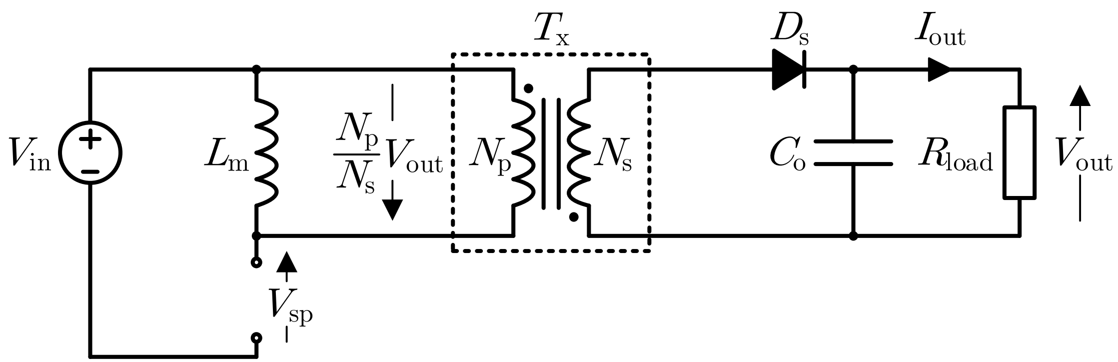
MOSFETs – example flyback converter

- Example flyback converter parameters:
- Input voltage (V_{in}): 30V
- Output voltage (V_{out}): 30V
- Turns ratio ($\frac{N_p}{N_s}$): 1
- Operating frequency: 100kHz
- Duty cycle: 0.5
- MOSFET maximum voltage: 100V
- Coupling factor = 1
- Discontinuous conduction mode



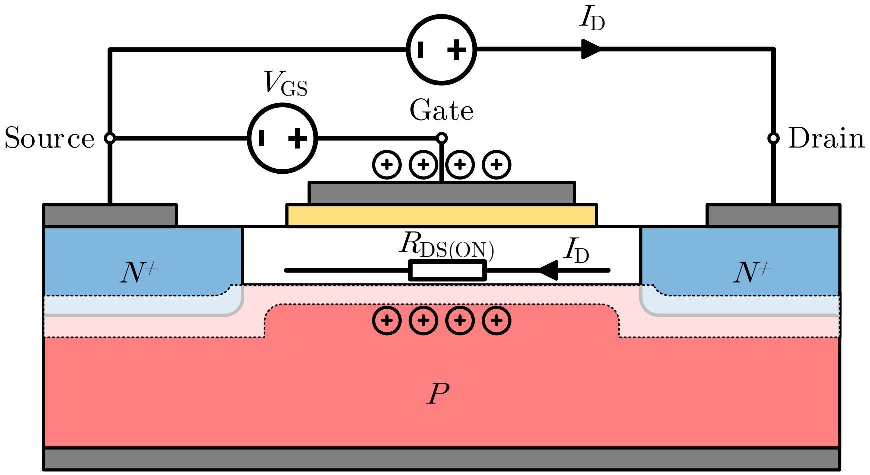
MOSFETs – switch voltage

- When the switch is off, the switch sees the input voltage (V_{in}) and output voltage (V_{out}).
- Output voltage on the secondary is kept up by the capacitor. Secondary voltage is reflected to the primary by the turns ratio ($\frac{N_p}{N_s}$).
- Switch voltage is given by:
- $V_{\text{sp(max)}} = V_{\text{in}} + \frac{N_p}{N_s} V_{\text{out}}$
- $\therefore V_{\text{sp(max)}} = 30 + 1 \times 30 = 60\text{V}$
- FQP13N10 has absolute maximum rating of 100V across the switch.
- Check the simulations for any transients above 100V.



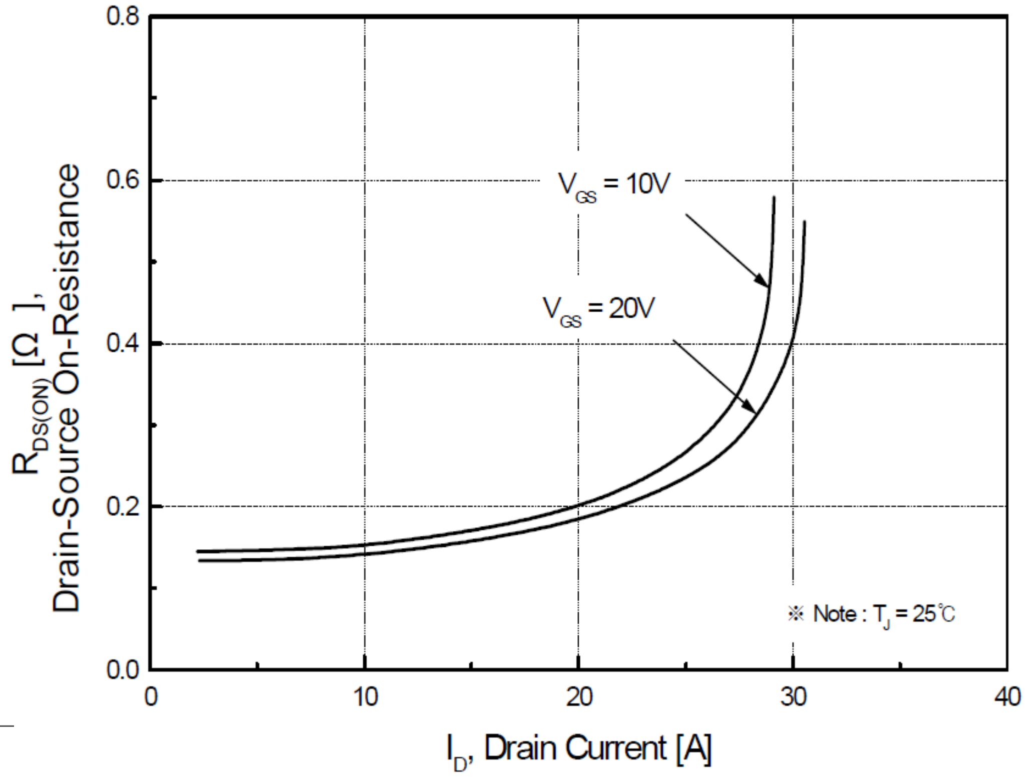
MOSFETs – on-characteristics

- On-resistance ($R_{DS(ON)}$) includes all resistances in the MOSFET in the path of current flow.
- A higher V_{GS} provides a wider channel to reduce $R_{DS(ON)}$.
- A trade-off between shorter channel length reducing $R_{DS(ON)}$ and longer channel lengths improving breakdown voltage.



$R_{DS(on)}$	Static Drain-Source On-Resistance	V_{GS} = 10 V, I_D = 6.4 A	--	0.142	0.18	Ω

- I_D and V_{GS} characteristics from FQP13N10 datasheet [13]

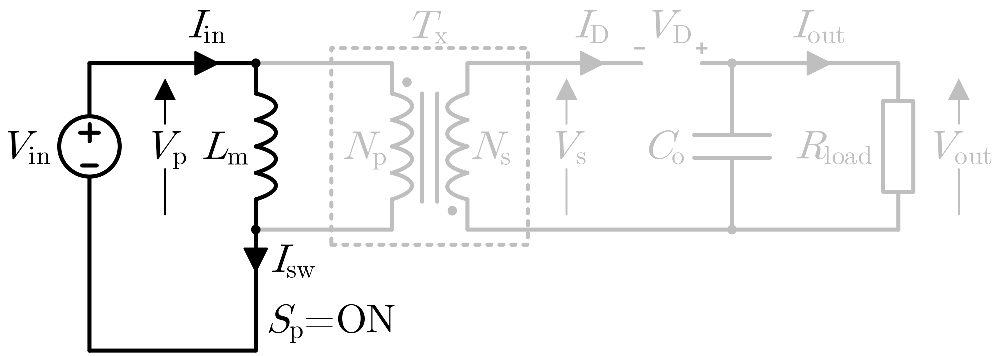


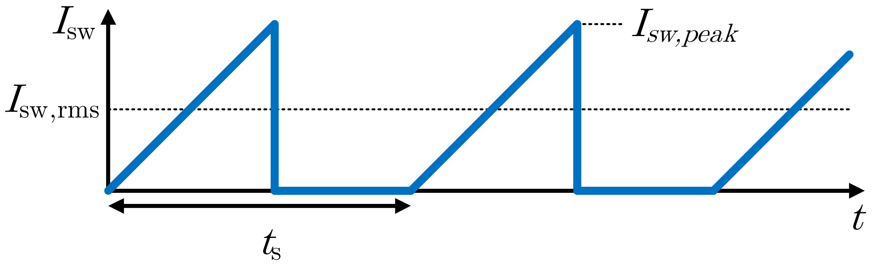
- On-region characteristics from FQP13N10 datasheet [13]

