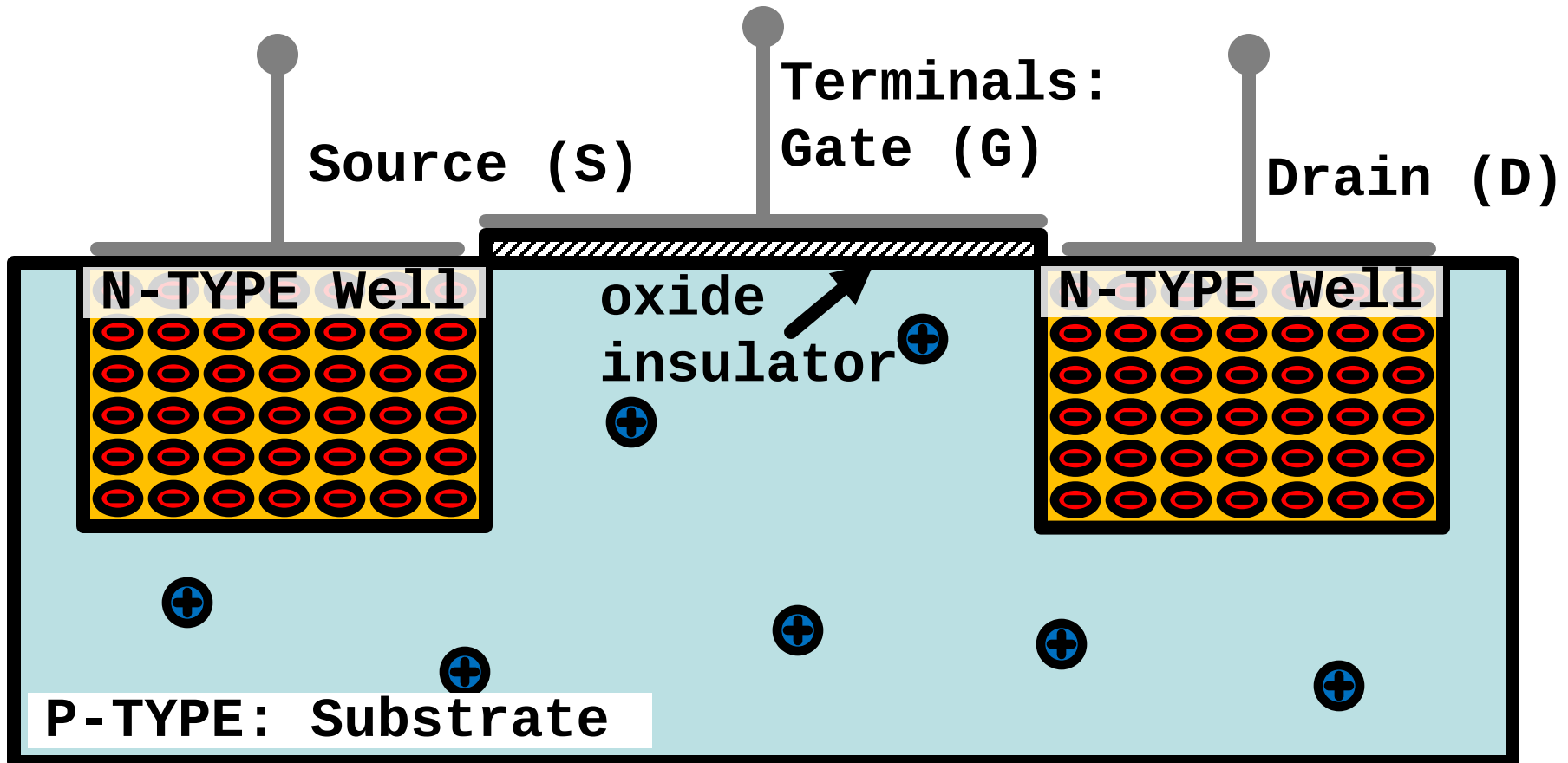


MOSFET - Structure

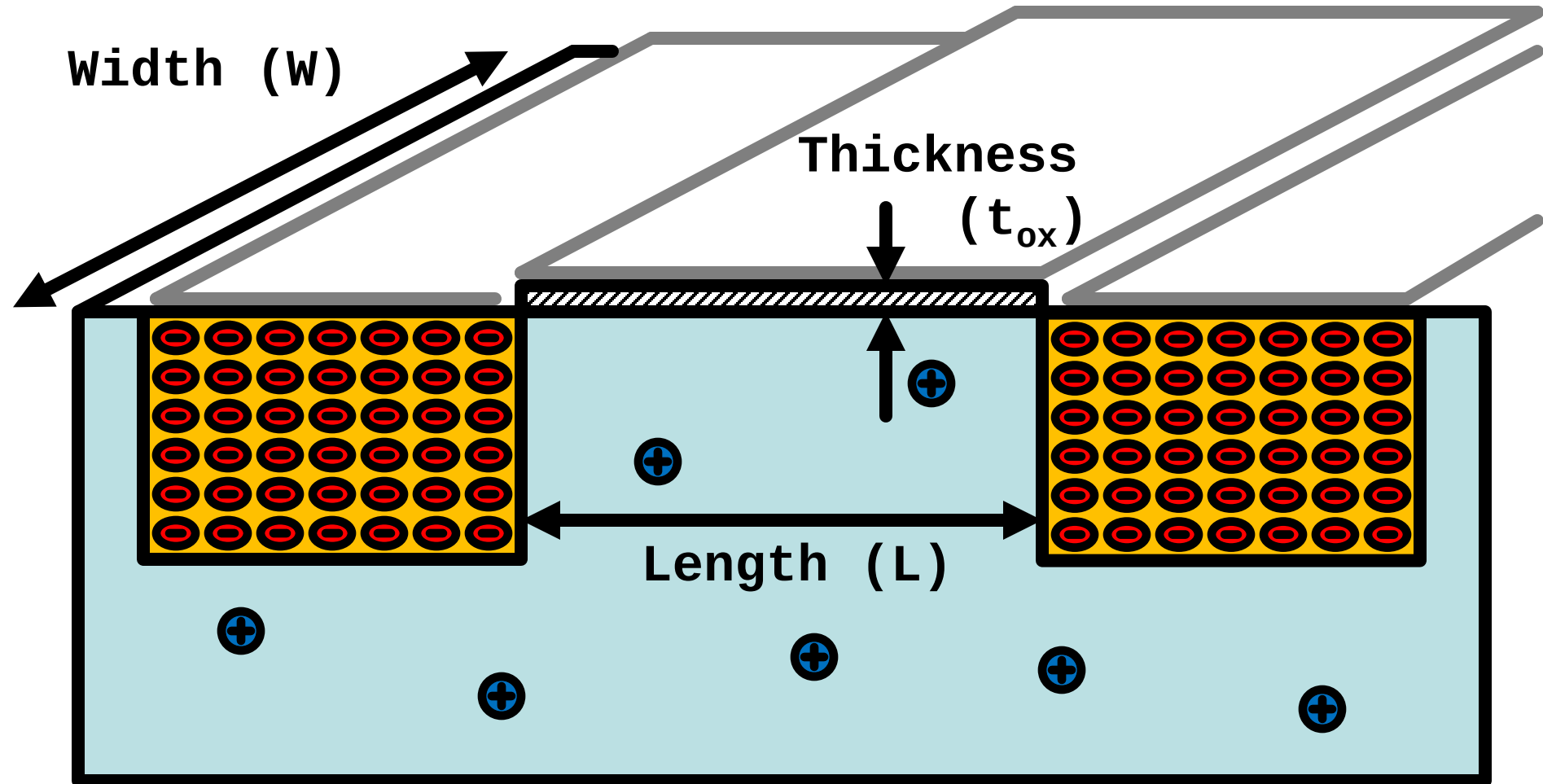
Properties

Oxide Insulator: $\epsilon_{ox} =$

N-Type: $\mu_n =$

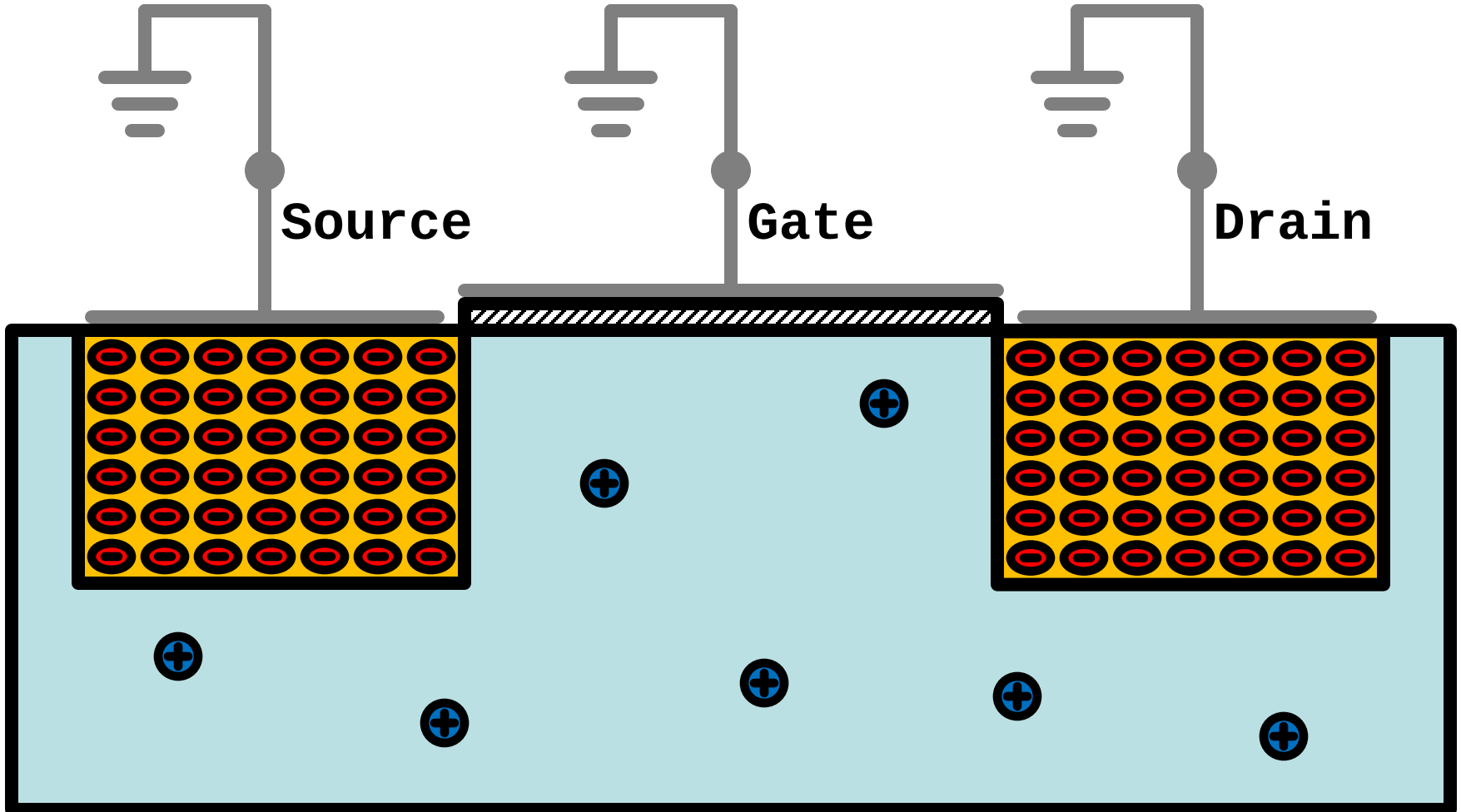


MOSFET - Dimensions

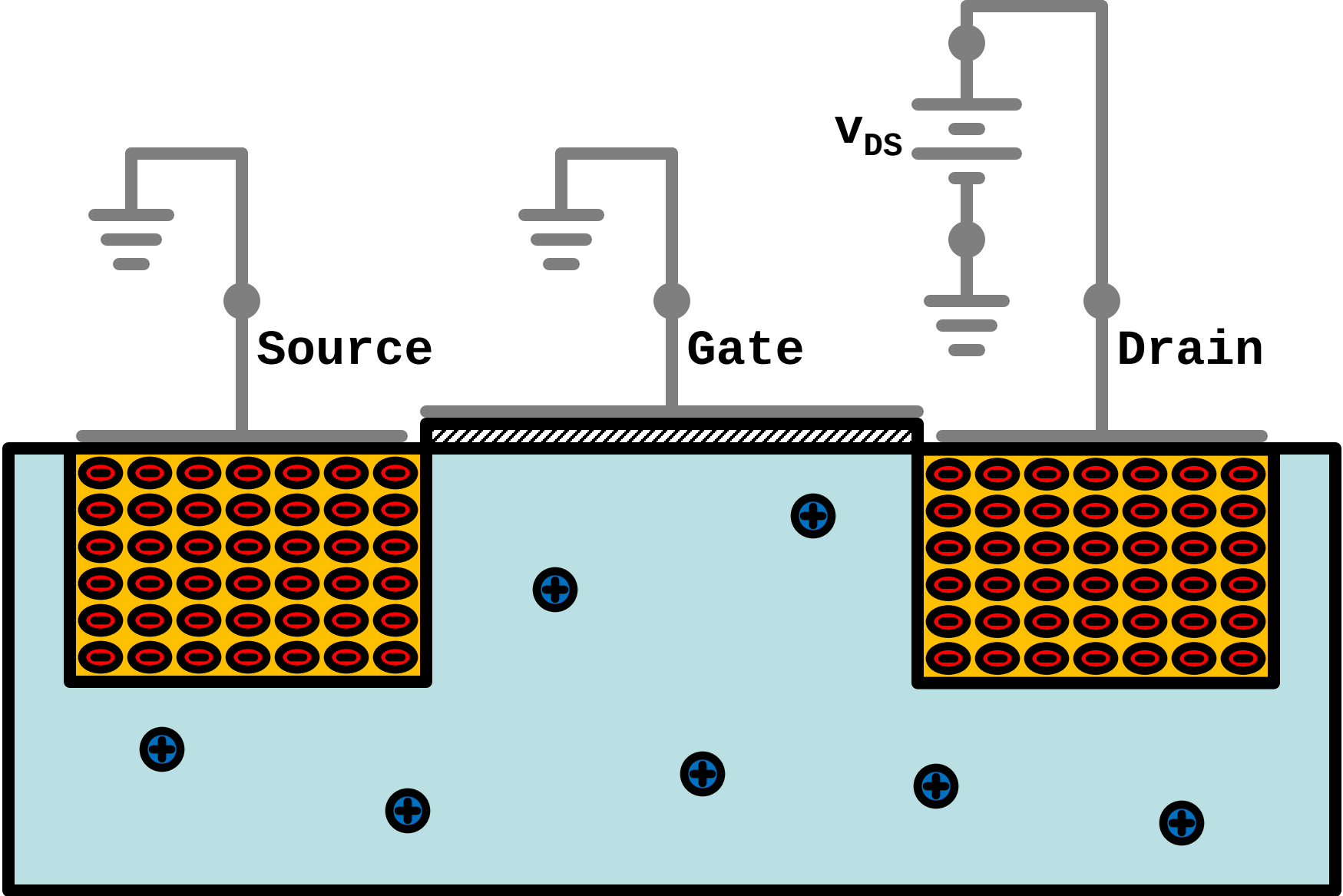


MOSFET – Operation and Modes

No current flows into the gate.
Try to make current flow into the drain.

