CC2511 Week 5: Lecture 1

Assignment 2

- It’s time to start on Assignment 2
- The task sheet is on LearnJCU
- Organise yourselves into groups of 3 and email me **before the close of business Friday 30/08/19** with the names of your team members.

Assignment 2 schedule

Week Number	
5	We are here. Form groups and start hardware design.
6	
7	**Schematic due on Friday (10% of assignment grade).**
8	Receive feedback on your schematic, and modify as needed. Produce PCB layout.
9	**PCB due on Monday (10% of assignment grade).** PCBs sent for manufacturing immediately.
Lecture Recess	
10	Expect to receive manufactured boards by week 10.
11	Solder your PCB and work on the software.
12	Continue working on the software.
13	**Demonstrate final product during the lab.** **(Product: 50%; Code: 10%; Report: 20%)**

Today: Field Effect Transistors (FETs)

- Crash course/recap of semiconductor physics.
- Structure of a FET.
- How to use FETs as switches.

Reminder: capabilities of the microprocessor

- What voltage can the microprocessor generate?
- How much current can it source/sink?

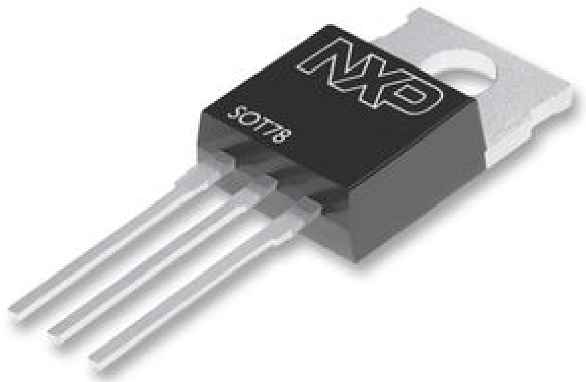
Capabilities of the microprocessor

- What voltage can the microprocessor generate?
  - 3.3 V
- How much current can it source/sink?
  - Maximum 25 mA

- What if we need 100 mA? 1 A? 10 A?

MOSFETs

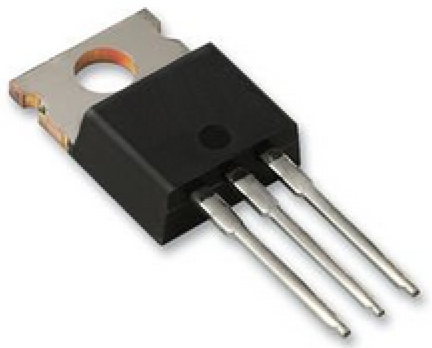
- A metal oxide semiconductor field effect transistors (MOSFET) is a type of transistor that is ubiquitous in electronics.
- The typical capacity of “power MOSFETS” is tens – hundreds of amps.
- Can switch very quickly (~ nanoseconds – microseconds depending upon device and driving circuitry).



Example power MOSFET

INTERNATIONAL RECTIFIER IRFB7437PBF MOSFET Transistor, N Channel, 195 A, 40 V, 0.0015 ohm, 10 V, 3

Add to Favourites



Click to zoom

Image is for illustrative purposes only. Please refer to product description.

International IOR Rectifier

Manufacturer: INTERNATIONAL RECTIFIER
Order Code: 2253786
Manufacturer Part No IRFB7437PBF

Technical Data Sheet (248.57KB) EN

Product Information

- **Continuous Drain Current Id:** 195A
- **Drain Source Voltage Vds:** 40V
- **MSL:** MSL 1 - Unlimited
- **No. of Pins:** 3
- **On Resistance Rds(on):** 0.0015ohm

Availability

Availability: 167

30 in stock for next day delivery

137 deliver in 6-7 days from our UK warehouse

see cut-off times

Check stock and lead times

Price for: Each 1
Minimum order quantity: 1
Order multiple quantity: 1

Price: $2.99

Quantity 1 **Buy**

Price

Quantity	List Price
1 - 24	$2.99
25 - 99	$2.49
100 - 249	$2.18

Properties of MOSFETs

- A single MOSFET can **only switch direct current (DC)**.
- Typical devices designed to handle **tens – hundreds of amps**.
- **Solid state** (no moving parts).
- Suitable for **high speed switching** (kilohertz – megahertz frequencies typical).
- Can be **destroyed by large voltage spikes**.