[13] https://www.onsemi.com/pdf/datasheet/fqp13n10-d.pdf

MOSFETs – conduction loss

- Switch RMS current is given by:
- $I_{\text{sw,rms}} = \sqrt{\frac{1}{t_s}\int_0^{t_s} I^2(t)\,dt}$
- Here, when switch is conducting:
- $I(t) = \frac{I_{\text{sw,peak}}}{Dt_s}t$
- $I_{\text{sw,rms}} = \sqrt{\frac{1}{t_s}\int_0^{Dt_s} \frac{I_{\text{sw,peak}}^2 t^2}{D^2 t_s^2}\,dt} = \frac{I_{\text{sw,peak}}^2 D^3 t_s^3}{3D^2 t_s^3} = \sqrt{\frac{D}{3}} I_{\text{sw,peak}}$
- $I_{\text{sw,rms}} = \sqrt{\frac{D}{3}} I_{\text{sw,peak}}$
- In this example, $I_{\text{sw,peak}} = 4\text{A}$ and $R_{\text{ds,on}} = 0.142\text{m}\Omega$.
- $I_{\text{sw,rms}} = \sqrt{\frac{0.5}{3}} \times 4 = 1.63\text{A}$
- Conduction loss is given by:
- $P_{\text{cond}} = {I_{\text{sw,rms}}}^2 R_{\text{ds,on}}$
- $P_{\text{cond}} = 1.63^2 \times 0.142 = 377\text{mW}$





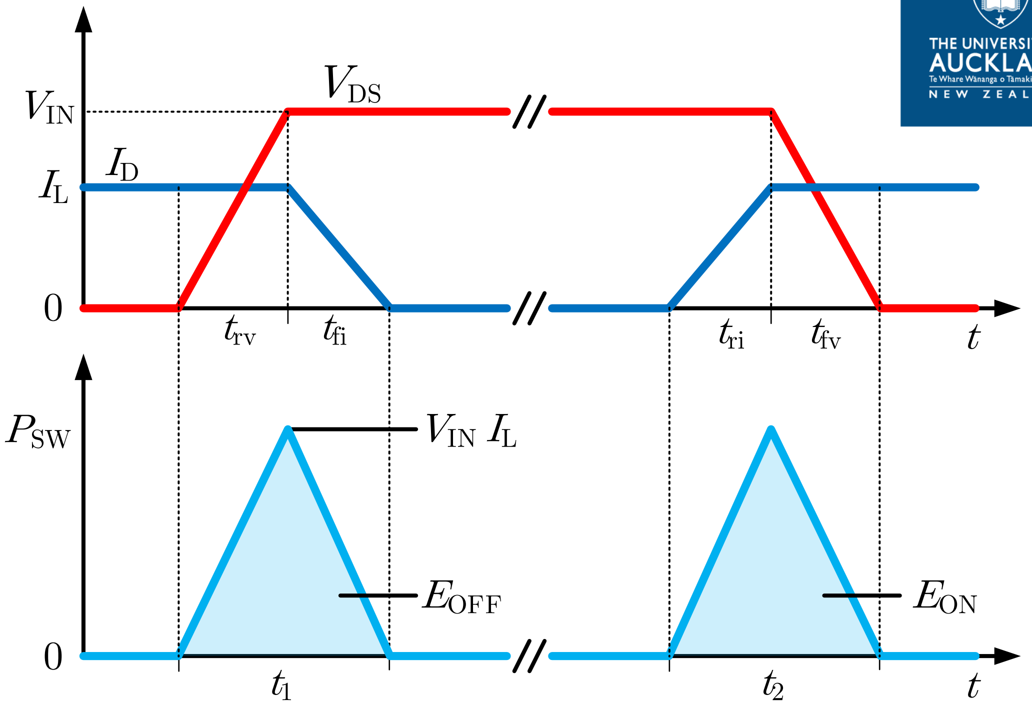
$R_{DS(on)}$	Static Drain-Source On-Resistance	V_{GS} = 10 V, I_D = 6.4 A	--	0.142	0.18	Ω

- On-resistance from FQP13N10 datasheet [13]

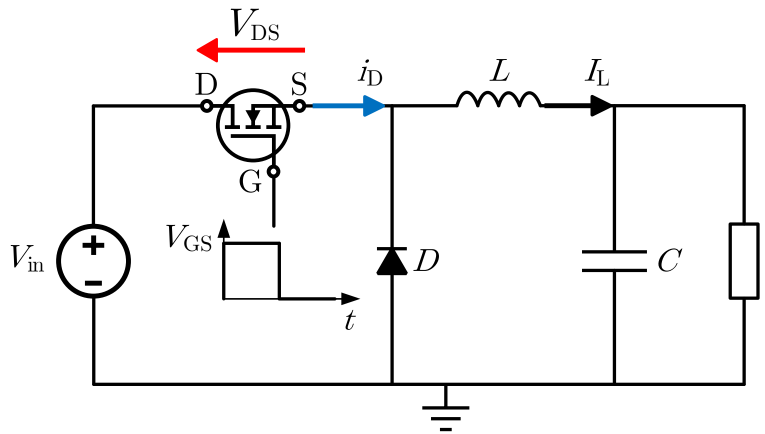
[13] https://www.onsemi.com/pdf/datasheet/fqp13n10-d.pdf

MOSFETs – switching loss

- Switching losses (P_{sw}) is the power lost when the MOSFET turns on or off.
- A very simplified example is shown here.
- Energy lost (E) = $\frac{1}{2} V_{\mathrm{in}} I_{\mathrm{L}}(t_{rv} + t_{fi}) + \frac{1}{2} V_{\mathrm{in}} I_{\mathrm{L}}(t_{ri} + t_{fv})$
- Energy lost (E) = $E_{\mathrm{ON}} + E_{\mathrm{OFF}}$
- Switching loss (P_{SW}) = $\frac{1}{\mathrm{T}} E_{\mathrm{TOTAL}} = (E_{\mathrm{ON}} + E_{\mathrm{OFF}})f$
- Assume $t_{rv} = t_{fi}$ and $t_{ri} = t_{fv}$
- $\therefore P_{\mathrm{SW}} = (V_{\mathrm{in}} I_{\mathrm{L}} t_{fi} + V_{\mathrm{in}} I_{\mathrm{L}} t_{ri})f$