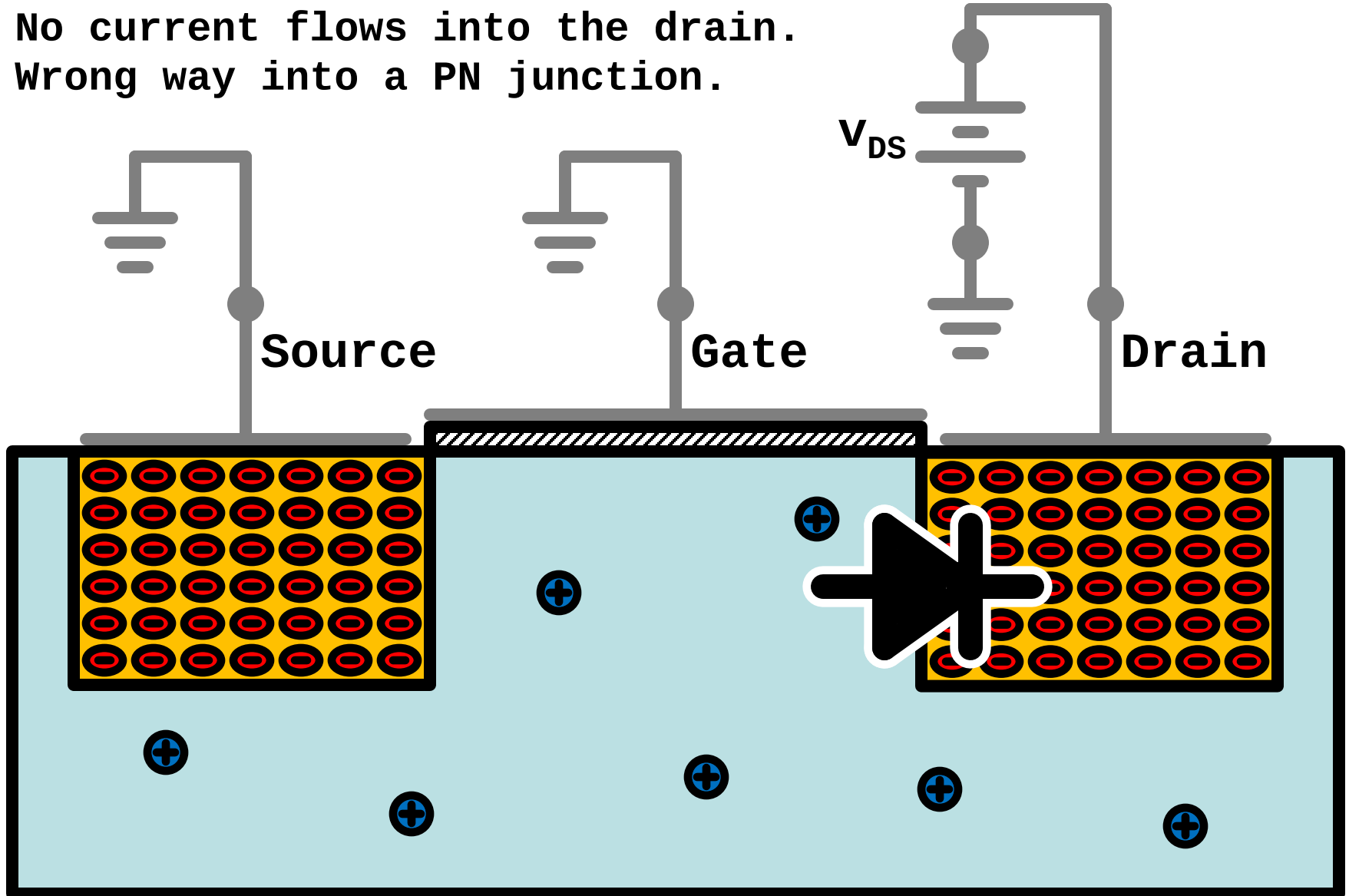


The diagram illustrates the physical structure and electrical connections of a MOSFET. The device is shown in cross-section, with a light blue substrate containing several blue circles with plus signs, representing acceptor ions. A central channel region is defined by a hatched area. On either side of the channel are two yellow regions, each containing a grid of red circles with minus signs, representing donor ions. The electrical connections are shown above the device: the Source is connected to ground, the Gate is connected to ground, and the Drain is connected to a positive voltage source V_{DS} .



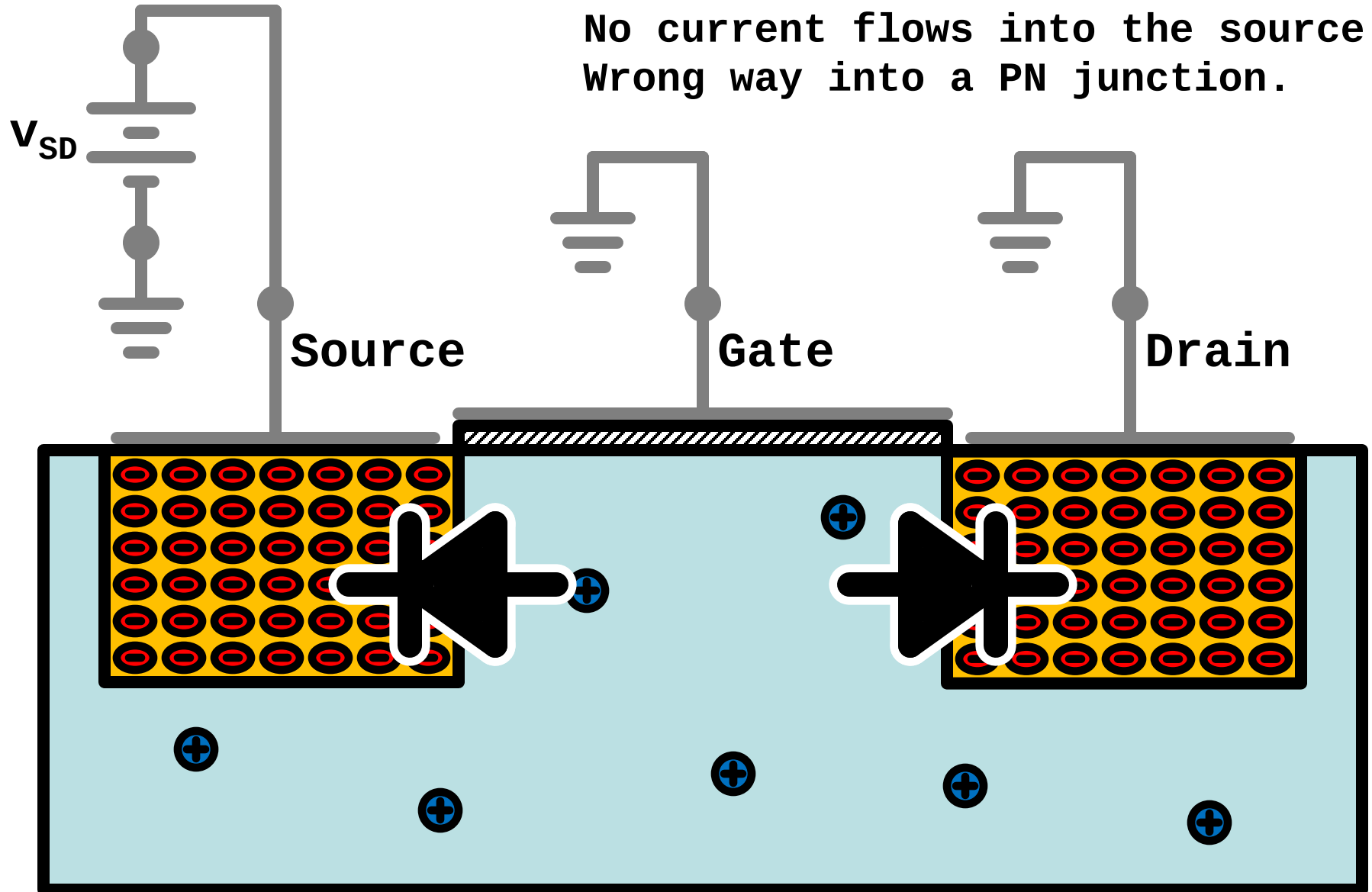
MOSFET – Operation and Modes

No current flows into the drain.
Wrong way into a PN junction.



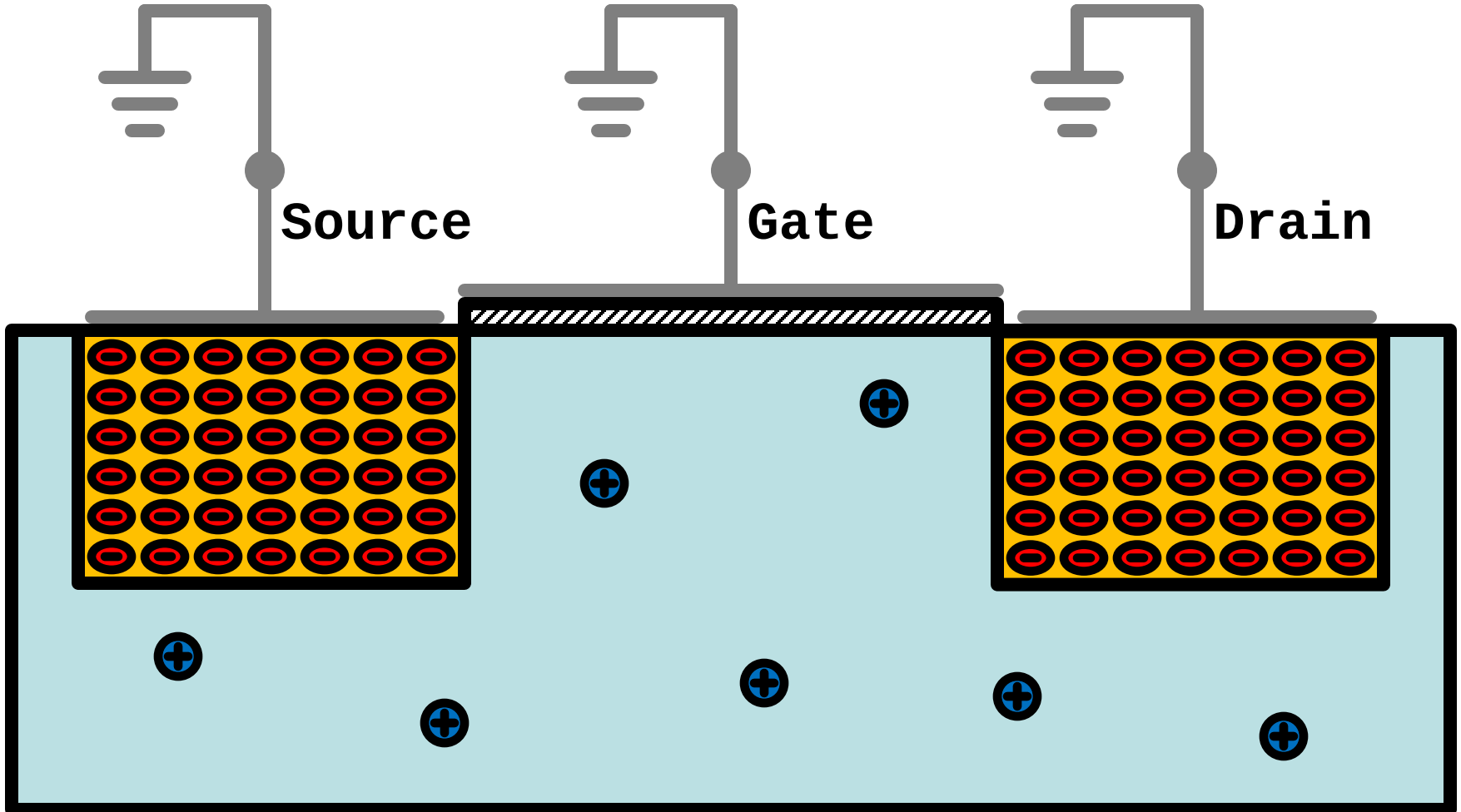
MOSFET – Operation and Modes

No current flows into the source.
Wrong way into a PN junction.



MOSFET – Operation and Modes

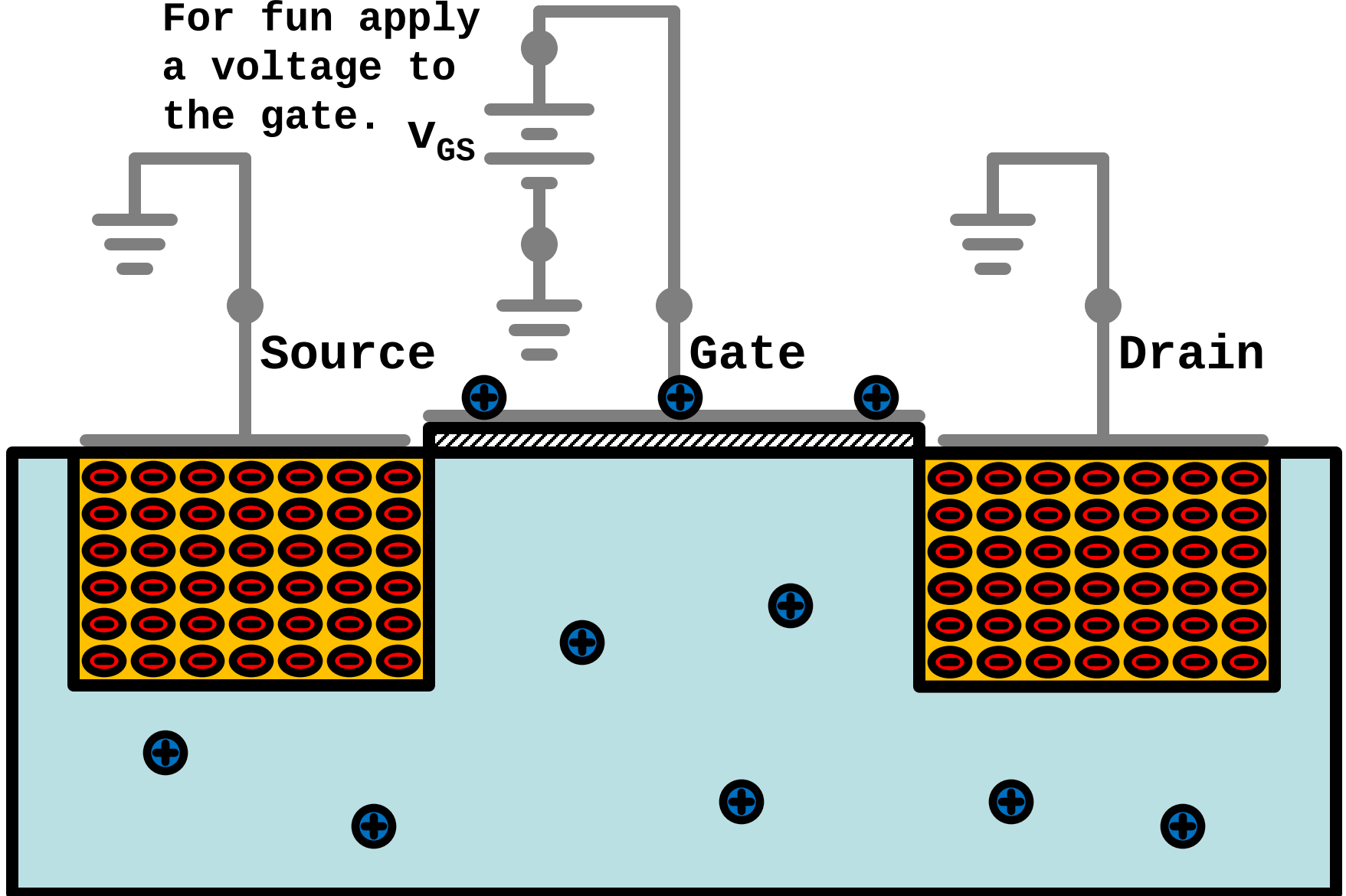
For fun apply a voltage to the gate.



MOSFET – Operation and Modes

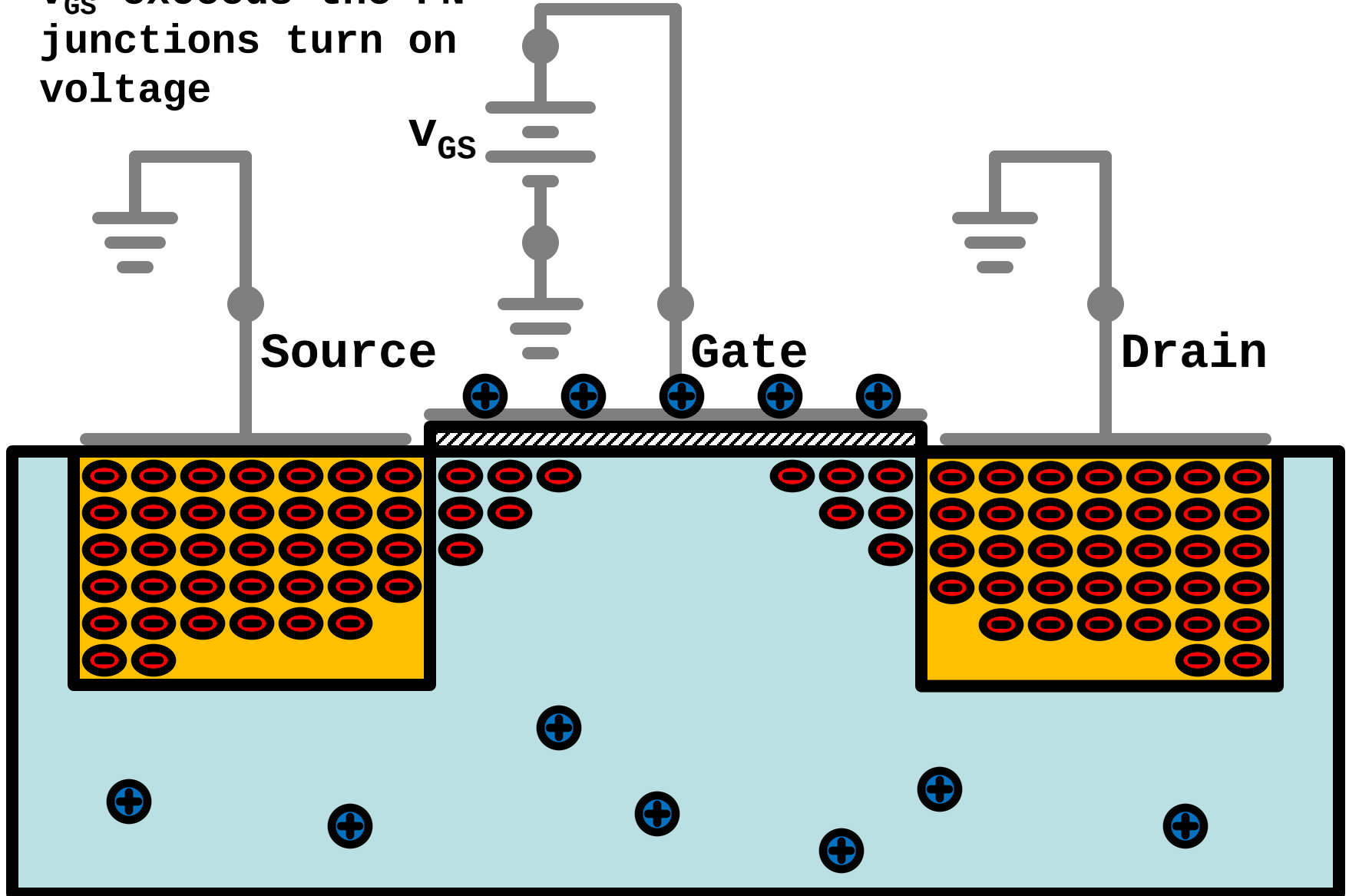
For fun apply
a voltage to
the gate.