How do MOSFETs work?

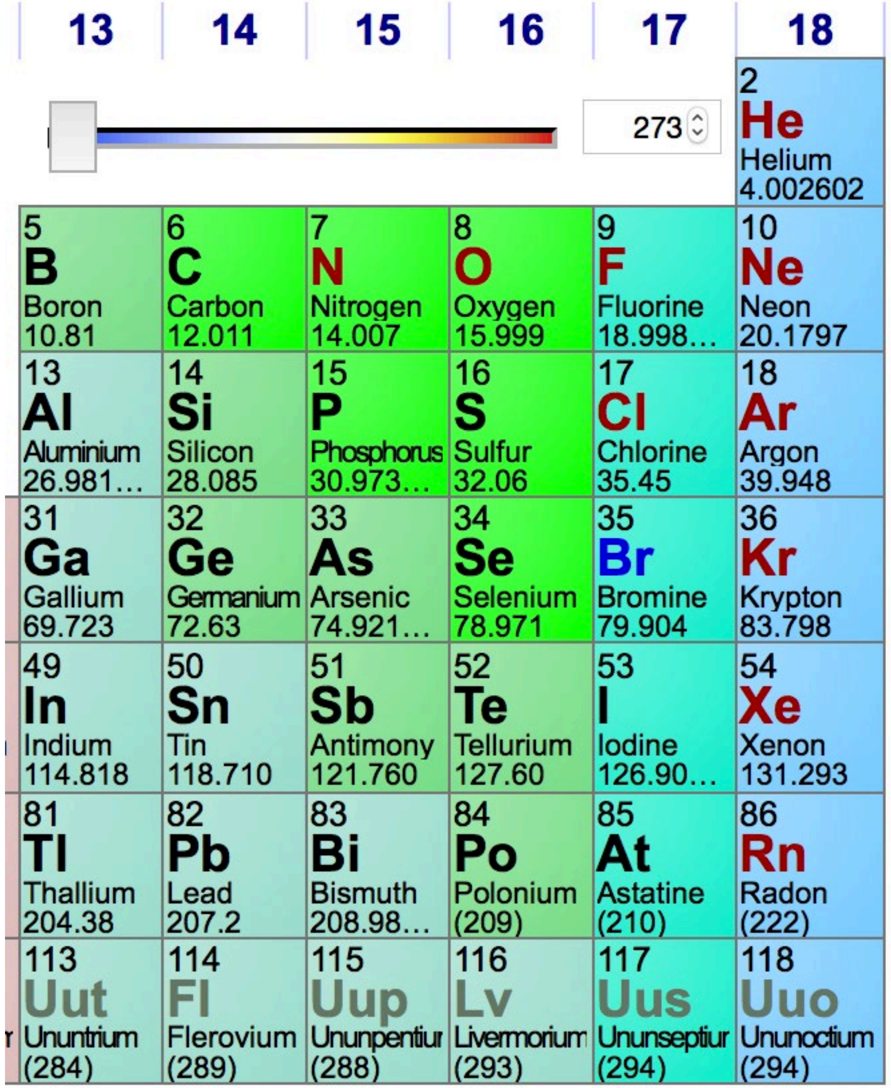
- MOSFETs are built from silicon.
- To understand their operation, we need to study solid state physics.
- Silicon is a semiconductor, meaning properties partway between metals and insulators.

Physics background

- In a semiconductor there may be **electrons** (negatively charged) and **holes** (positively charged).
- Current is the net movement of electrons and/or holes.
- The **hole** is the absence of an electron, but it should be treated as a particle in its own right:
  - It has an effective mass,
  - It carries momentum and energy, and
  - It has properties different from that of an electron.

Silicon and its dopants

- Silicon has 4 valence electrons and thus forms 4 covalent bonds with adjacent atoms.
- These covalent bonds are hard to break, thereby holding the electrons fixed to the atoms.
- Therefore, pure silicon barely conducts.