- Example switching waveforms when MOSFET turns on or off



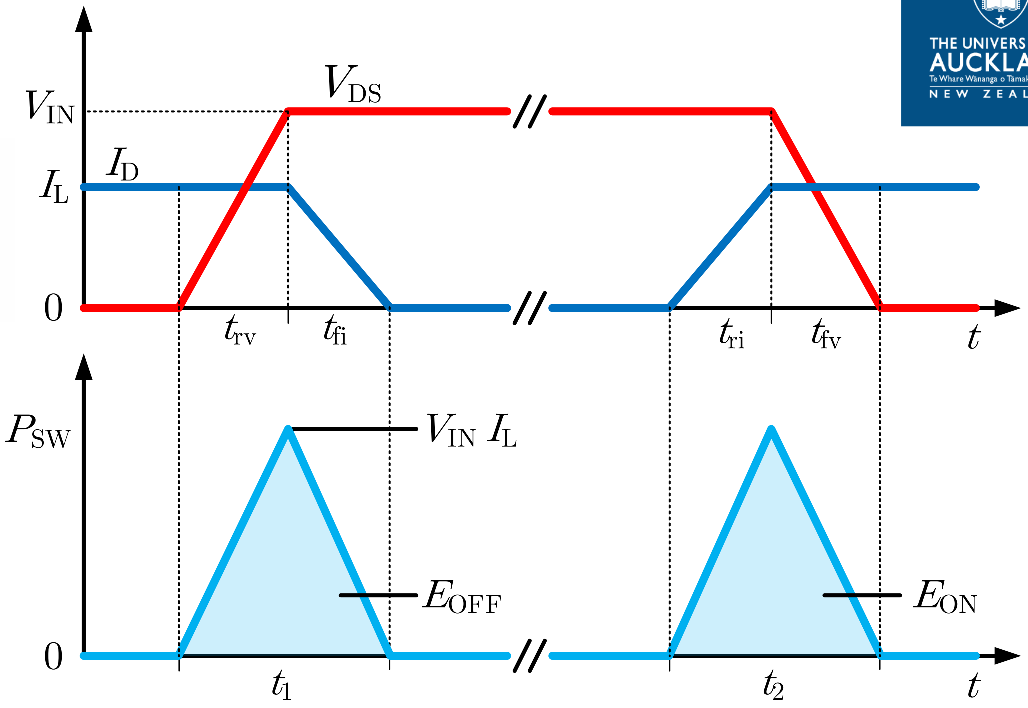
- An example circuit using a MOSFET

MOSFETs – switching loss

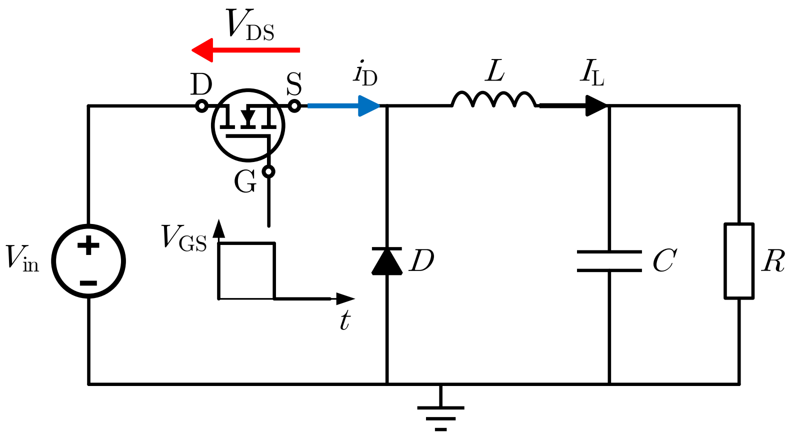
Switching Characteristics						
$t_{d(on)}$	Turn-On Delay Time	V_{DD} = 50 V, I_D = 12.8 A, R_G = 25 Ω (Note 4)	--	5	20	ns
t_r	Turn-On Rise Time		--	55	120	ns
$t_{d(off)}$	Turn-Off Delay Time		--	20	50	ns
t_f	Turn-Off Fall Time		--	25	60	ns

- Switching characteristics from FQP13N10 datasheet [13]

- In this example, $V_{\text{in}} = 30\text{V}$, $I_{\text{sw,peak}} = 4\text{A}$ and $f = 100\text{kHz}$.
- $t_{ri} = t_{fv} = 55\text{ns}$
- $t_{fi} = t_{rv} = 25\text{ns}$
- $P_{\text{SW}} = (V_{\text{in}} I_{\text{L}} t_{fi} + V_{\text{in}} I_{\text{L}} t_{ri}) f$
- $P_{\text{SW}} = (30 \times 4 \times 55\text{n} + 30 \times 4 \times 25\text{n})100\text{k}$
- $P_{\text{SW}} = 960\text{mW}$
- Switching losses tend to be much higher than conduction losses.
- Switching losses are proportional to switching frequency.
- Note that in the flyback converter operating in discontinuous conduction mode, the current is 0A at turn on.



- Example switching waveforms when MOSFET turns on or off



- An example circuit using a MOSFET

[13] https://www.onsemi.com/pdf/datasheet/fqp13n10-d.pdf

MOSFETs – thermal characteristics

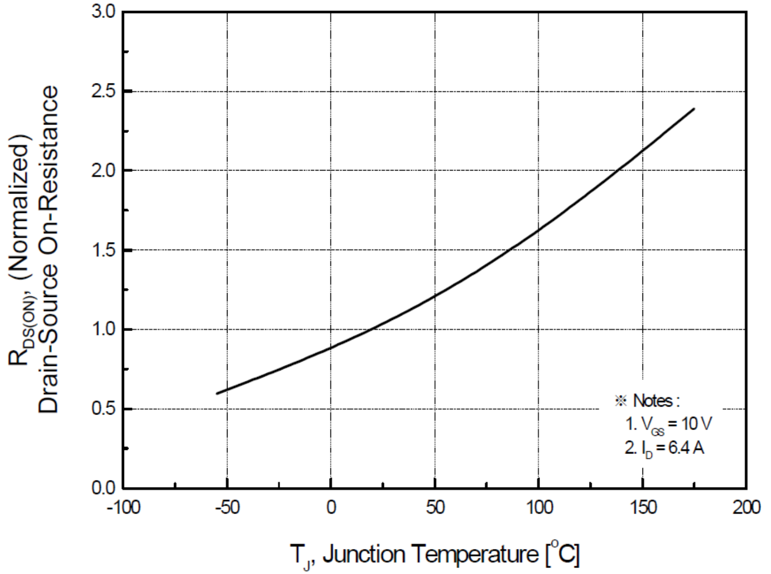
- As the temperature of the MOSFET increases, $R_{\mathrm{DS(ON)}}$ also increases that leads to higher power loss.
- The capacity of the MOSFET to handle I_{D} also reduces as the temperature increases.
- Care should be taken to not exceed the maximum junction temperature of 175C as listed in the datasheet for FQP13N10.

Thermal Characteristics

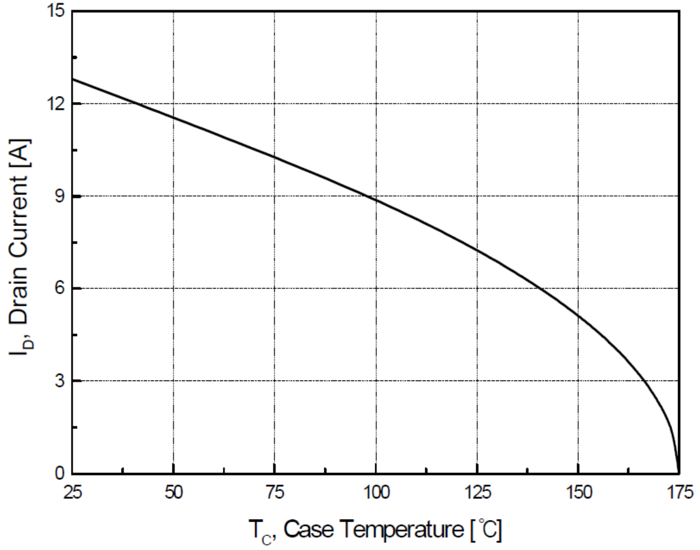
Symbol	Parameter	FQP13N10	Unit
$R_{\theta JC}$	Thermal Resistance, Junction-to-Case, Max.	2.31	°C/W
$R_{\theta JA}$	Thermal Resistance, Junction-to-Ambient, Max.	62.5	°C/W

- Thermal resistance from FQP13N10 datasheet [13]

- Given the information in the datasheet, the maximum power dissipation in the MOSFET can be estimated.
- For ambient temperature of 25C:
- $\frac{1}{R_{\theta \mathrm{JA}}}(\mathrm{T_{junction}} - \mathrm{T_{ambient}}) = P_{\mathrm{MAX}}$
- $P_{\mathrm{MAX}} = \frac{1}{62.5}(175 - 25) = 2.4\mathrm{W}$



- On-resistance variation against temperature [13]

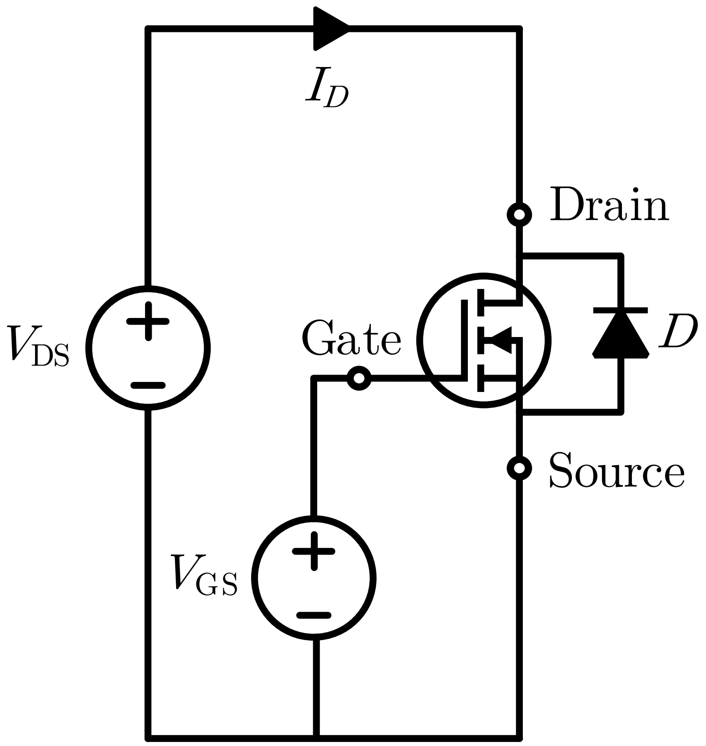


- Maximum drain current against temperature

[13] https://www.onsemi.com/pdf/datasheet/fqp13n10-d.pdf

MOSFETs – summary

- Different operating regions – Ohmic, active and cut-off.
- Source to body connection and body diode.
- Breakdown voltages: 100V for FQP13N10.
- Conduction losses: $P_{\text{cond}} = I_{\text{sw,rms}}{}^{2} R_{\text{ds,on}}$.
- $R_{\text{ds,on}}$ decreased when V_{GS} is higher.
- Usually a trade-off between breakdown voltages and $R_{\text{ds,on}}$.
- Switching losses: $P_{\text{SW}} = (E_{\text{ON}} + E_{\text{OFF}})f = P_{\text{SW}} = \left(V_{\text{in}} I_{\text{L}} t_{fi} + V_{\text{in}} I_{\text{L}} t_{ri}\right) f$
- Maximum junction temperature: 175℃ for FQP13N10.