V_{GS}



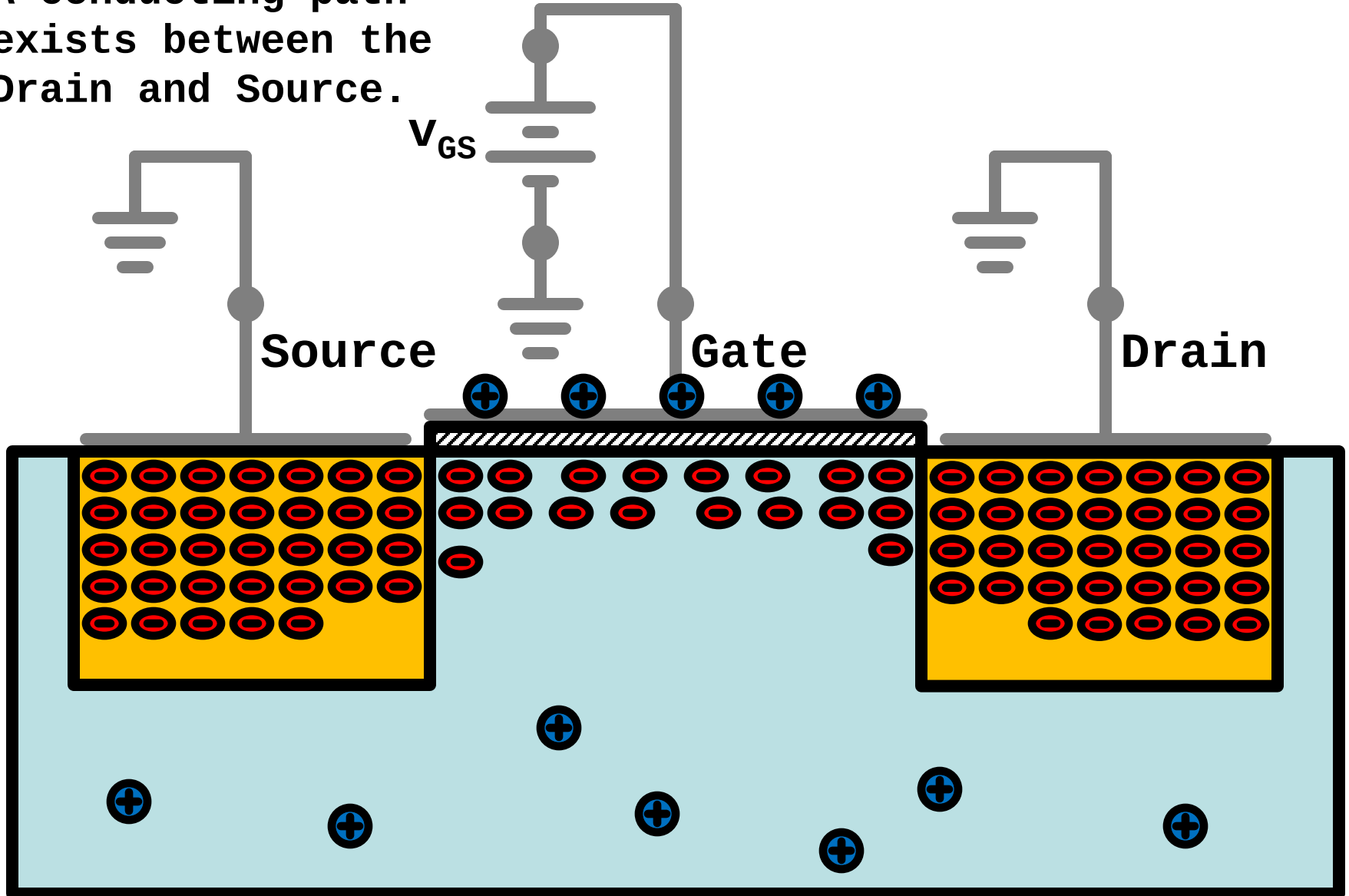
MOSFET – Operation and Modes

V_{GS} exceeds the PN junctions turn on voltage



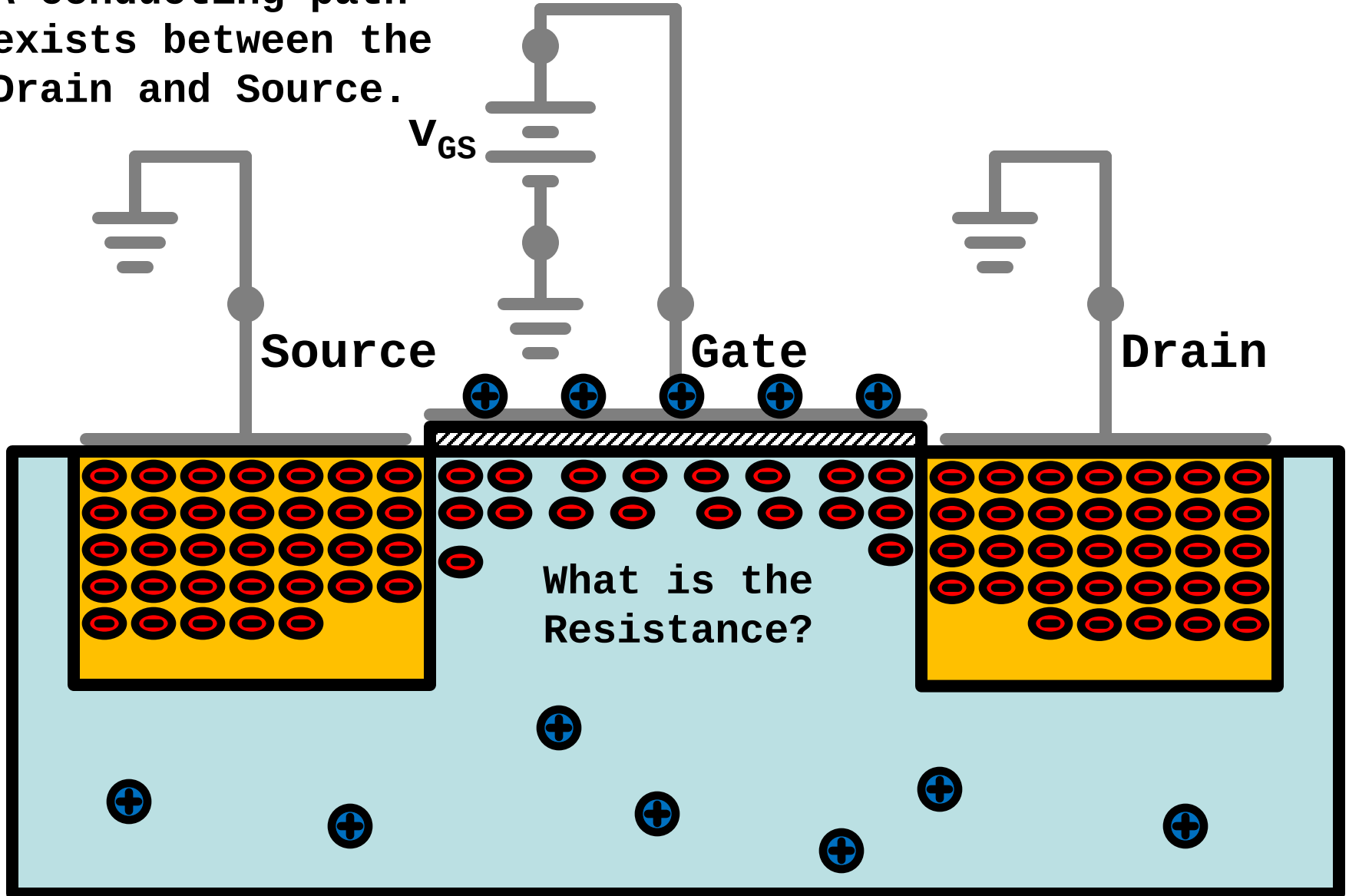
MOSFET – Operation and Modes

A conducting path exists between the Drain and Source.



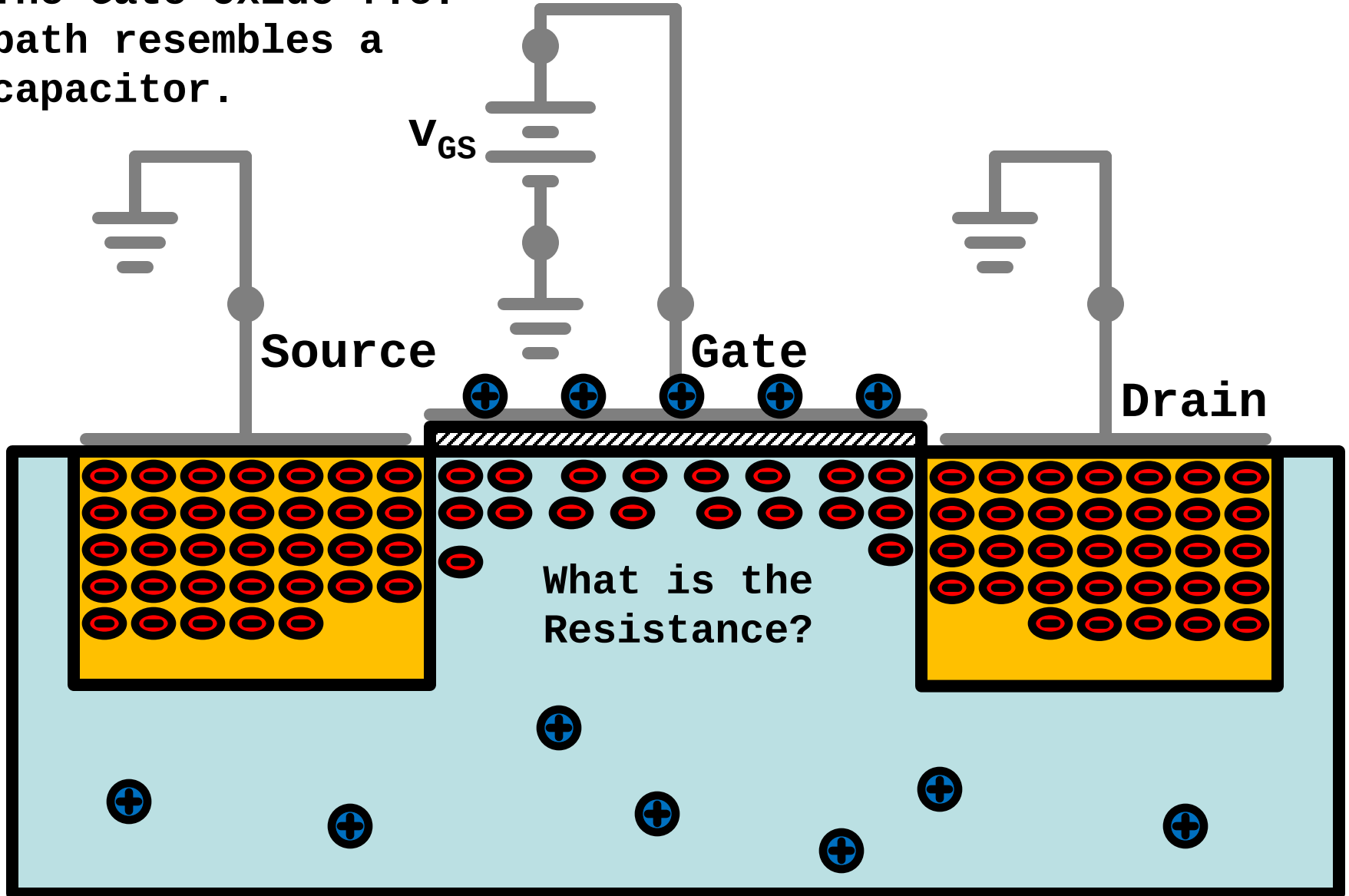
MOSFET – Operation and Modes

A conducting path exists between the Drain and Source.



MOSFET – Operation and Modes

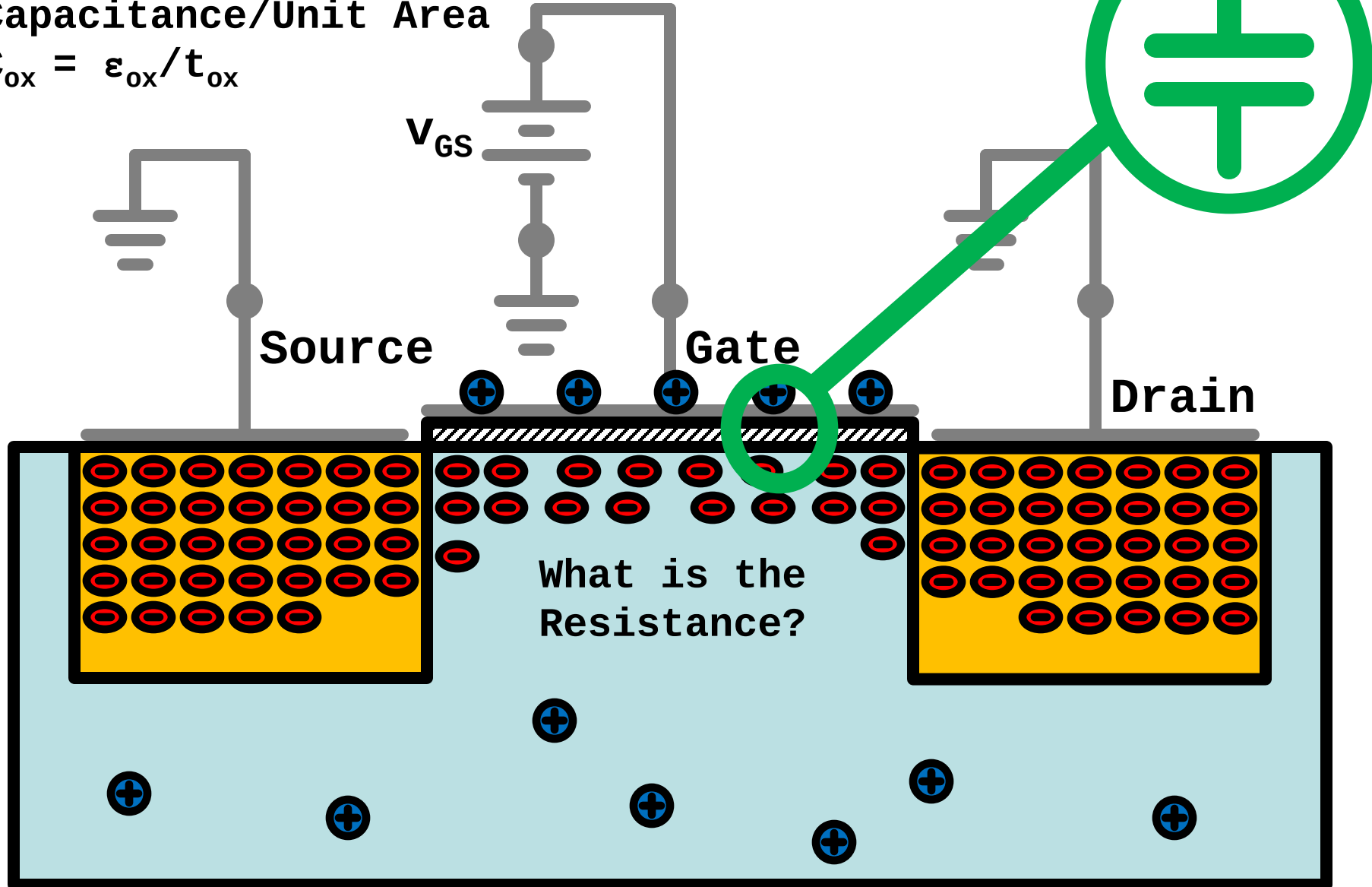
The Gate-Oxide-f.e.
path resembles a
capacitor.