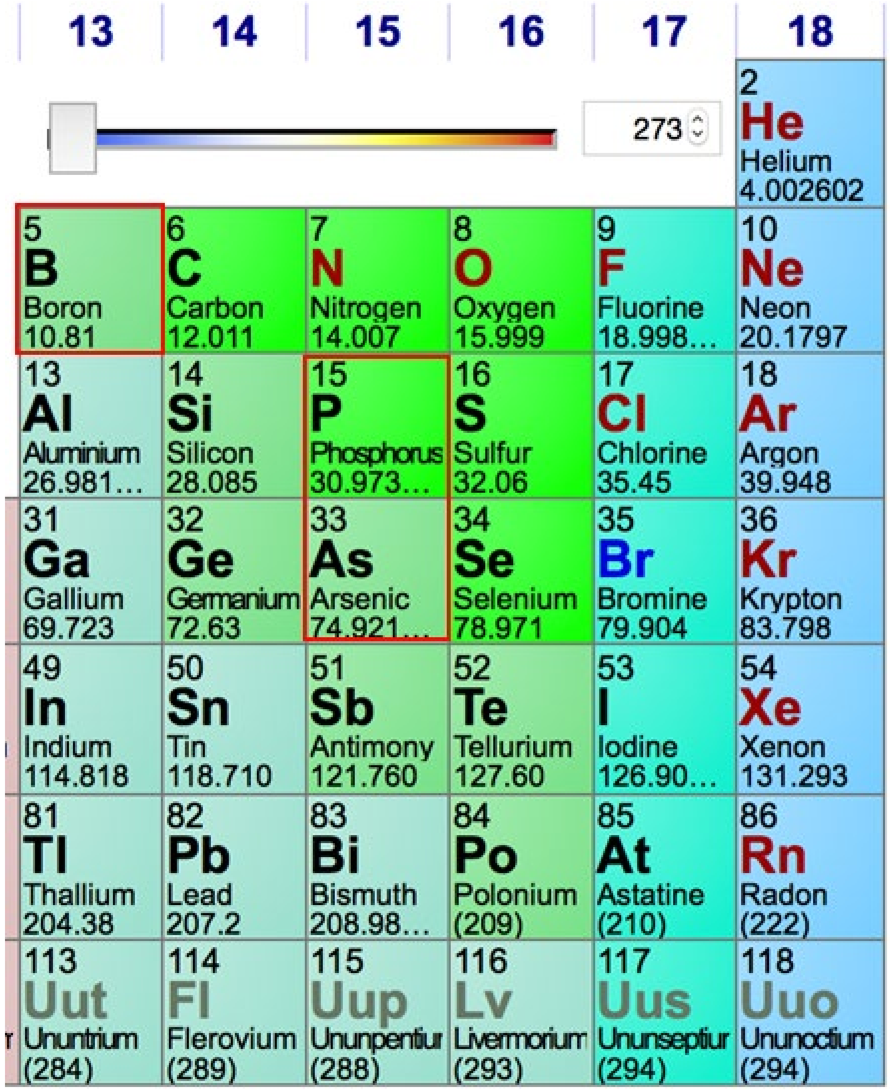


Silicon and its dopants

- The introduction of trace amounts of:
  - Boron,
  - Phosphorous, or
  - Arsenic

will leave some atoms with too many or too few electrons.

- Typical doping concentrations are parts per million (e.g. 10 ppm boron impurities in the Si crystal).
- The result: charge carriers (electrons or holes) that are not part of covalent bonds **are free to move**.