- An example N-type enhancement MOSFET circuit

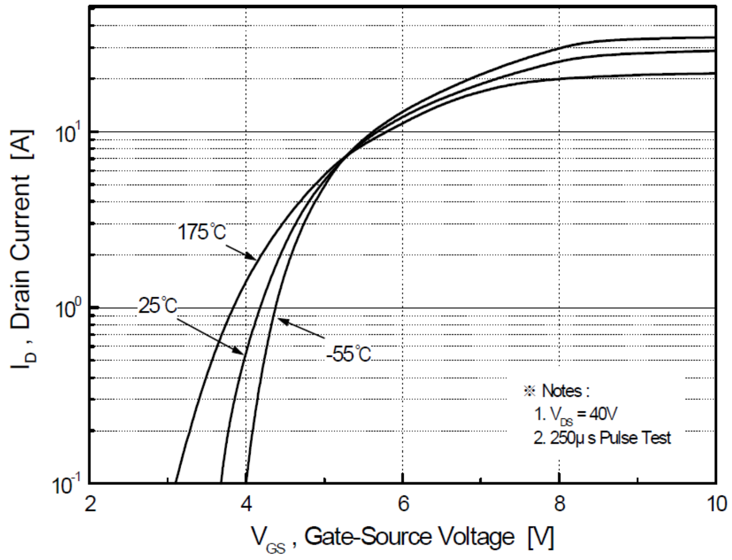
THE UNIVERSITY OF AUCKLAND
Te Whare Wānanga o Tāmaki Makaurau
NEW ZEALAND

MOSFETs

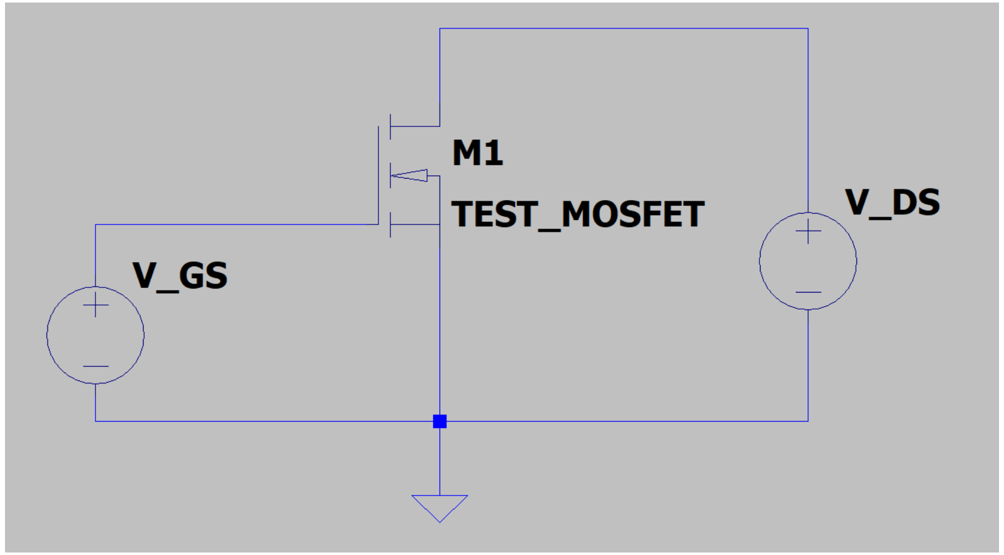
Drivers and simulation examples

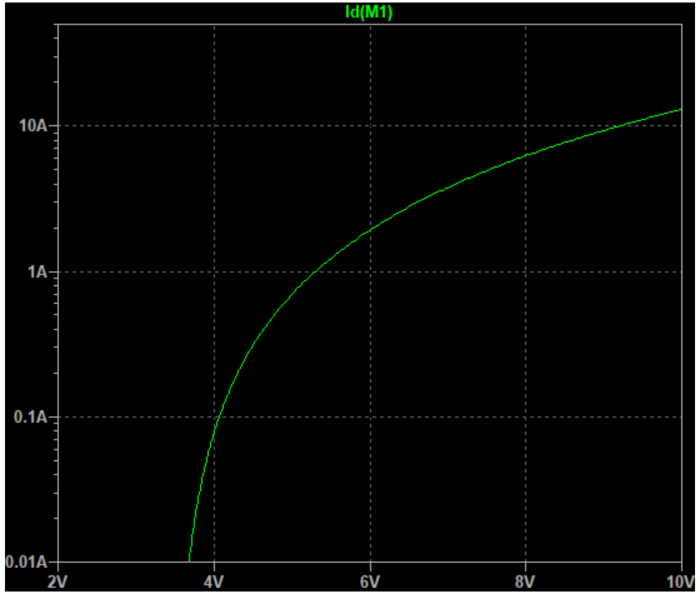
MOSFETs – simulation model

- A simple MOSFET model can be made on LTSpice to approximate the operation.
- More accurate simulation models quickly get much more complicated and involves a lot of empirical data.
- For the purposes of this course, the simulation model can be downloaded from [14].



- Transfer characteristics [13]



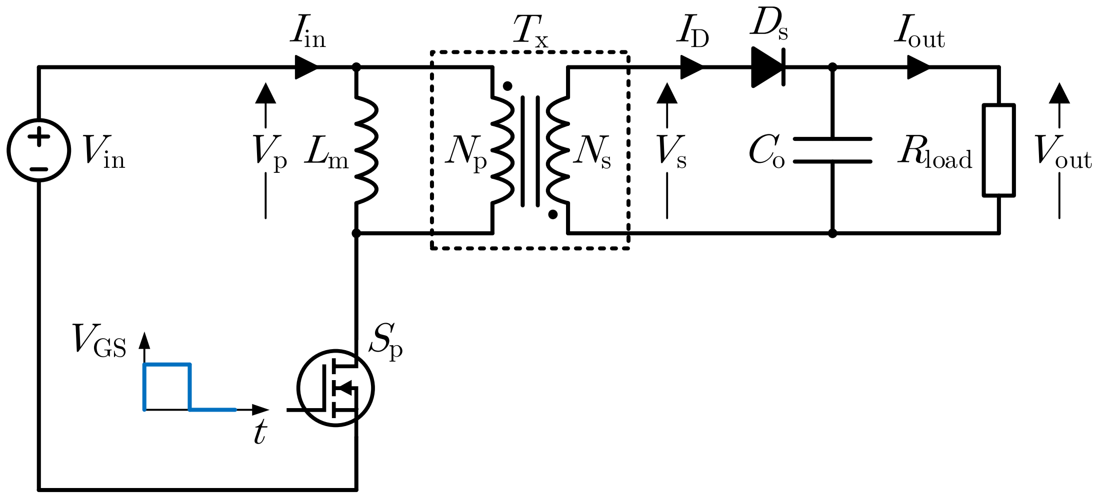


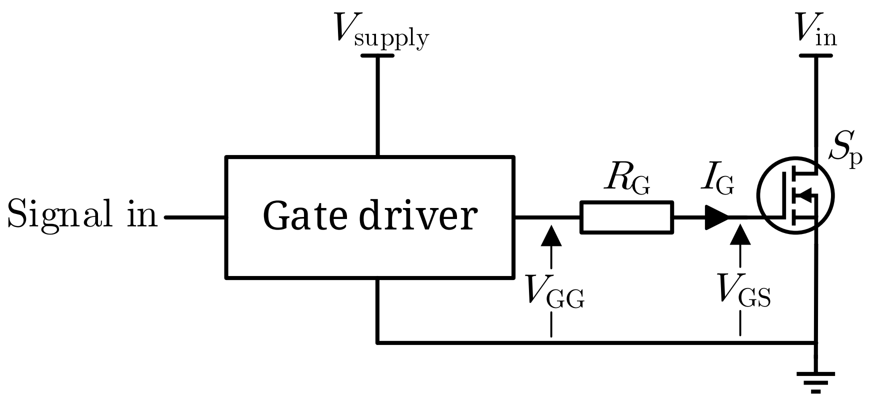
- Simulation of a simple MOSFET model

[13] https://www.onsemi.com/pdf/datasheet/fqp13n10-d.pdf
[14] https://www.onsemi.com/support/design-resources/models?rpn=FQP13N10