MOSFET – Operation and Modes

Capacitance/Unit Area

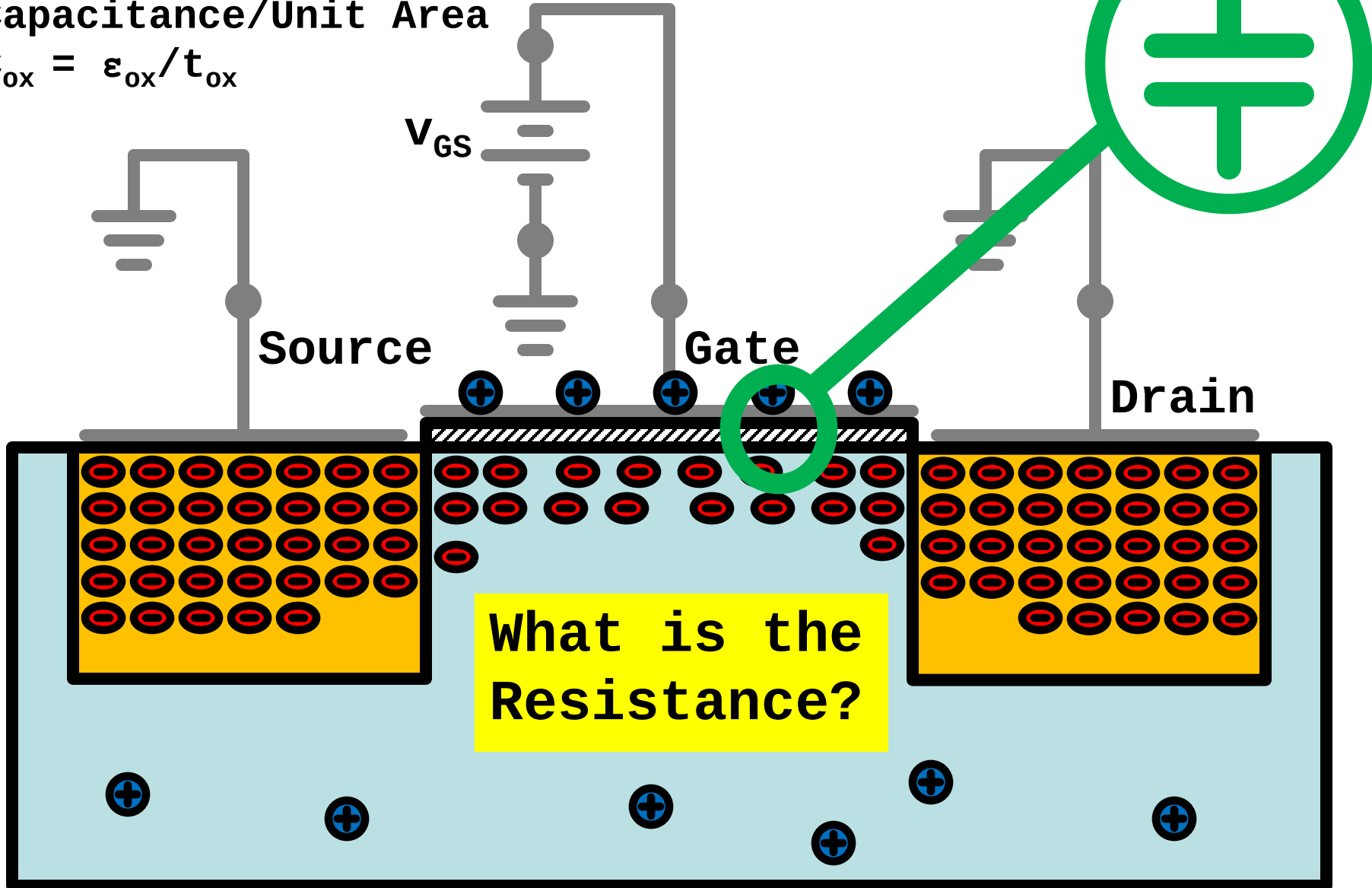
$$C_{ox} = \epsilon_{ox} / t_{ox}$$



MOSFET – Operation and Modes

Capacitance/Unit Area

$$C_{ox} = \epsilon_{ox} / t_{ox}$$



Resistance Calculation

V_{GS} exceeds the
PN junctions turn
on voltage, V_t .

Resistance of uniform charge distribution:

$$R = \text{Length} / ((\text{mobility}) \cdot (\text{charge per unit length}))$$

Capacitance/Unit Area: $C_{ox} = \epsilon_{ox} / t_{ox}$

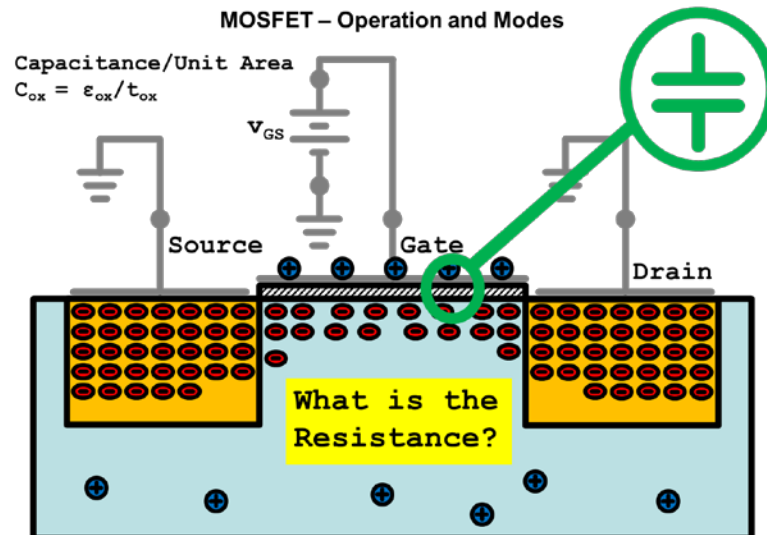
Area = $W \cdot L$ (from MOSFET Dimensions Slide)

Total Capacitance: $C = C_{ox} \cdot \text{Area} = (C_{ox} \cdot W \cdot L)$

Total Charge ($Q = C \cdot V$): $Q = (C_{ox} \cdot W \cdot L) \cdot (V_{GS} - V_t)$

charge per unit length = $Q/L = (C_{ox} \cdot W) \cdot (V_{GS} - V_t)$

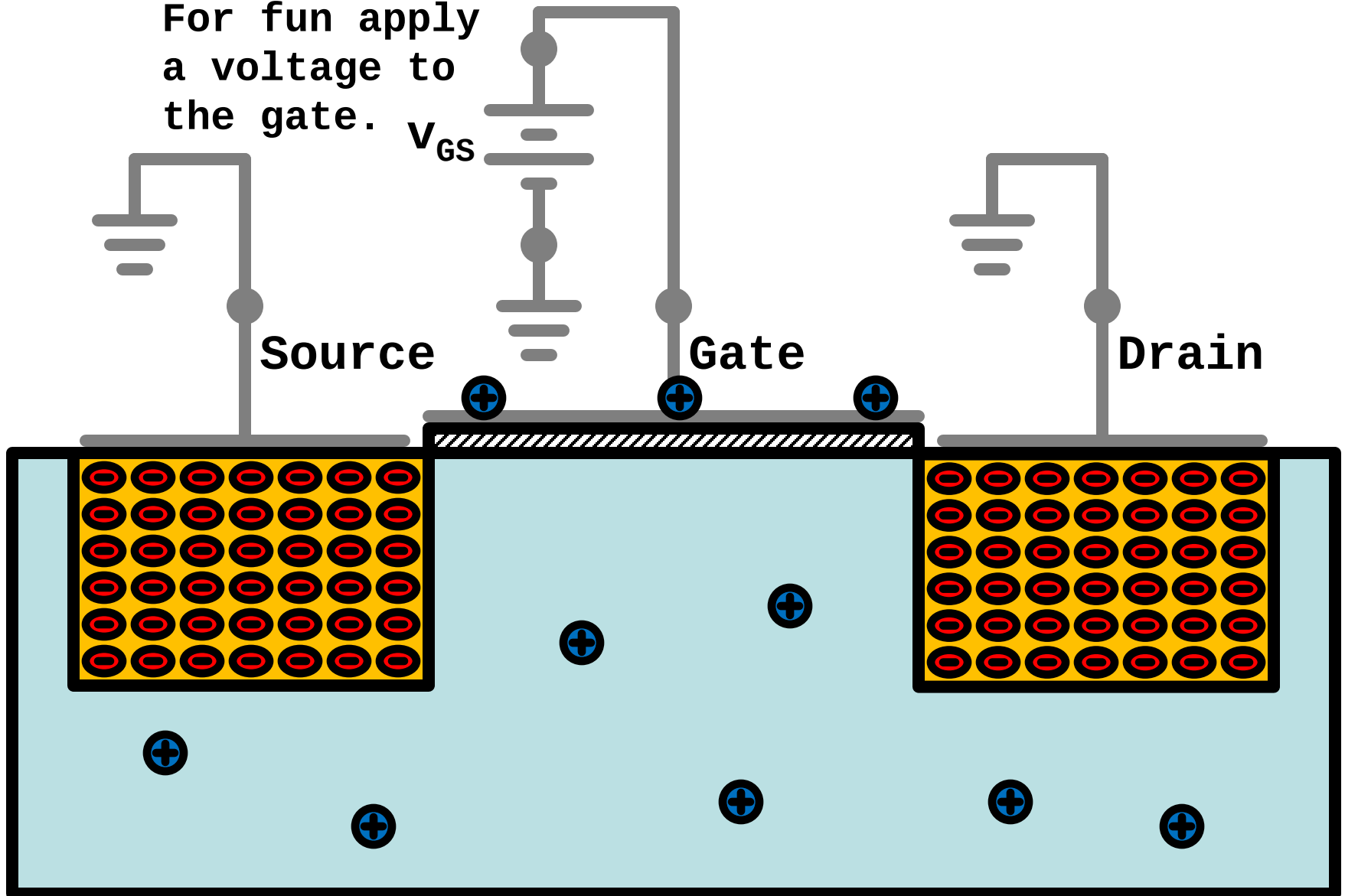
$$R = L / (\mu_n \cdot C_{ox} \cdot W \cdot (V_{GS} - V_t))$$



MOSFET – Review channel shape

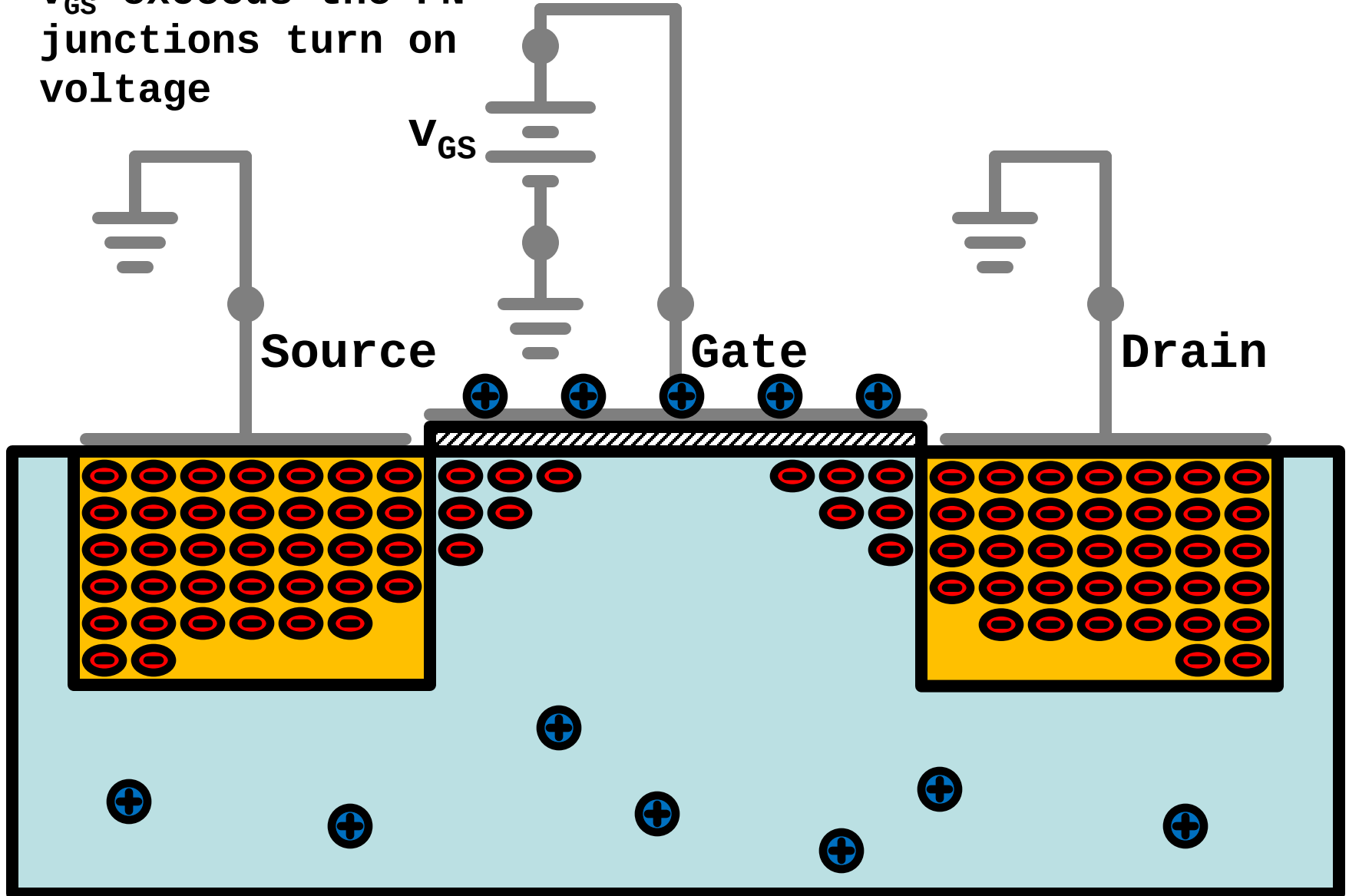
For fun apply
a voltage to
the gate.