Doping. (a) n-type (excess electrons); (b) p-type (excess holes)

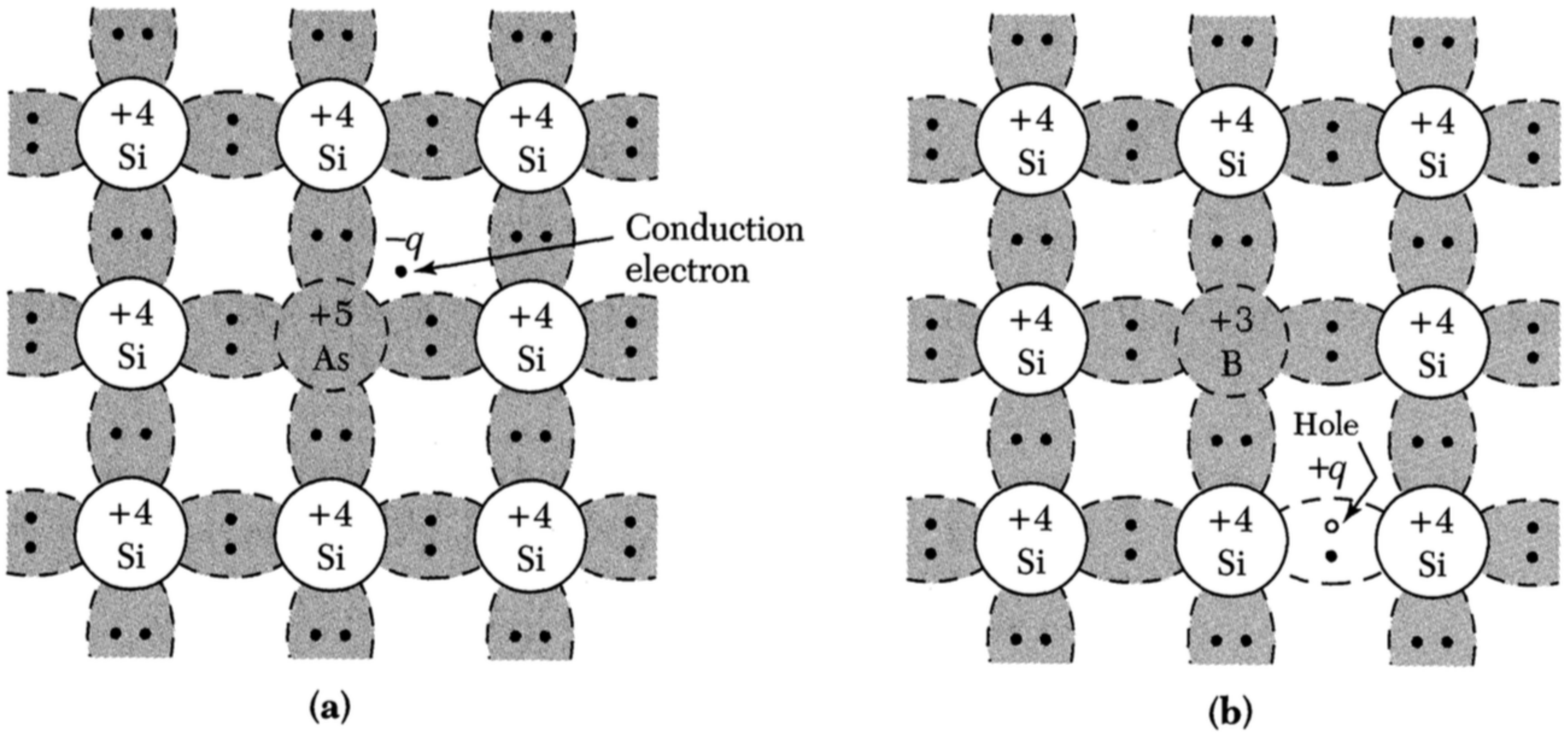


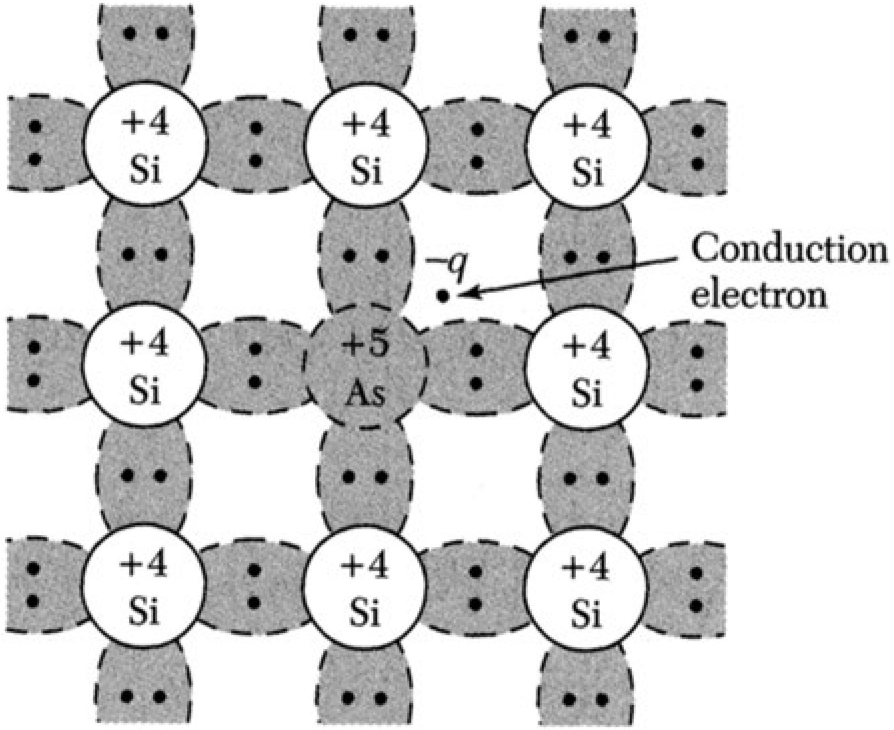
Image by S. M. Sze, “Semiconductor Devices, Physics and Technology”, 2nd edition, Wiley, 2002.

Silicon doping

- **N-type silicon** has an excess of electrons.
  - Its electrons are free to move and conduct electricity.
- **P-type silicon** has an excess of holes.
  - Its holes are free to move and conduct electricity.
- Undoped (or intrinsic) silicon has a low conductivity unless electrons or holes are provided from elsewhere.
- A plus symbol is added to signify very strong doping, e.g. “N+” is highly doped N-type silicon.

Immobile dopants

- Charge carriers introduced by doping leave behind charged atoms (ions).
- In **N-type** material the ions are **positively charged**.
- In **P-type** material the ions are **negatively charged**.
- Overall there is no net charge.