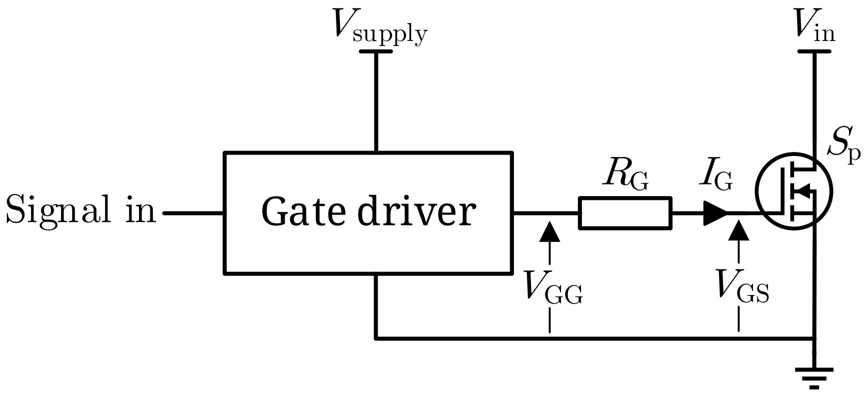
MOSFETs – drivers

- Generally, a separate circuit called **MOSFET drivers** are used to turn MOSFETs on and off.
- MOSFET drivers are specifically designed to achieve high voltage across the gate and source (V_{GS}) and current into the gate (I_G) that may not be achievable by using a standard controller circuit.
- MOSFET driver is needed to:
  - Achieve high V_{GS} to increase I_D flow through the switch as shown before in the characteristics curve.
  - High V_{GS} helps to improve the conduction loss as $R_{DS(ON)}$ is reduced.
  - Achieve high current into the gate (I_G) helps to charge the gate faster for to enable higher switching frequency.
  - Faster switching times helps to reduce switching losses.
- MOSFET driver can be considered as a 'power amplifier' for the gate.





MOSFETs – UC3843 driver



- The MOSFET is driven by UC3843 chip in this project.
- Ideally, there would be no gate resistance from the MOSFET driver to the gate of the MOSFET.
- Sometimes, the switching is too fast and needs to be slowed down to reduce transients (overshoots and ringing) caused by parasitics that could damage the circuit.
- Gate resistance can be approximated by:
- $R_G = \frac{V_{GG}}{I_G}$
- If $V_{GG} = 15V$ and $I_G = 1A$,
- $R_G = \frac{15}{1} = 15\Omega$
- Here, 1A is from the UC3843 datasheet.
- In the practical circuit, the value may require some adjustment as parasitics are difficult to predict.

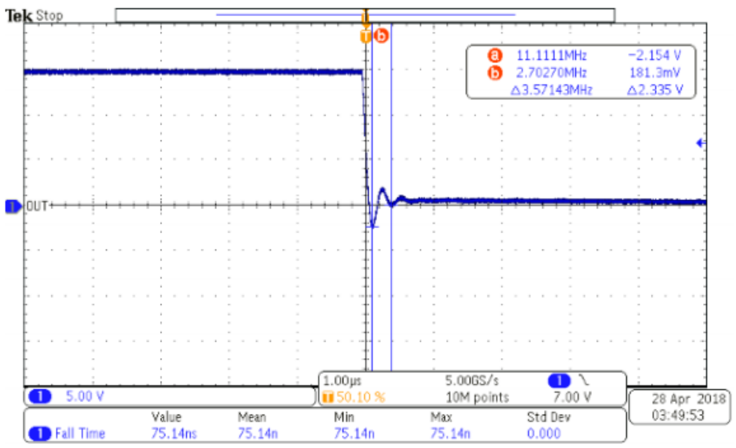


Figure 4. External Gate Resistor R_{GATE} = 0-Ω

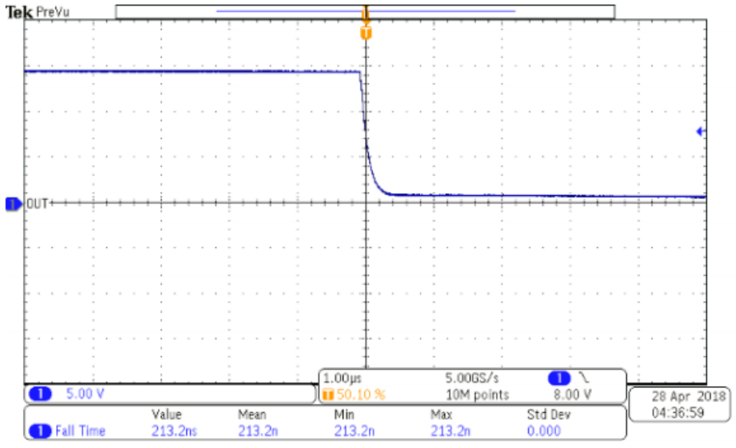


Figure 5. Critically Damped External Gate Resistor R_{GATE} = 7-Ω

- Scope measurements of a MOSFET with and without gate resistance.

[15]https://www.ti.com/lit/an/slla385a/slla385a.pdf?ts=1626929716610&ref_url=https%253A%252F%252Fwww.google.com%252F

THE UNIVERSITY OF AUCKLAND
Te Whare Wānanga o Tāmaki Makaurau
NEW ZEALAND

Appendix

MOSFETs – safe operating area

- Maximum voltage and current defined in the datasheet as 100V and 51.2A (pulsed).

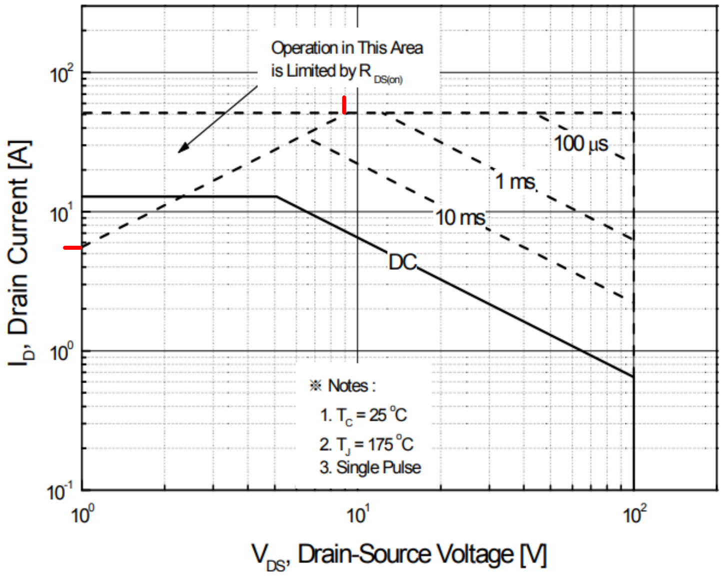
Absolute Maximum Ratings T_C = 25°C unless otherwise noted.

Symbol	Parameter		FQP13N10	Unit
V_{DSS}	Drain-Source Voltage		100	V
I_D	Drain Current	- Continuous (T_C = 25°C)	12.8	A
		- Continuous (T_C = 100°C)	9.05	A
I_{DM}	Drain Current	- Pulsed (Note 1)	51.2	A

Electrical Characteristics T_C = 25°C unless otherwise noted.

Symbol	Parameter	Test Conditions	Min	Typ	Max	Unit
On Characteristics						
$R_{DS(on)}$	Static Drain-Source On-Resistance	V_{GS} = 10 V, I_D = 6.4 A	--	0.142	0.18	Ω

- Operation is limited by the maximum $R_{\mathrm{DS(on)}}$.
- At $V_{\mathrm{DS}} = 1\mathrm{V}$, $I_{\mathrm{D}} = \dfrac{V_{\mathrm{DS}}}{R_{\mathrm{DS(on),max}}} = \dfrac{1}{0.18} = 5.56\mathrm{A}$
- At $I_{\mathrm{D}} = 51.2\mathrm{A}$, $V_{\mathrm{DS}} = I_{\mathrm{D}} R_{\mathrm{DS(on),max}} = 51.2 \times 0.18 = 9.22\mathrm{V}$
- Switch can only operate within the region bound by these two points.