V_{GS}



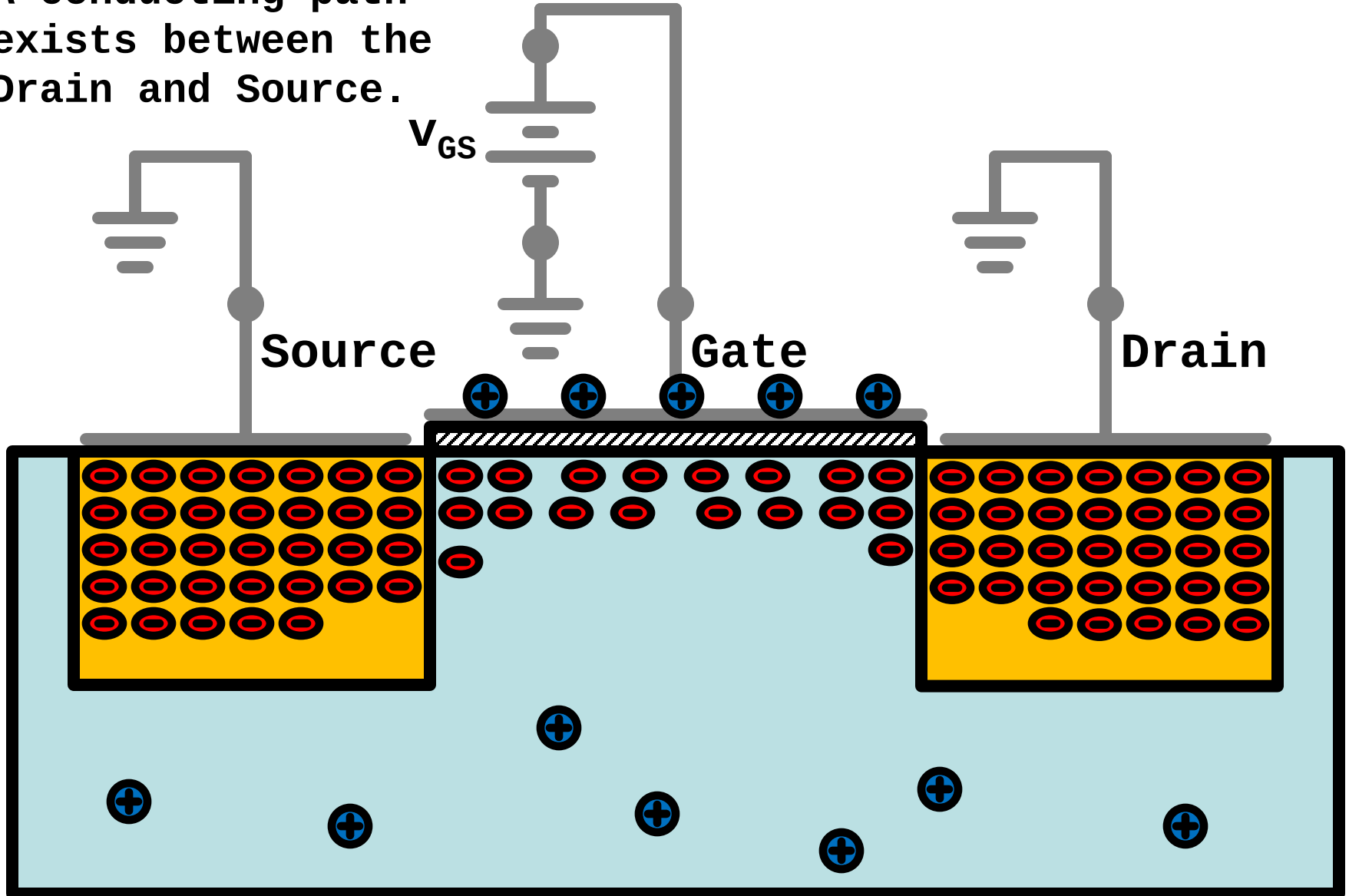
MOSFET – Operation and Modes

V_{GS} exceeds the PN junctions turn on voltage



MOSFET – Operation and Modes

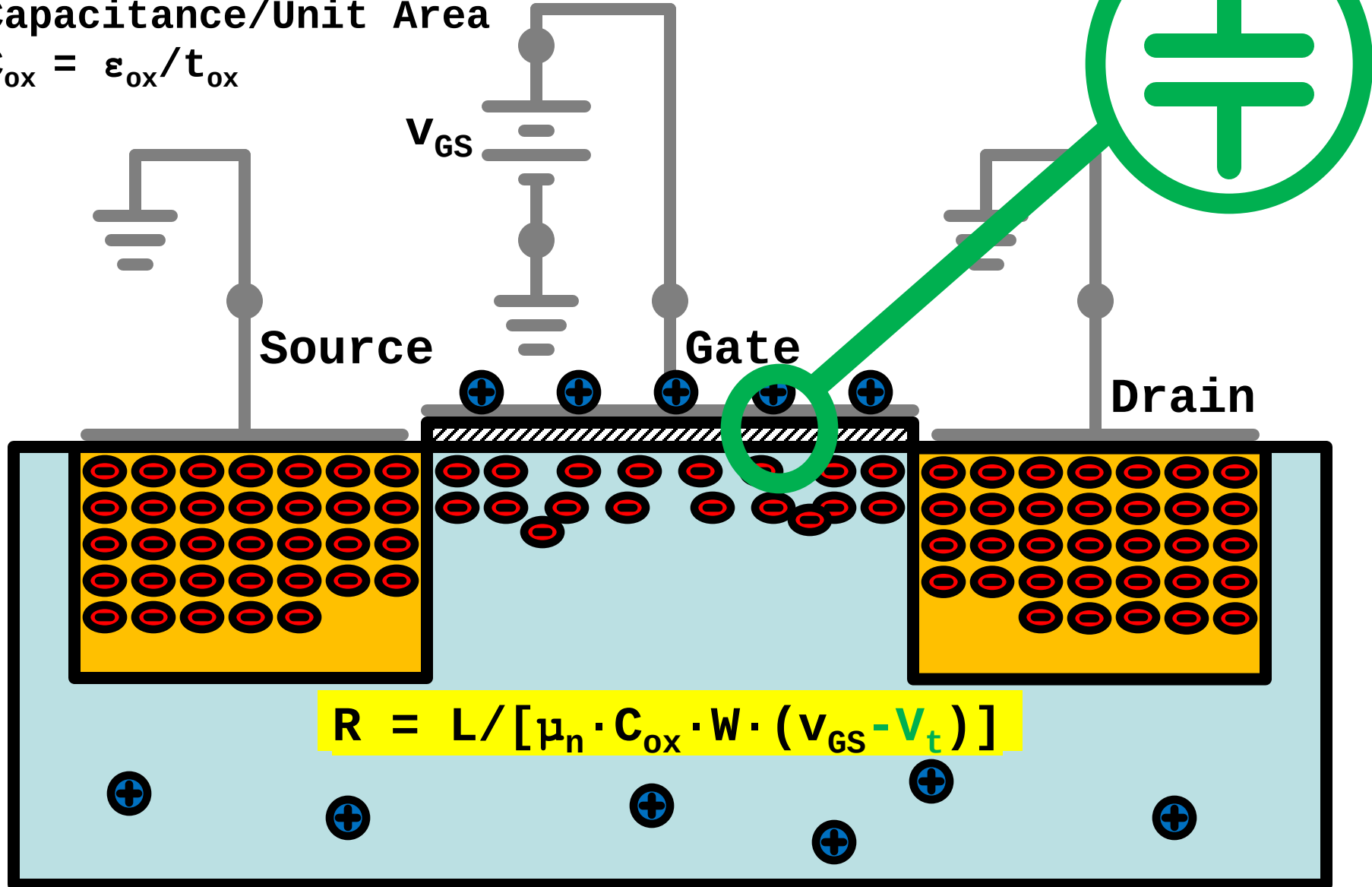
A conducting path exists between the Drain and Source.



MOSFET – Operation and Modes

Capacitance/Unit Area

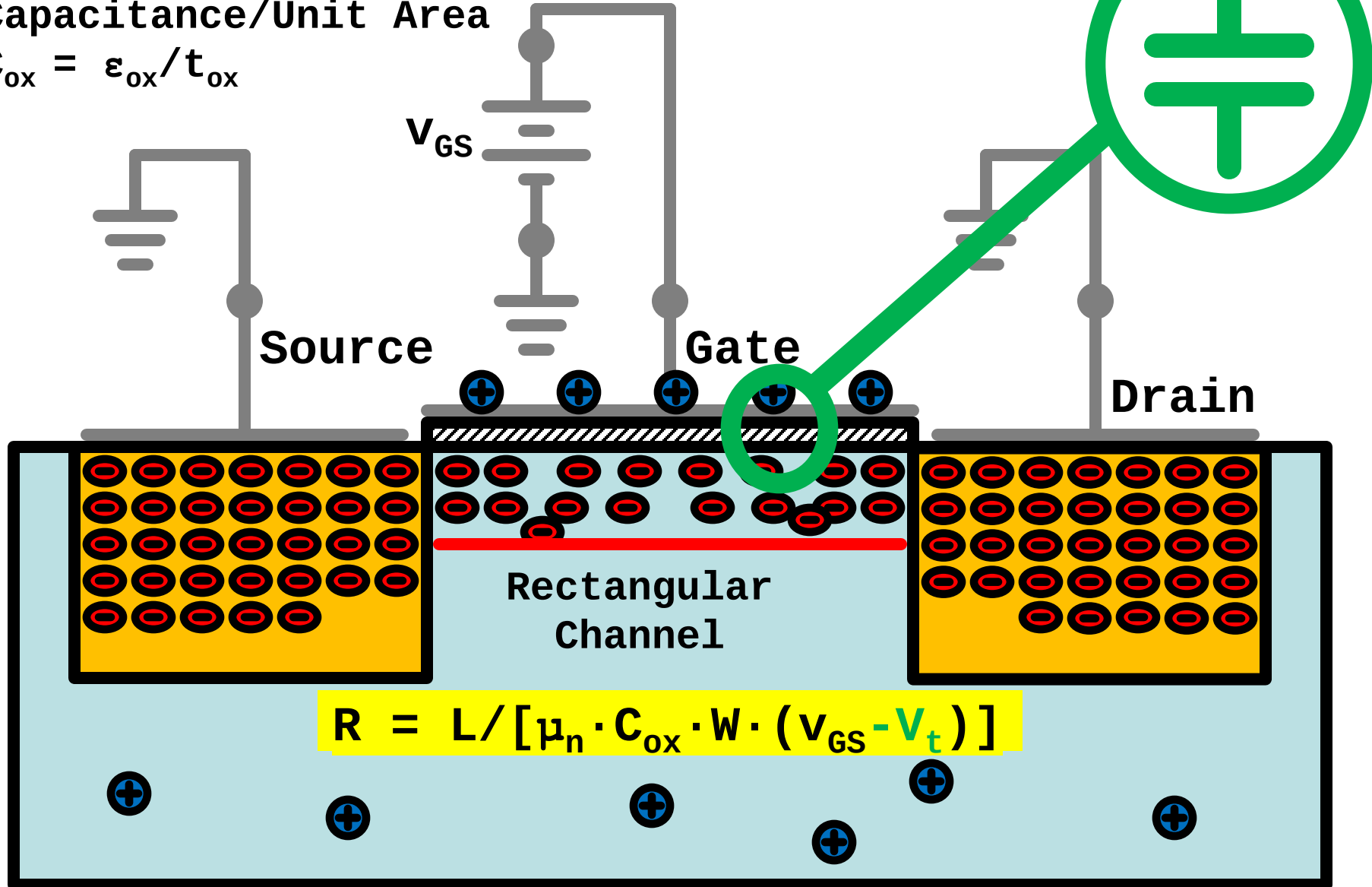
$$C_{ox} = \epsilon_{ox} / t_{ox}$$



MOSFET – Operation and Modes

Capacitance/Unit Area

$$C_{ox} = \epsilon_{ox} / t_{ox}$$





Gate



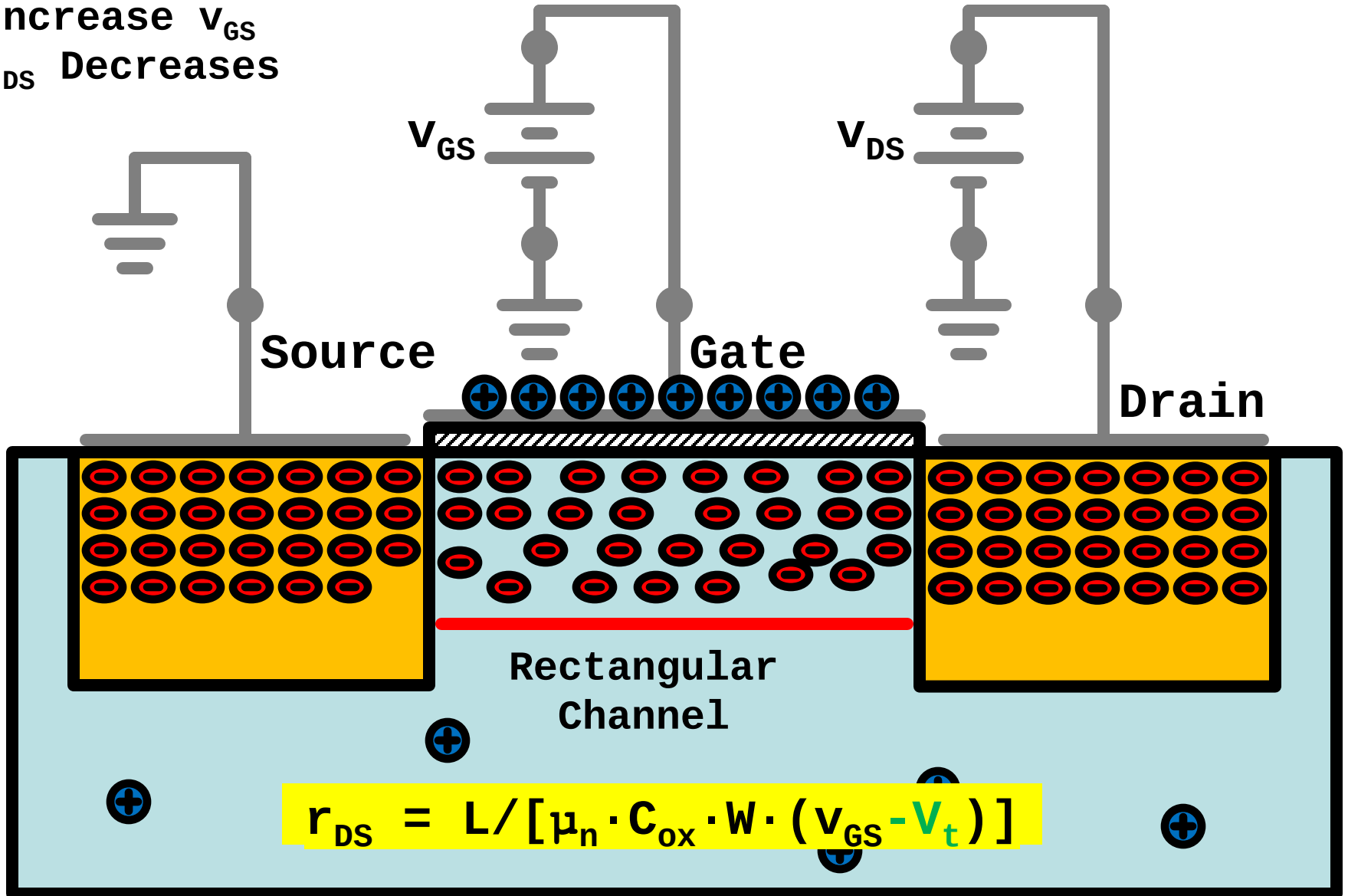
The diagram illustrates a MOSFET structure. The top gate region is divided into three sections: a left yellow region, a central light blue region labeled "Rectangular Channel", and a right yellow region. The channel region contains a red horizontal line and a green semi-circular arrow pointing to the right, representing electron flow. The source and drain regions are represented by yellow rectangles on the left and right, each containing a grid of red circles with black outlines. The substrate is light blue and contains several blue circles with black outlines and a plus sign, representing acceptor ions. A yellow box in the center contains the formula for resistance R :