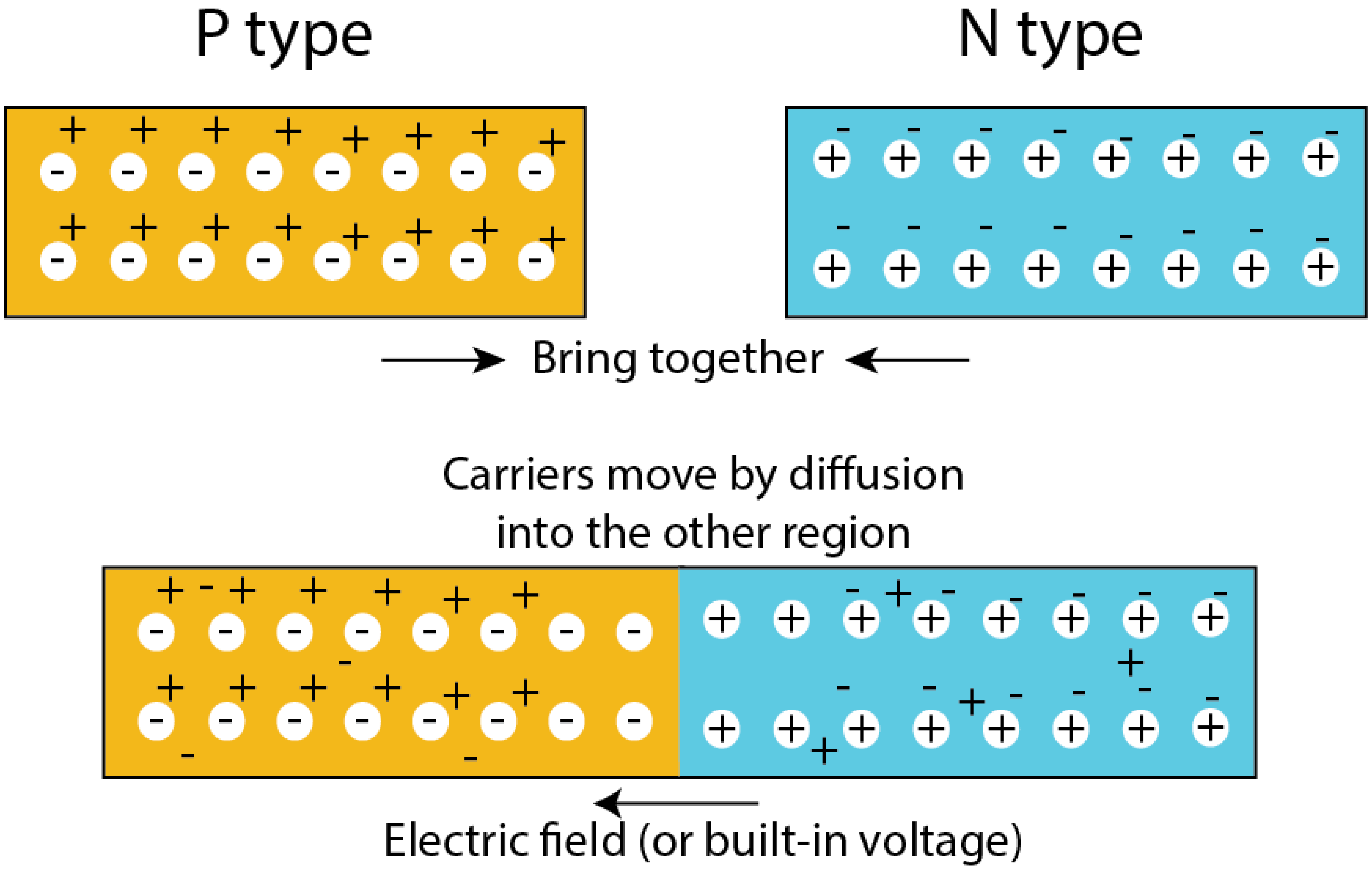


The p-n junction

Legend:

Immobile dopants are shown with white circles.

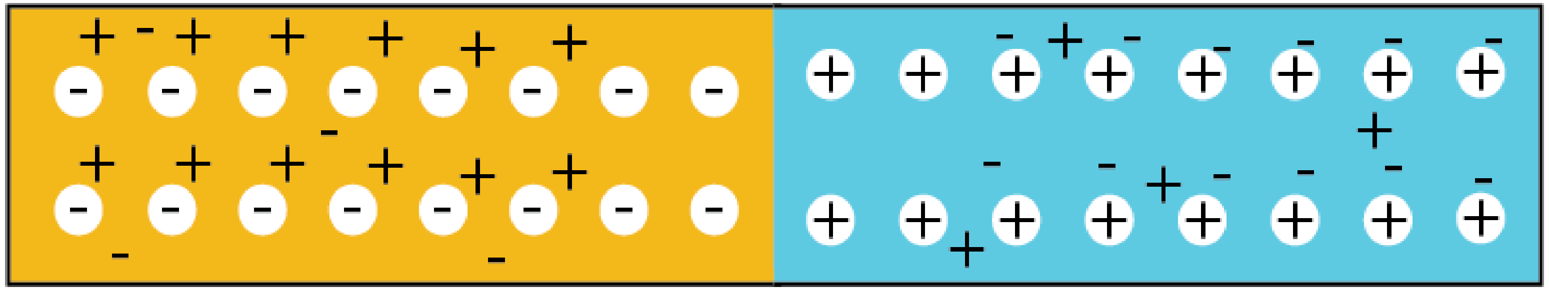
No carriers in the depletion region = no current can flow!