- Maximum safe operating area [13]

- On-resistance variation vs temperature [13]

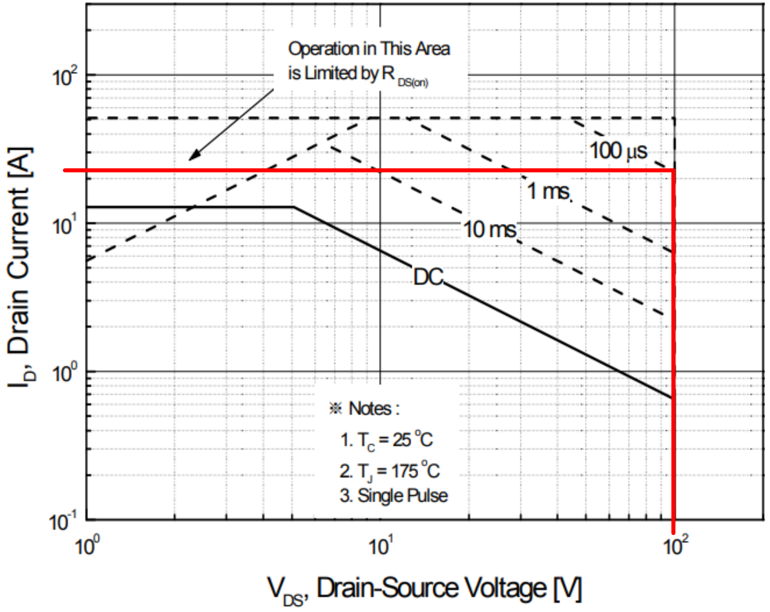
[13] https://www.onsemi.com/pdf/datasheet/fqp13n10-d.pdf

MOSFETs – safe operating area

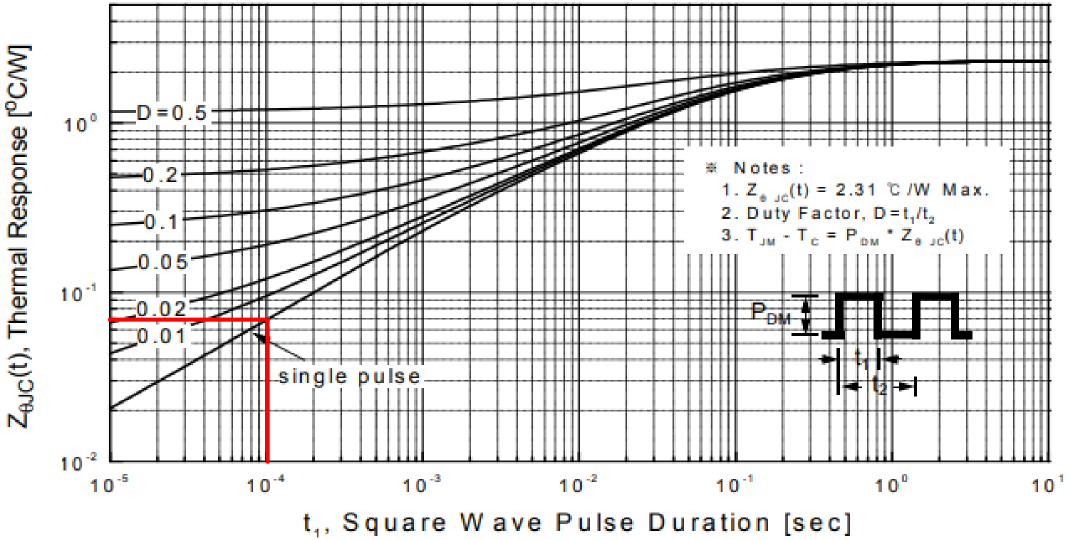
- According to the datasheet: $T_{\mathrm{j(max)}} - T_{\mathrm{c}} = P_{\mathrm{D(max)}} \times Z_{\theta\mathrm{jc}}$
- Here, $P_{\mathrm{D(max)}}$ is the power loss during the pulse and $Z_{\theta\mathrm{jc}}$ is the thermal response in ℃/W.
- For example, a single pulse of 100μs has $Z_{\theta\mathrm{jc}} \approx 0.07$℃/W.
- If $V_{\mathrm{DS}} = 100$V, what is the maximum pulse current?
- $T_{\mathrm{j(max)}} = 175$℃ and $T_{\mathrm{c}} = 25$℃
- $175 - 25 = 100 \times I_{\mathrm{D}} \times 0.07$
- $\frac{150}{100\times 0.07} = 21.4$A

Absolute Maximum Ratings T_C = 25°C unless otherwise noted.

Symbol	Parameter	FQP13N10	Unit
P_D	Power Dissipation (T_C = 25°C)	65	W
	- Derate above 25°C	0.43	W/°C
T_J, T_{STG}	Operating and Storage Temperature Range	-55 to +175	°C



- Maximum safe operating area [13]



- Transient thermal response curve [13]

[13] https://www.onsemi.com/pdf/datasheet/fqp13n10-d.pdf

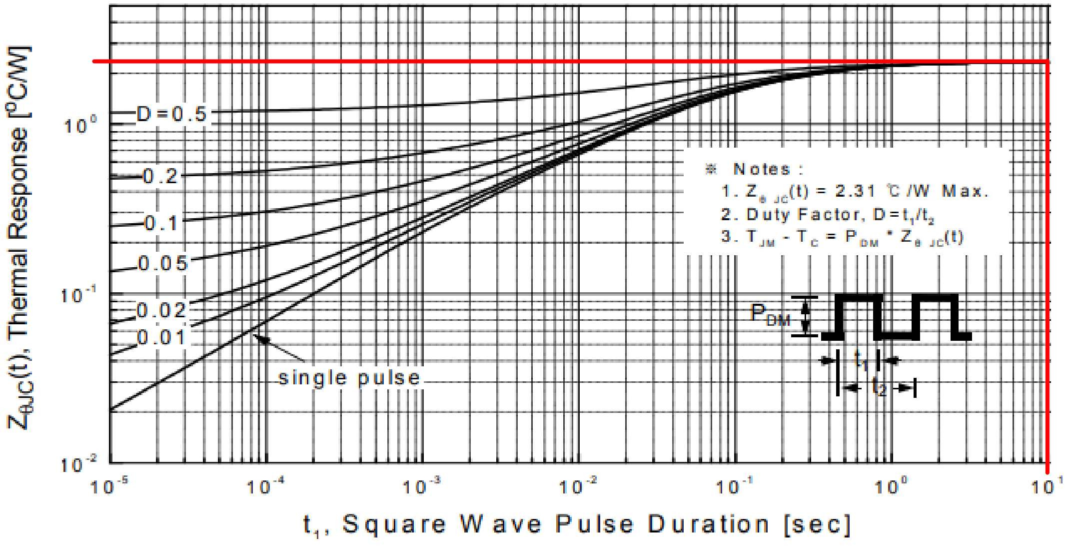
MOSFETs – safe operating area

- When duty cycle is increased, $Z_{\theta jc}$ is higher so P_D gets smaller.
- At the other end of the spectrum, if $D = 0.5$ and pulse is 10s long: $Z_{\theta jc(max)} = 2.31°C/W$
- $175 - 25 = P_{D(max)} \times 2.31$
- $\therefore P_{D(max)} = 65.0W$

Absolute Maximum Ratings T_C = 25°C unless otherwise noted.

Symbol	Parameter	FQP13N10	Unit
P_D	Power Dissipation (T_C = 25°C)	65	W
	- Derate above 25°C	0.43	W/°C
T_J, T_{STG}	Operating and Storage Temperature Range	-55 to +175	°C

- The datasheet numbers here assume T_c stays constant at 25°C. $Z_{\theta jc}$ will change in real life scenarios as T_c changes.