$$R = L / [\mu_n \cdot C_{ox} \cdot W \cdot (V_{GS} - V_t)]$$

$$R = L / [\mu_n \cdot C_{ox} \cdot W \cdot (V_{GS} - V_t)]$$

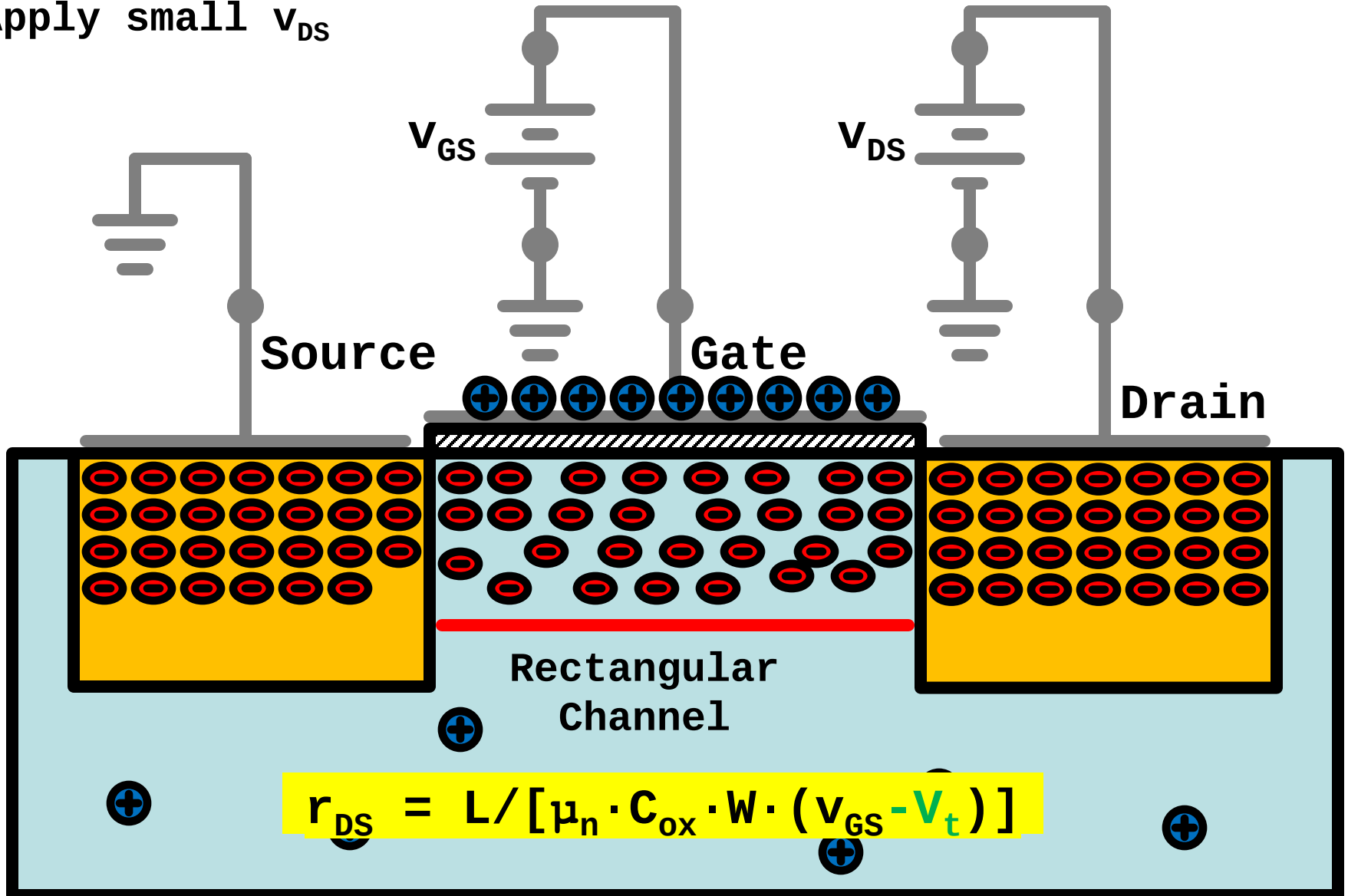
MOSFET – Operation and Modes

**Increase V_{GS}
 r_{DS} Decreases**



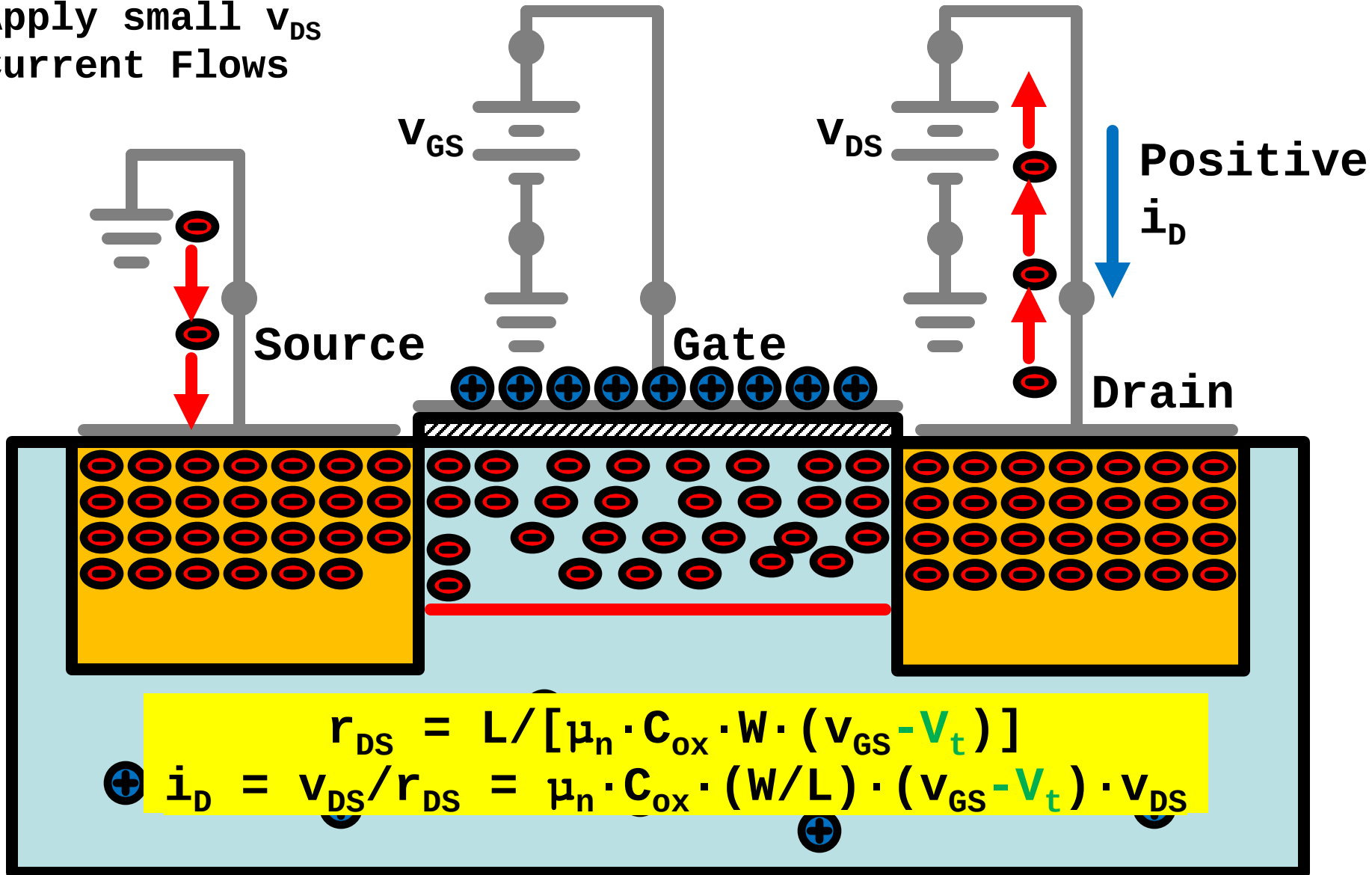
MOSFET – Operation and Modes

Apply small v_{DS}



MOSFET – Operation and Modes

Apply small v_{DS}
Current Flows

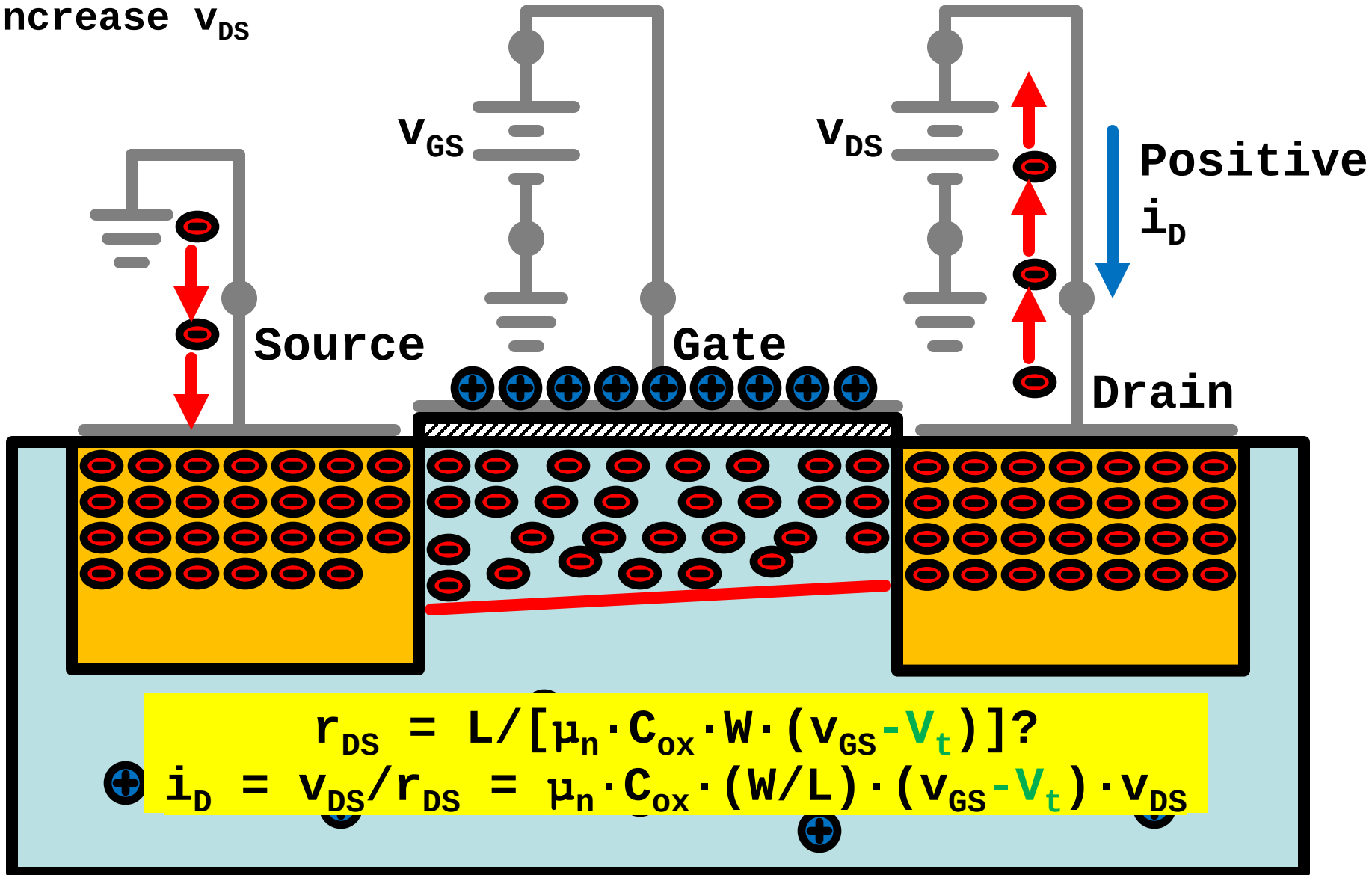


$$r_{DS} = L / [\mu_n \cdot C_{ox} \cdot W \cdot (v_{GS} - V_t)]$$

$$i_D = v_{DS} / r_{DS} = \mu_n \cdot C_{ox} \cdot (W/L) \cdot (v_{GS} - V_t) \cdot v_{DS}$$