The charged dopants cannot move and an electric field is formed

Reverse bias

P type N type

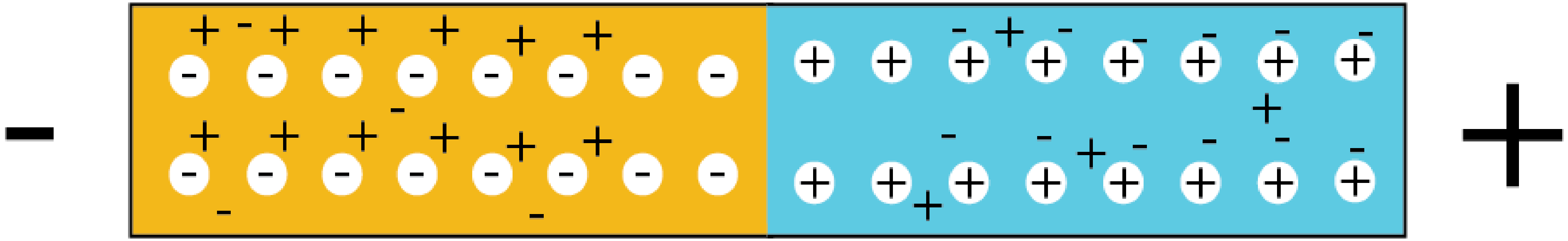


A voltage in this direction enlarges the depletion region.

Holes in this region are repelled by the uncompensated positive ions at the junction.

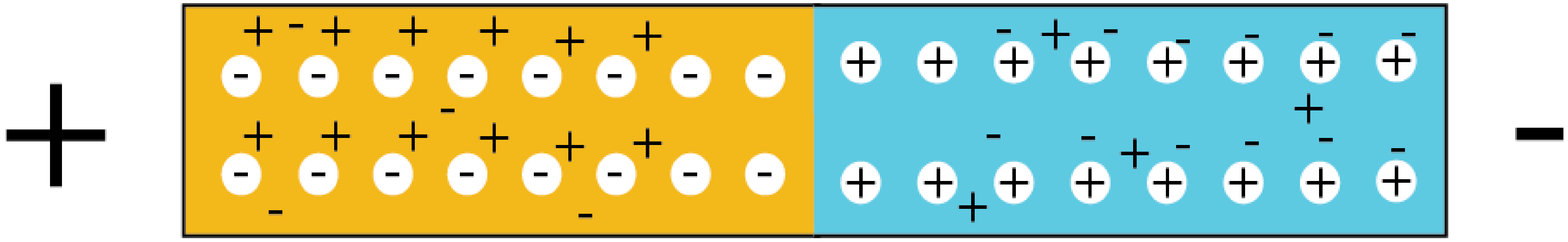
Electrons in this region are repelled by the uncompensated negative ions at the junction.

The unconductive region becomes larger.



An applied voltage in this direction “makes it worse”.
Carriers are even more repelled from the junctions.