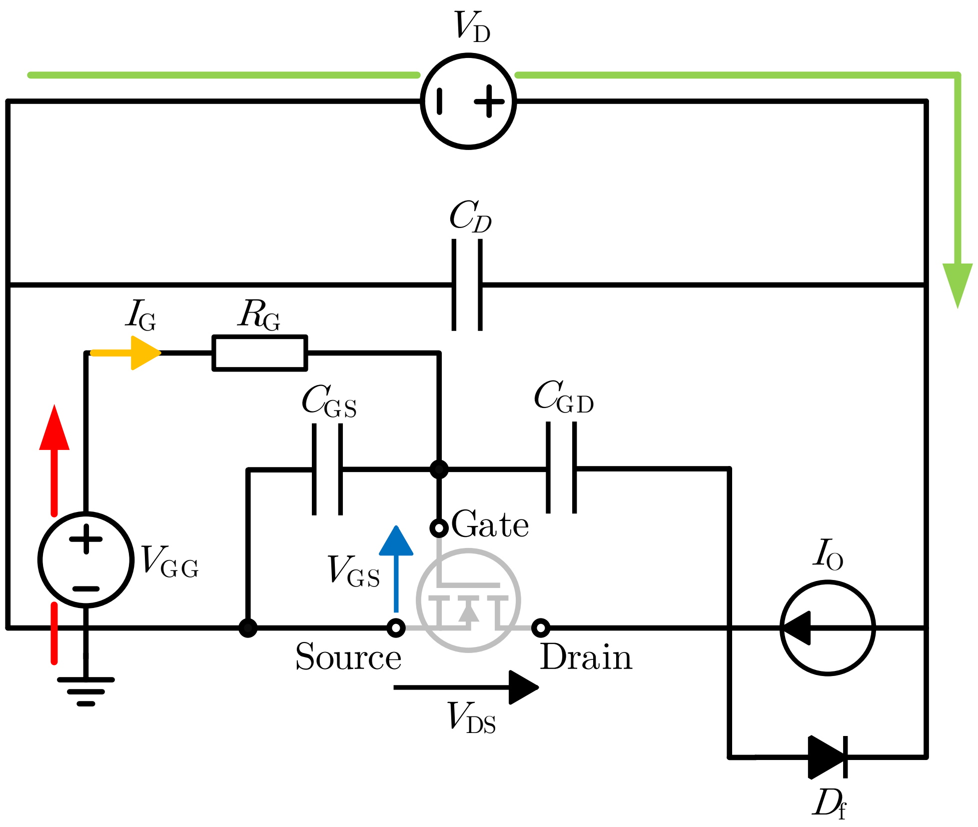


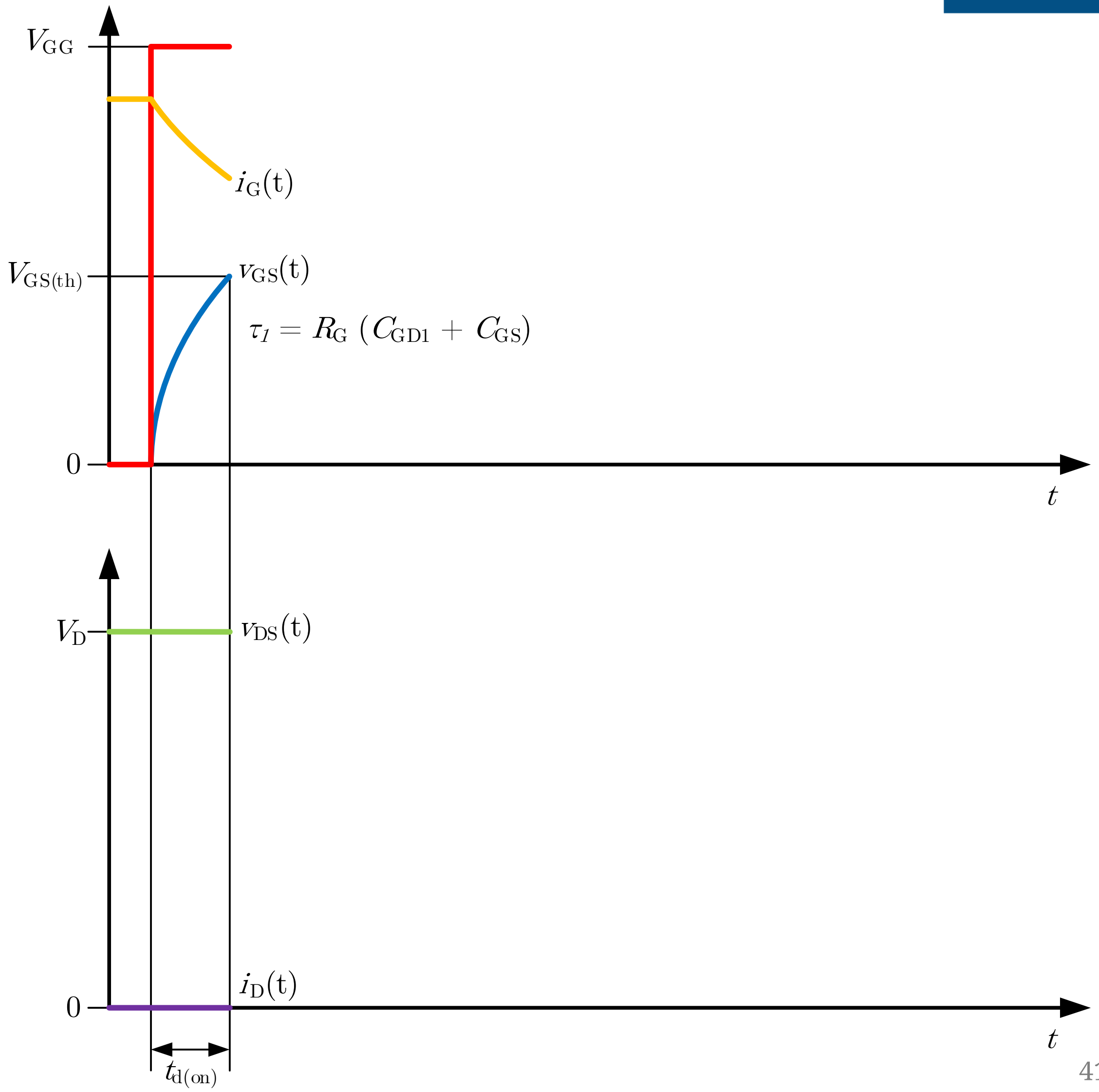
- Transient thermal response curve [13]

[13] https://www.onsemi.com/pdf/datasheet/fqp13n10-d.pdf

MOSFETs – switching losses

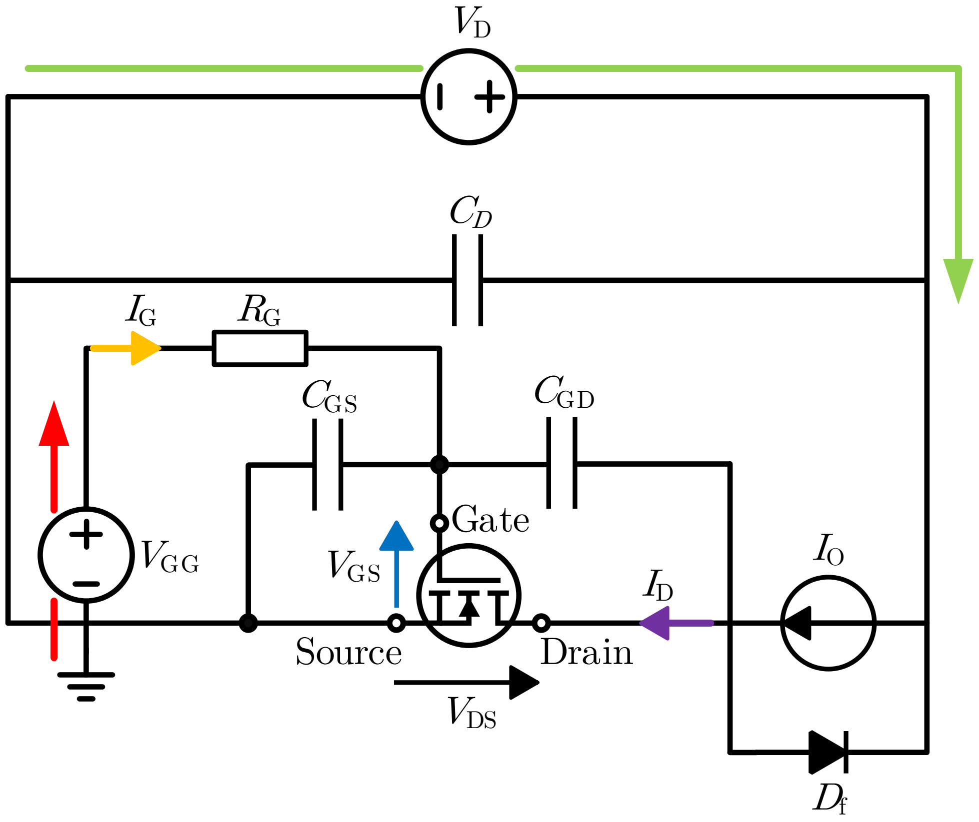
- Voltage (V_{GG}) applied at the gate.
- Capacitors (C_{GS} and C_{GD}) charge up.