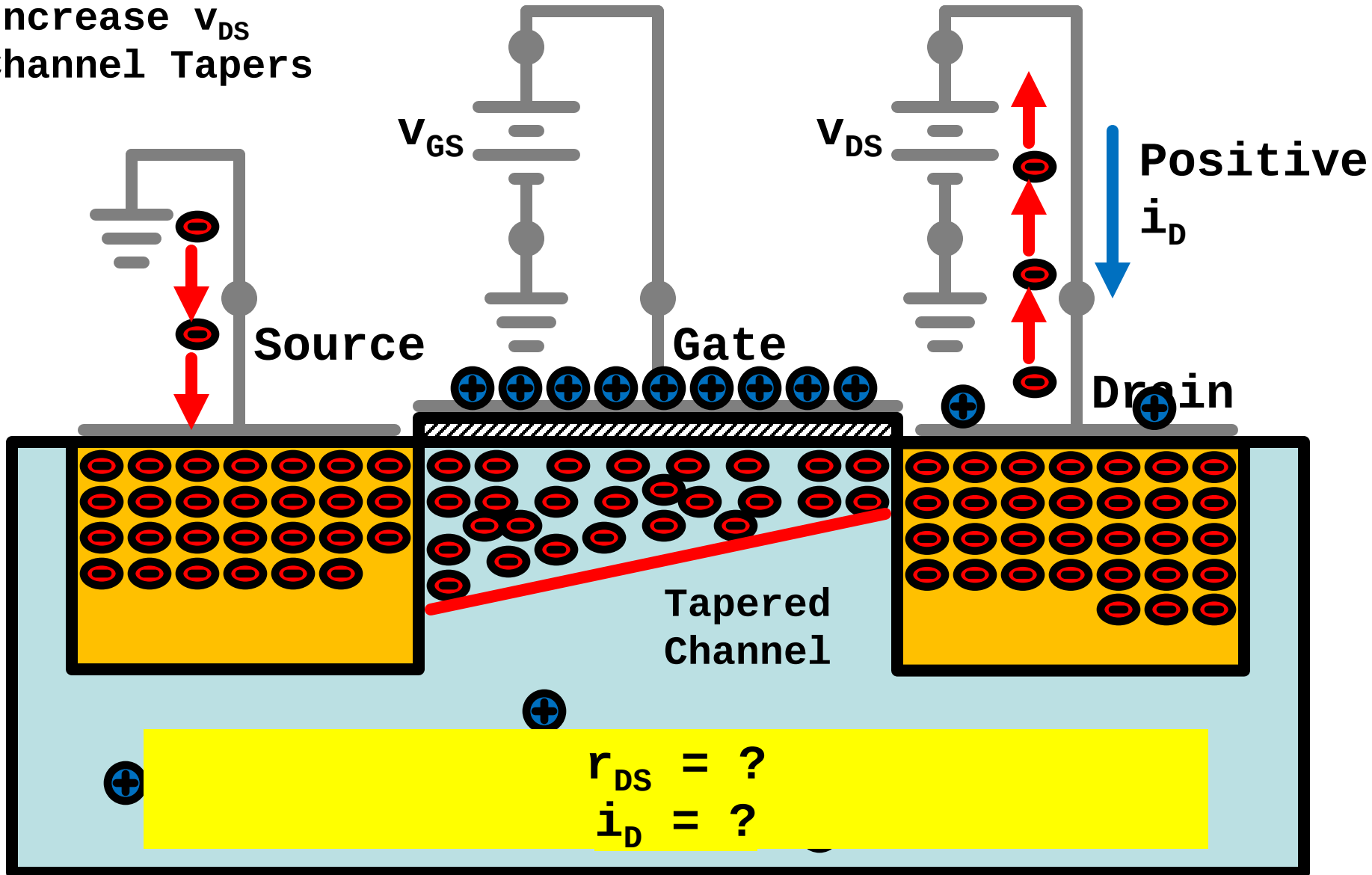
MOSFET – Operation and Modes

Increase V_{DS}



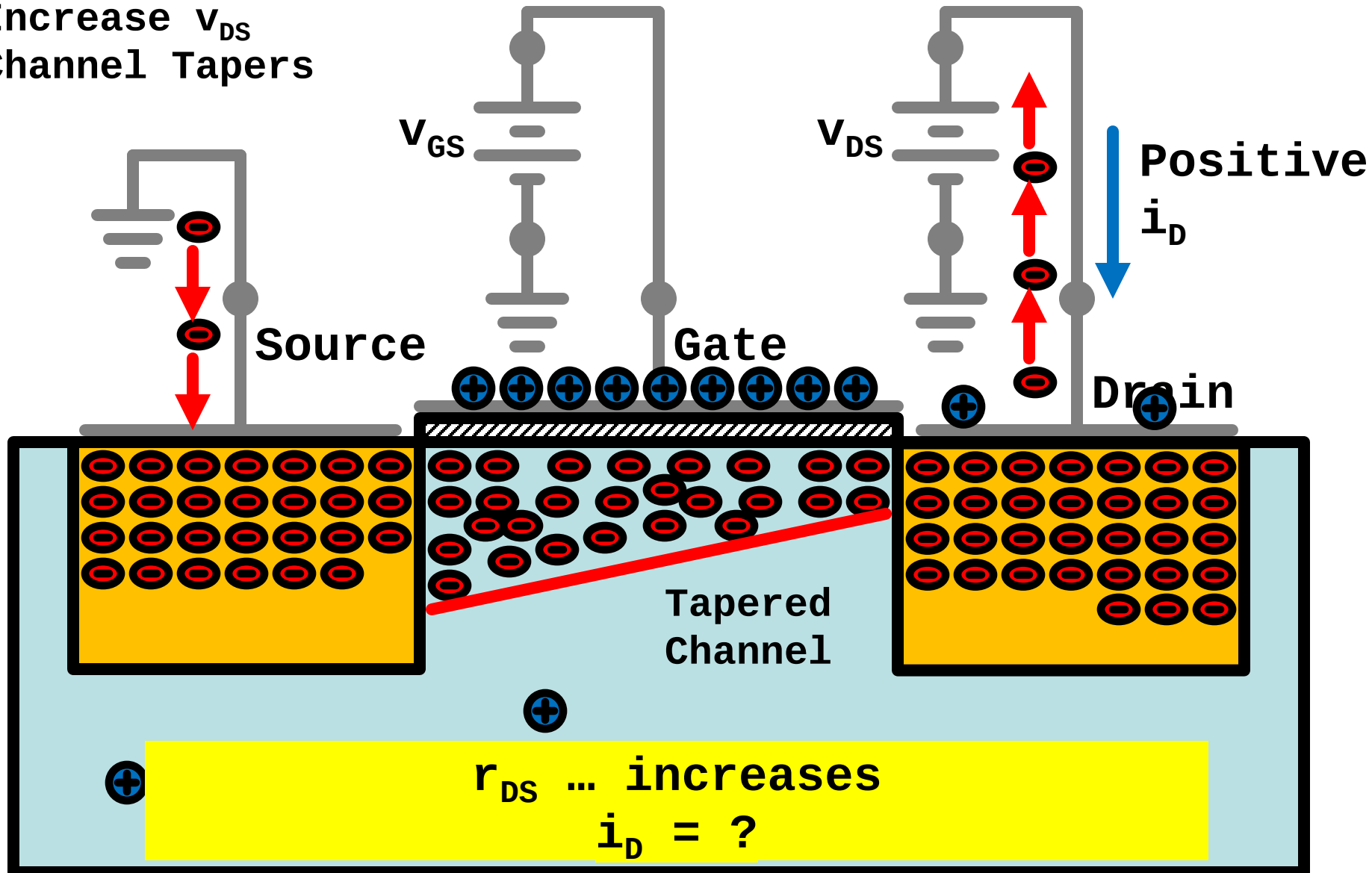
MOSFET – Operation and Modes

Increase V_{DS}
Channel Tapers



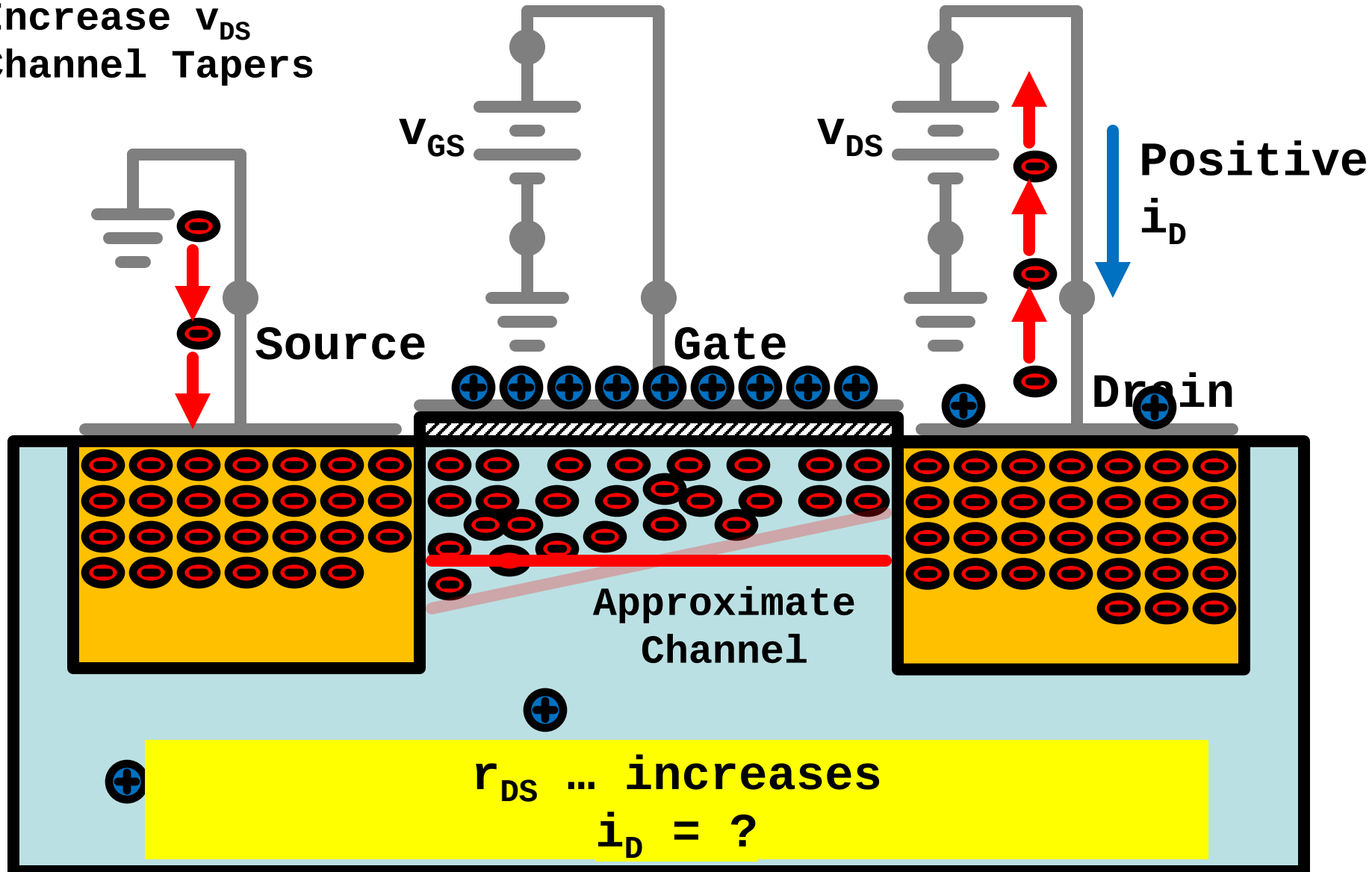
MOSFET – Operation and Modes

Increase V_{DS}
Channel Tapers



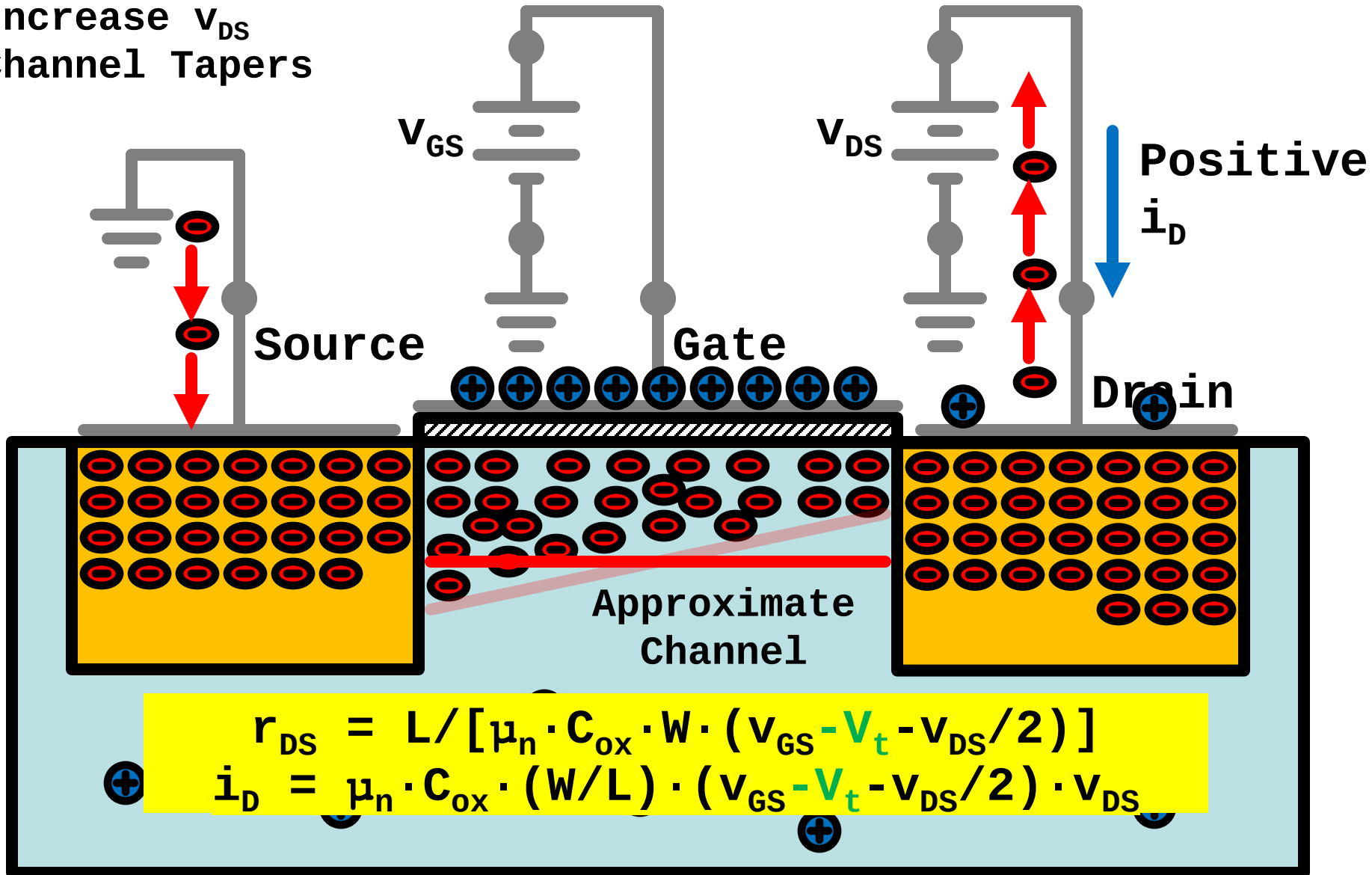
MOSFET – Operation and Modes

Increase V_{DS}
Channel Tapers



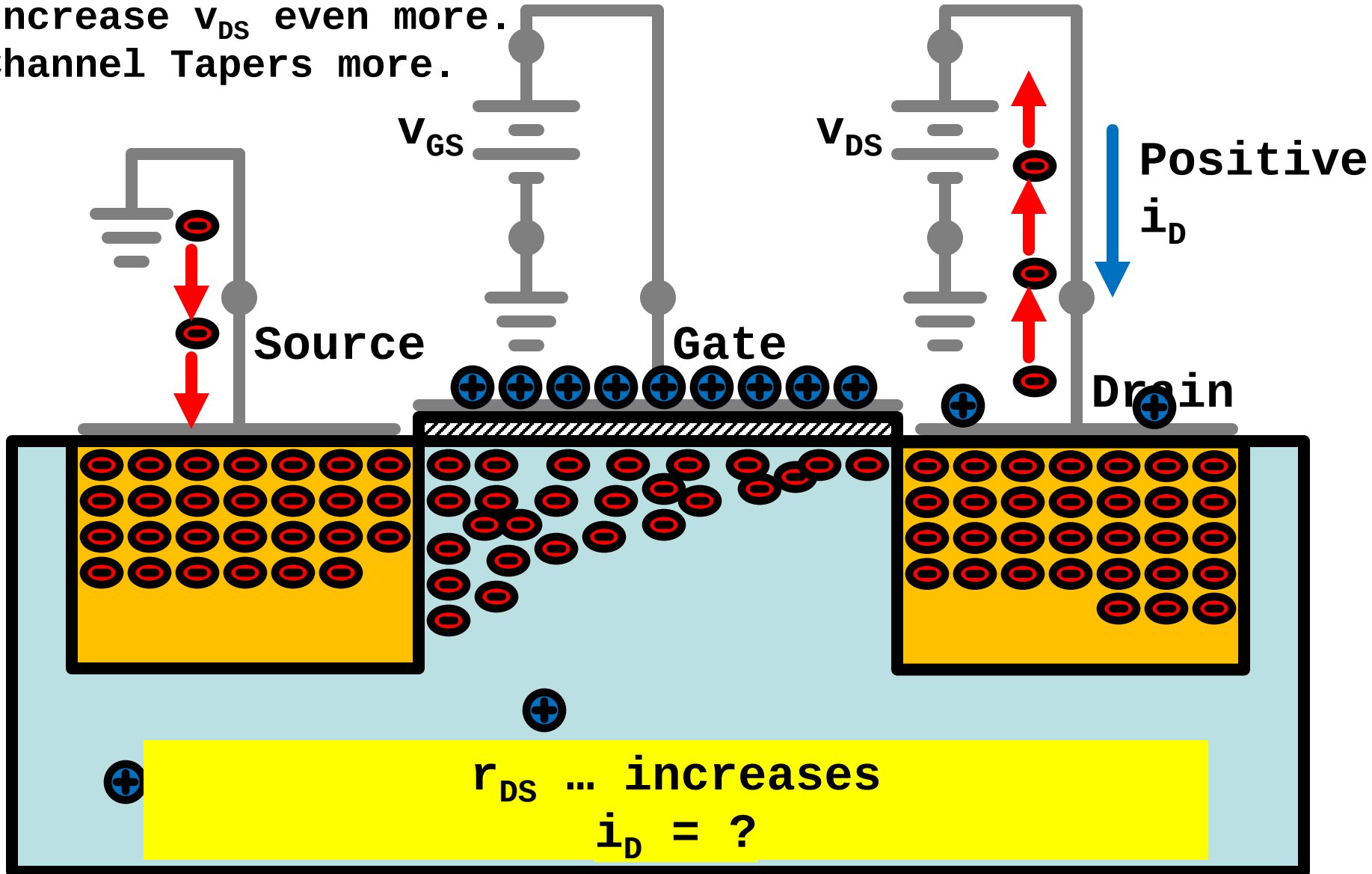
MOSFET – Operation and Modes

Increase V_{DS}
Channel Tapers



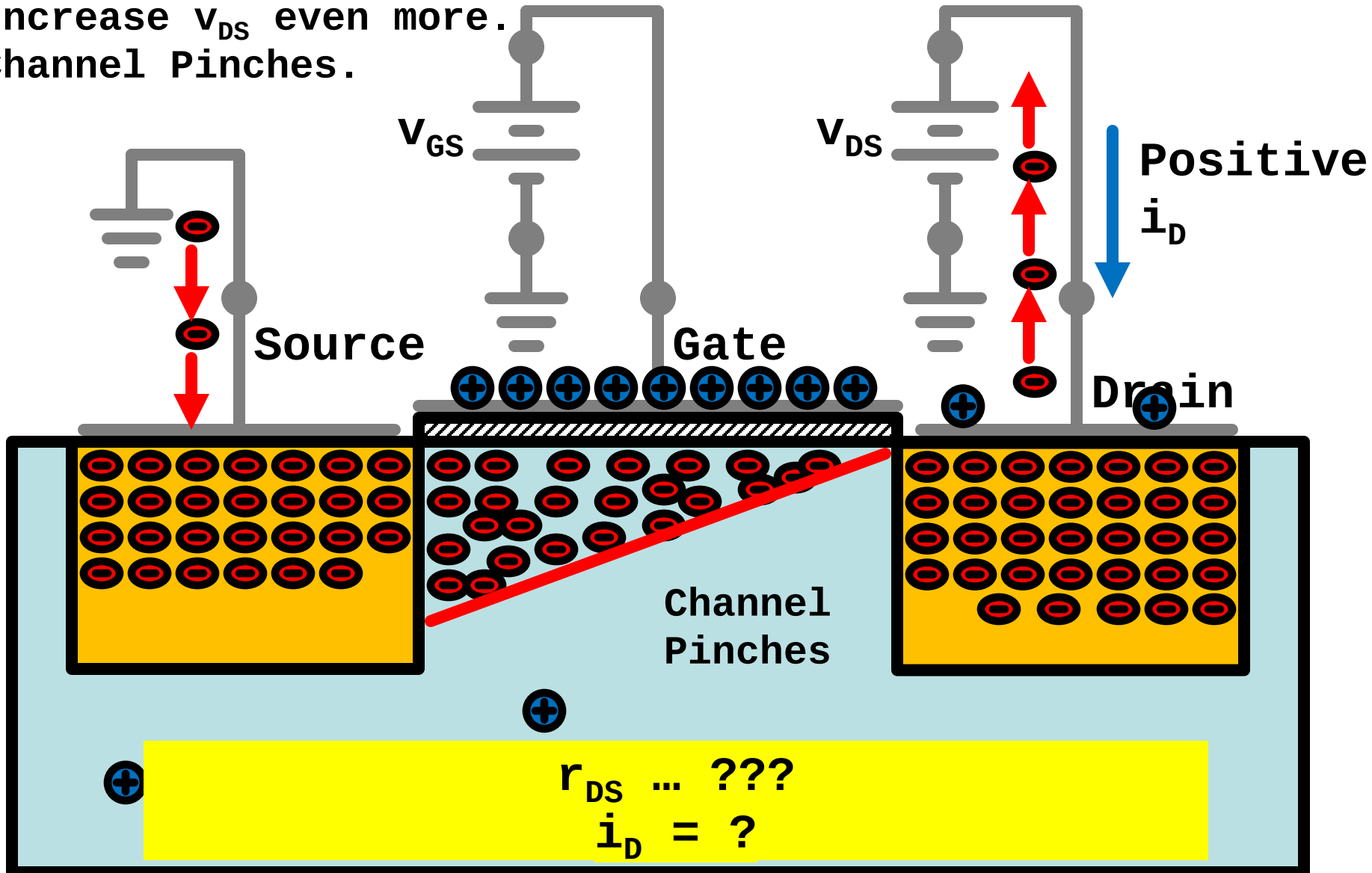
MOSFET – Operation and Modes

Increase V_{DS} even more.
Channel Tapers more.



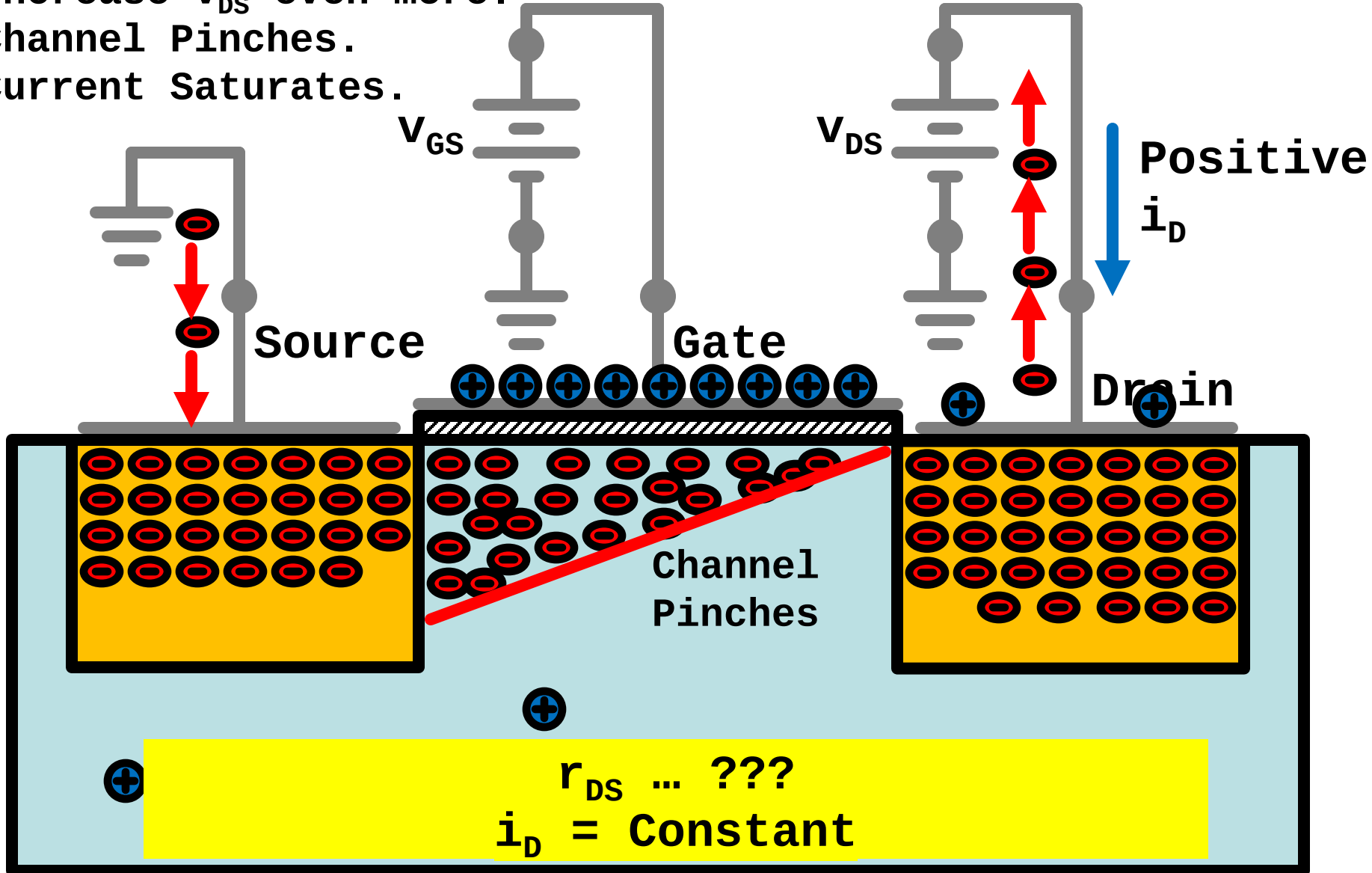
MOSFET – Operation and Modes

Increase V_{DS} even more.
Channel Pinches.