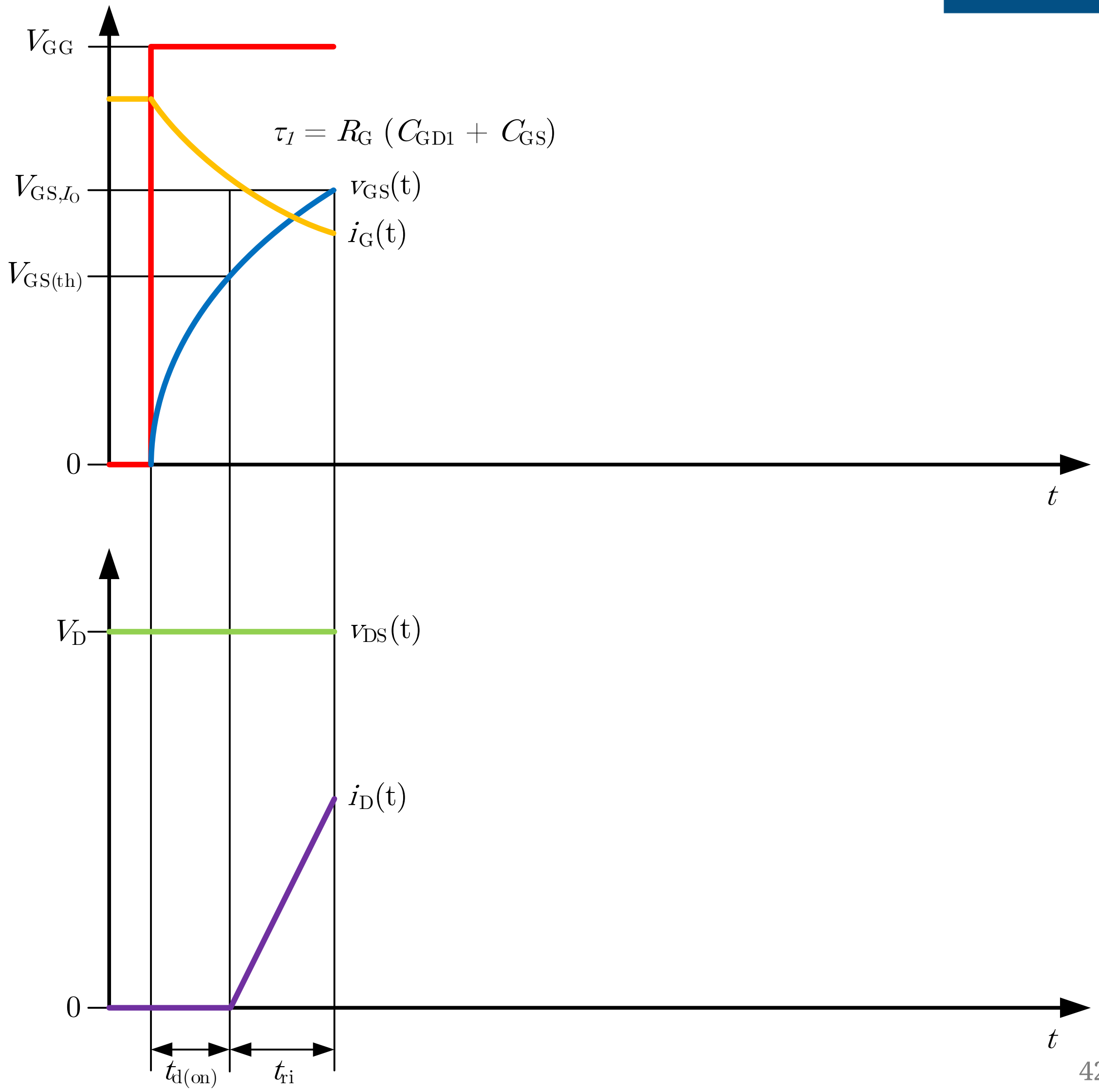




MOSFETs – switching losses

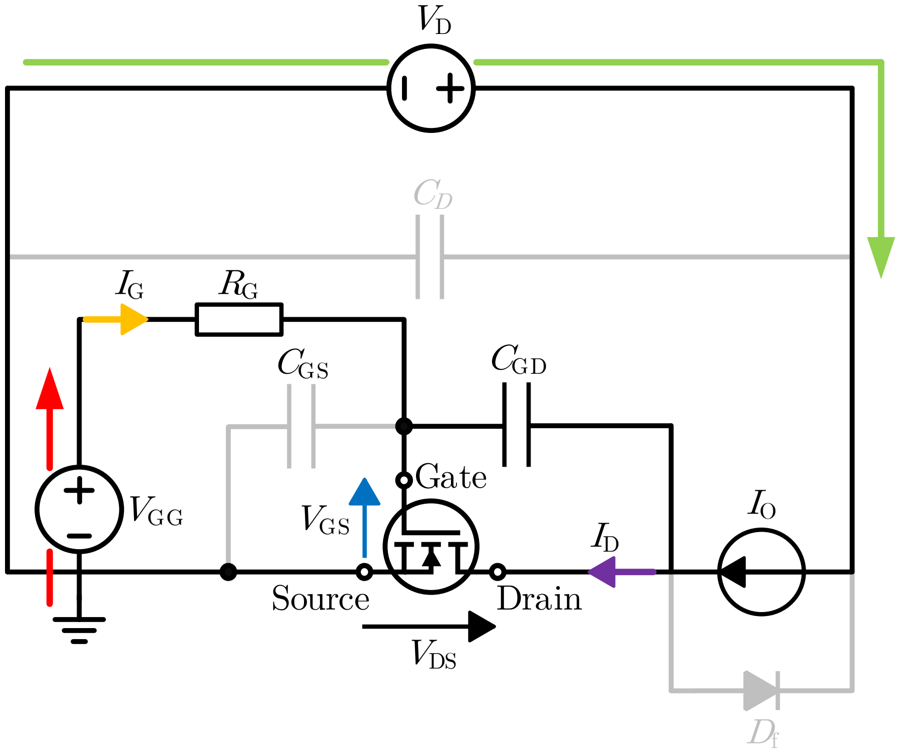
- Threshold voltage ($V_{GS(TH)}$) is reached.
- Switch starts conducting current (I_D).

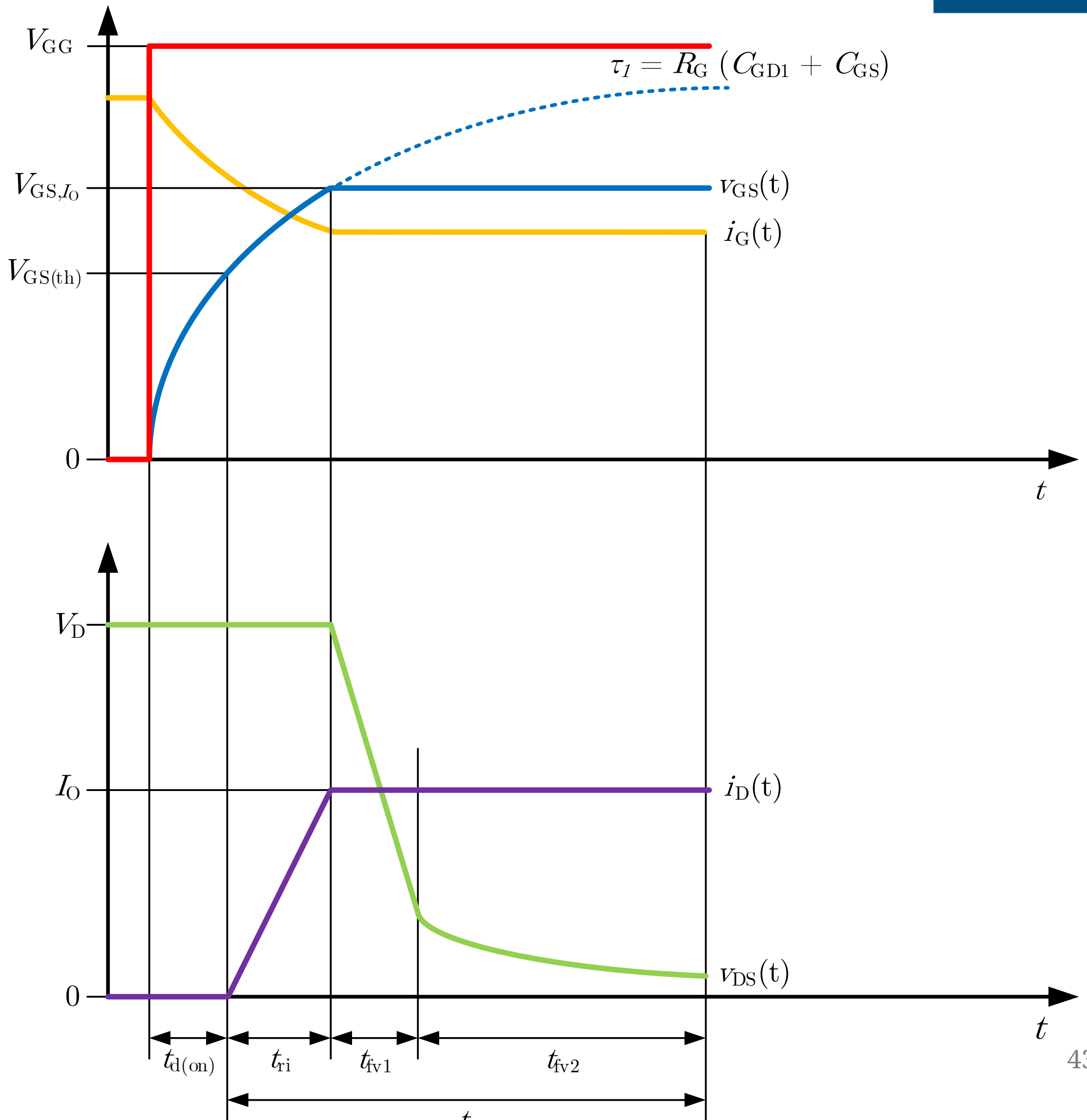




MOSFETs – switching losses

- All I_O into the switch as I_D.
- No current through D_f and C_{GS}.
- v_{DS} reduces as switch is fully turned on. This is the transition from ohmic region to active region.





MOSFETs – switching losses

- V_{GS} continues to rise towards V_{GG}.
- Switch fully on so $V_{DS(ON)} = I_D R_{DS(ON)}$.