MOSFET – Operation and Modes

Increase V_{DS} even more.
Channel Pinches.
Current Saturates.



MOSFETs: Mode Dependence

$$i_D = 0$$

for $v_{GS} - V_t < 0$ (cutoff)

$$i_D = \mu_n C_{ox} \left(\frac{W}{L} \right) [(v_{GS} - V_t) v_{DS}]$$

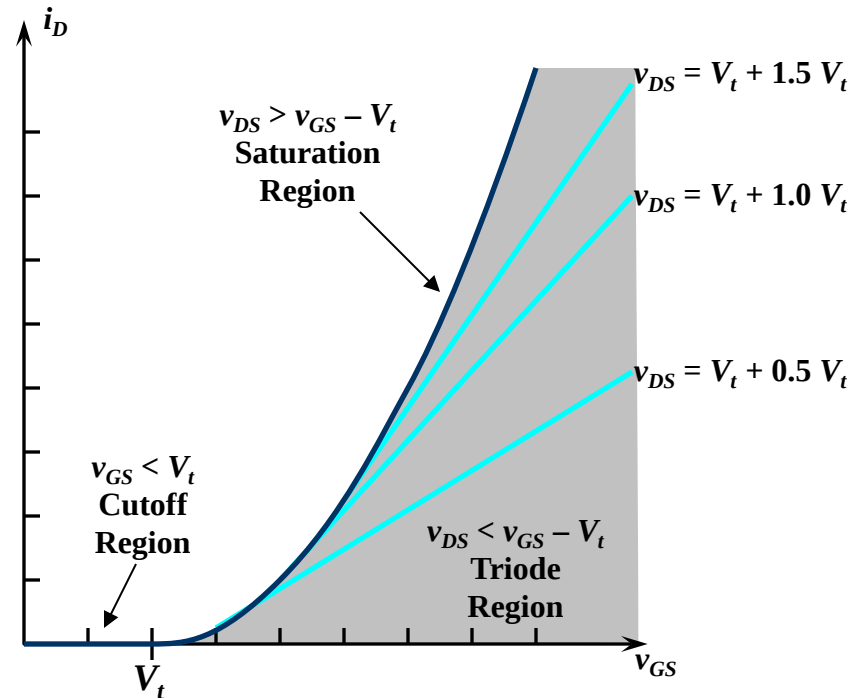
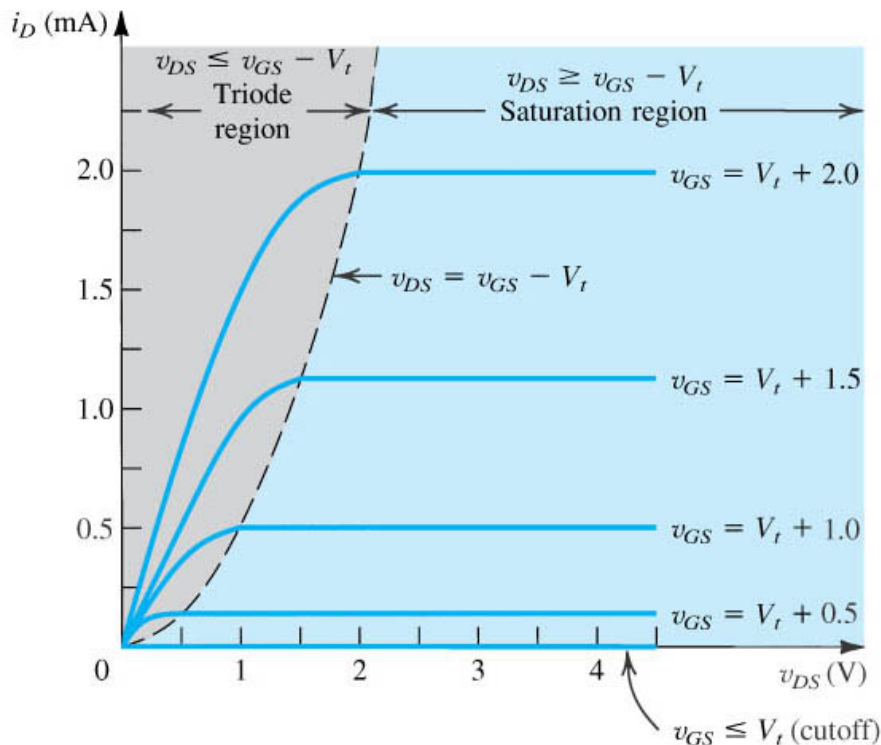
for $v_{GS} - V_t > 0$ (Triode, $v_{DS} \ll v_{GS} - V_t$)

$$i_D = \mu_n C_{ox} \left(\frac{W}{L} \right) \left[(v_{GS} - V_t) v_{DS} - \frac{1}{2} v_{DS}^2 \right]$$

for $v_{GS} - V_t > 0$ (Triode, $v_{DS} < v_{GS} - V_t$)

$$i_D = \mu_n C_{ox} \left(\frac{W}{L} \right) \left[\frac{1}{2} (v_{GS} - V_t)^2 \right]$$

for $v_{GS} - V_t > 0$ (Saturation, $v_{DS} > v_{GS} - V_t$)



NMOS: Equations and Models

Mode	i-v Characteristic	Inequality Conditions	Channel Shape
Cut-off	$i_D = 0$	$v_{GS} - V_{tn} < 0$	No Channel
Triode	$i_D = \mu_n C_{ox} \left(\frac{W}{L}\right) \left(v_{GS} - V_{tn} - \frac{1}{2} v_{DS}\right) v_{DS}$	$v_{GS} - V_{tn} > 0$ $v_{DS} < v_{GS} - V_{tn}$	Tapered
Triode (small v_{DS})	$i_D = \frac{v_{DS}}{r_{DS}} = \mu_n C_{ox} \left(\frac{W}{L}\right) (v_{GS} - V_{tn}) v_{DS}$	$v_{GS} - V_{tn} > 0$ $v_{DS} \ll v_{GS} - V_{tn}$	Rectangular
Saturation*	$i_D = I'_D = \frac{1}{2} \mu_n C_{ox} \left(\frac{W}{L}\right) (v_{GS} - V_{tn})^2$	$v_{GS} - V_{tn} > 0$ $v_{DS} \geq v_{GS} - V_{tn}$	Pinched
Saturation with Finite Output Resistance	$i_D = \frac{1}{2} \mu_n C_{ox} \left(\frac{W}{L}\right) (v_{GS} - V_{tn})^2 (1 + \lambda v_{DS})$	$v_{GS} - V_{tn} > 0$ $v_{DS} \geq v_{GS} - V_{tn}$	Pinched

$$V_{GS} = V_G - V_S$$

$$V_{DS} = V_D - V_S$$

i_D : Drain Current

V_{tn} : Threshold Voltage, $V_{tn} > 0$

$V_{OV} = v_{GS} - V_{tn}$: Excess Gate Voltage

μ_n : Free Electron Mobility

$C_{ox} = \epsilon_{ox}/t_{ox}$: Capacitance/Area

ϵ_{ox} : Oxide Permittivity

t_{ox} : Oxide Thickness

$k_n' = \mu_n C_{ox}$: Process Parameter

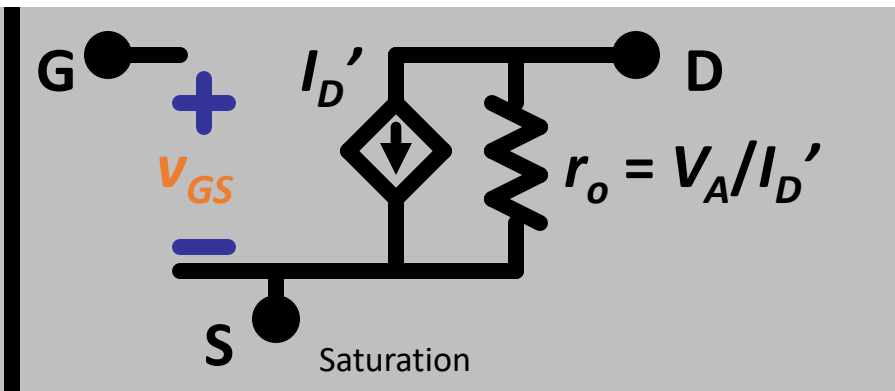
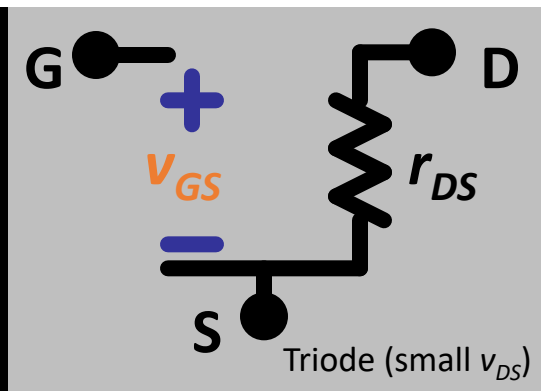
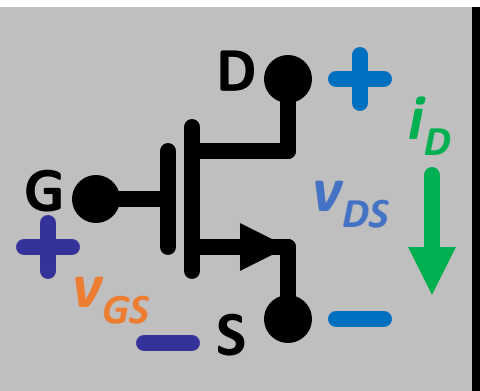
W: Channel Width

L: Channel Length

W/L: Aspect Ratio

$k_n = k_n'(W/L)$: Device Parameter

$V_A = 1/\lambda$: Early Voltage, $V_A > 0$



PMOS: Equations and Models

Mode	i-v Characteristic	Inequality Conditions	Channel Shape
Cut-off	$i_D = 0$	$v_{SG} - V_{tp} < 0$	No Channel
Triode	$i_D = \mu_p C_{ox} \left(\frac{W}{L}\right) \left(v_{SG} - V_{tp} - \frac{1}{2} v_{SD}\right) v_{SD}$	$v_{SG} - V_{tp} > 0$ $v_{SD} < v_{SG} - V_{tp} $	Tapered
Triode (small v_{SD})	$i_D = \frac{v_{SD}}{r_{SD}} = \mu_p C_{ox} \left(\frac{W}{L}\right) (v_{SG} - V_{tp}) v_{SD}$	$v_{SG} - V_{tp} > 0$ $v_{SD} \ll v_{SG} - V_{tp} $	Rectangular
Saturation*	$i_D = I'_D = \frac{1}{2} \mu_p C_{ox} \left(\frac{W}{L}\right) (v_{SG} - V_{tp})^2$	$v_{SG} - V_{tp} > 0$ $v_{SD} \geq v_{SG} - V_{tp} $	Pinched
Saturation with Finite Output Resistance	$i_D = \frac{1}{2} \mu_p C_{ox} \left(\frac{W}{L}\right) (v_{SG} - V_{tp})^2 (1 + \lambda v_{SD})$	$v_{SG} - V_{tp} > 0$ $v_{SD} \geq v_{SG} - V_{tp} $	Pinched

$$v_{SG} = v_S - v_G$$

$$v_{SD} = v_S - v_D$$

i_D : Drain Current

V_{tp} : Threshold Voltage, $V_{tp} < 0$

$v_{OV} = v_{SG} - |V_{tp}|$: Excess Gate Voltage

μ_p : Hole Mobility

$C_{ox} = \epsilon_{ox}/t_{ox}$: Capacitance/Area

ϵ_{ox} : Oxide Permittivity

t_{ox} : Oxide Thickness

$k_p' = \mu_p C_{ox}$: Process Parameter

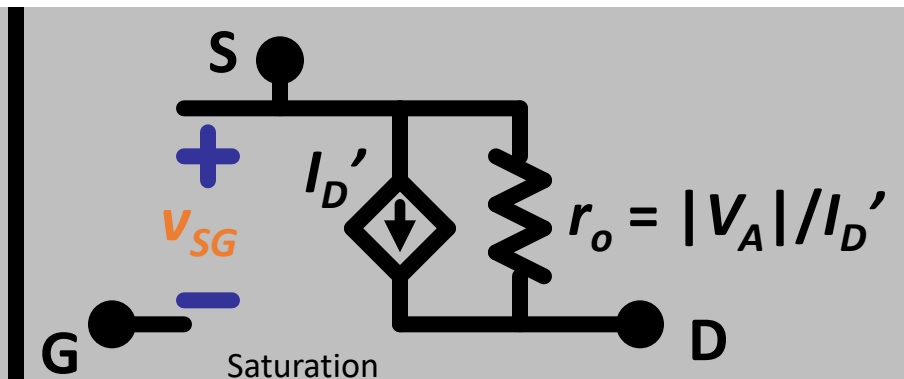
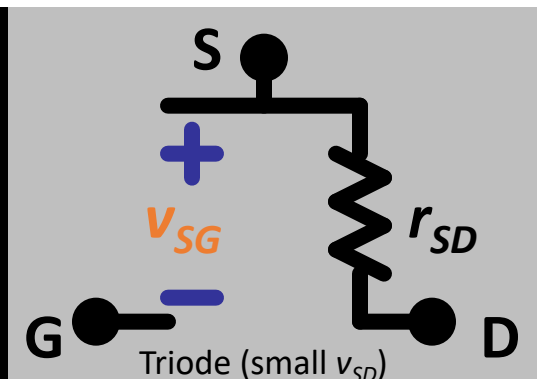
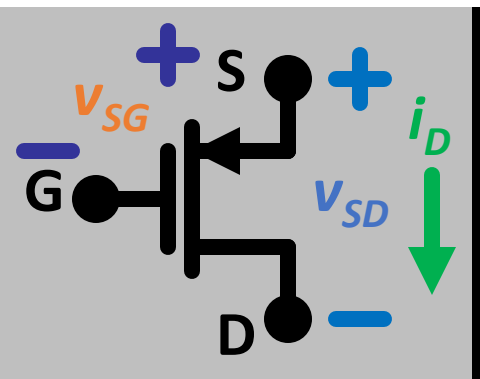
W: Channel Width

L: Channel Length

W/L: Aspect Ratio

$k_p = k_p' (W/L)$

$V_A = 1/\lambda$: Early Voltage, $V_A < 0$



MOSFET Small Signal Model: Saturation Mode of Operation

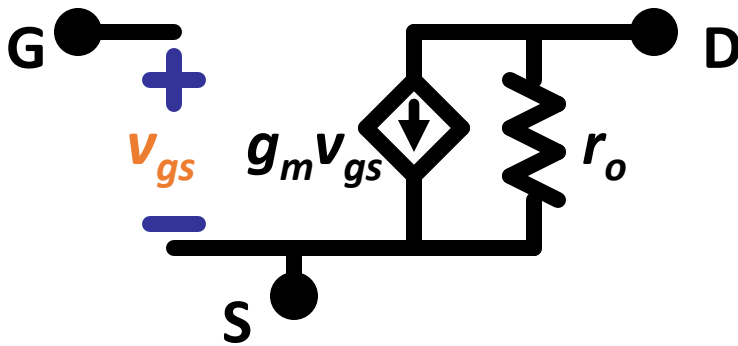
NMOS

$$i_D = \frac{1}{2} \mu_n C_{ox} \left(\frac{W}{L} \right) (v_{GS} - V_{tn})^2$$

$$g_m = \left. \frac{di_D}{dv_{GS}} \right|_{v_{GS}=V_{GS}} = \mu_n C_{ox} \left(\frac{W}{L} \right) (V_{GS} - V_{tn})$$

$$i_D = \frac{1}{2} \mu_n C_{ox} \left(\frac{W}{L} \right) (v_{GS} - V_{tn})^2 (1 + \lambda v_{DS})$$

$$r_o = \left. \frac{dv_{DS}}{di_D} \right|_{i_D=I_D} = \frac{1}{\lambda I_D} = \frac{V_A}{I_D}$$



PMOS

$$i_D = I'_D = \frac{1}{2} \mu_p C_{ox} \left(\frac{W}{L} \right) (v_{SG} - |V_{tp}|)^2$$

$$g_m = \left. \frac{di_D}{dv_{SG}} \right|_{v_{SG}=V_{SG}} = \mu_p C_{ox} \left(\frac{W}{L} \right) (V_{SG} - |V_{tp}|)$$

$$i_D = \frac{1}{2} \mu_p C_{ox} \left(\frac{W}{L} \right) (v_{SG} - |V_{tp}|)^2 (1 + |\lambda| v_{SD})$$

$$r_o = \left. \frac{dv_{SD}}{di_D} \right|_{i_D=I_D} = \frac{1}{|\lambda| I_D} = \frac{|V_A|}{I_D}$$