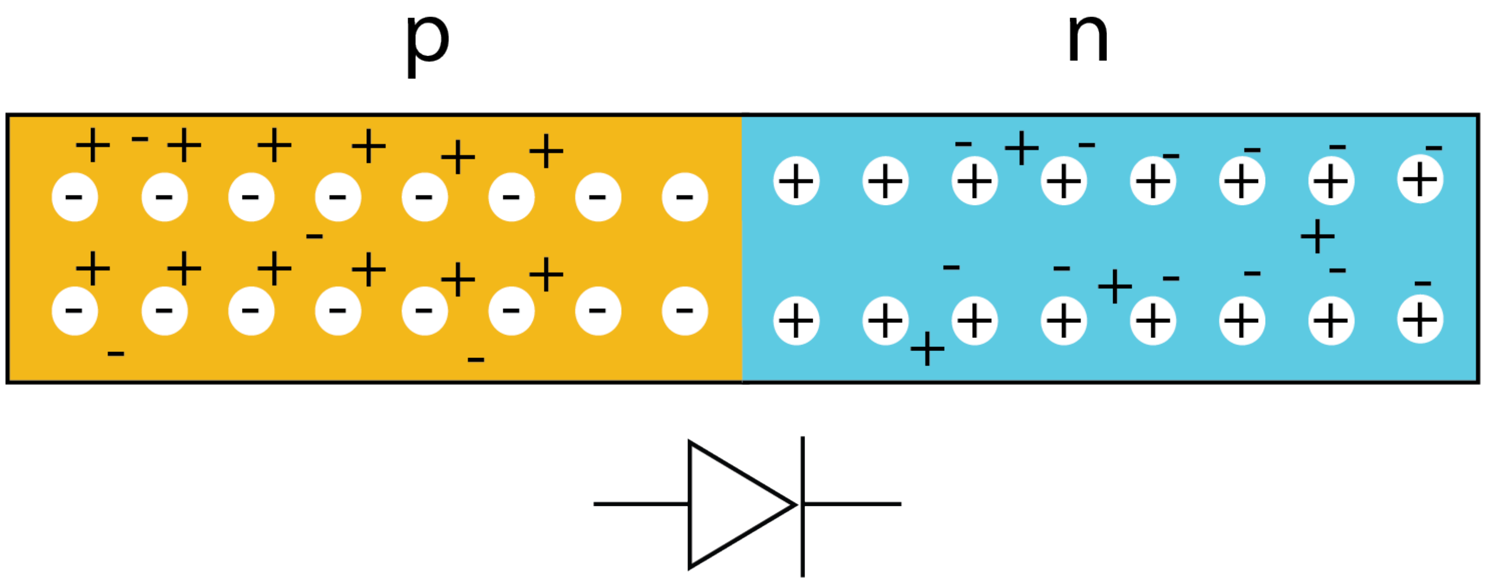
Forward bias



A big enough voltage in this direction overcomes the electric field at the junction. Carriers are able to cross.

- A voltage in the forward direction will fill in the depletion region, restoring conductivity.

Diodes

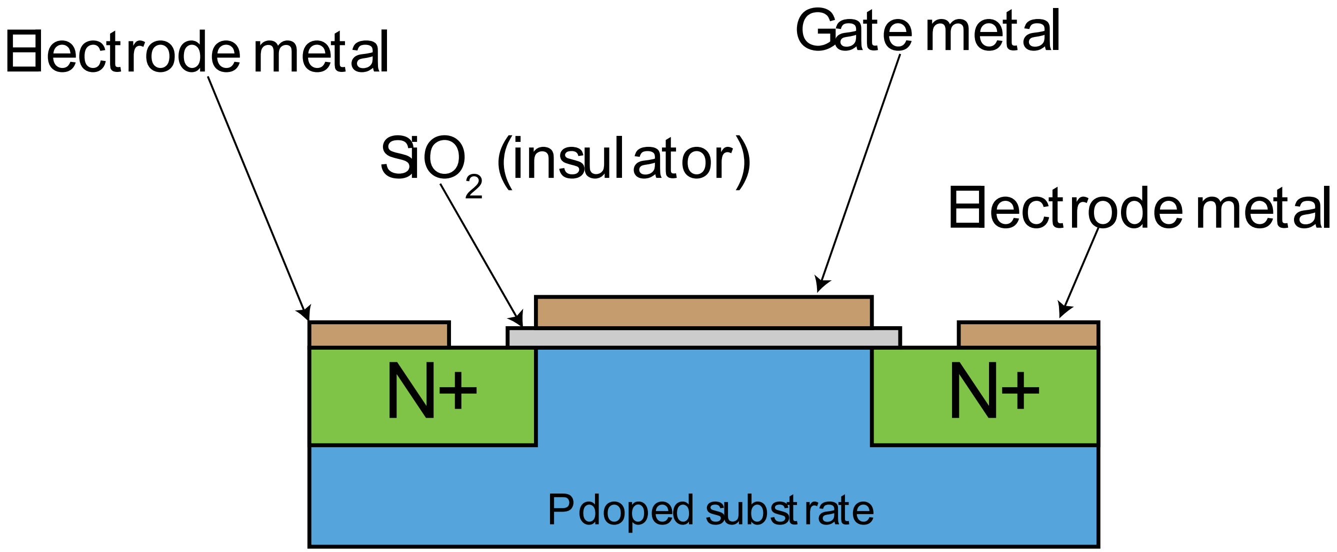


- A diode allows current to flow only in one direction.
- Current can flow from “p-to-n” but not “n-to-p”.

Field Effect Transistor (FET) structure

We will explain MOSFET operation using a simplified model with:

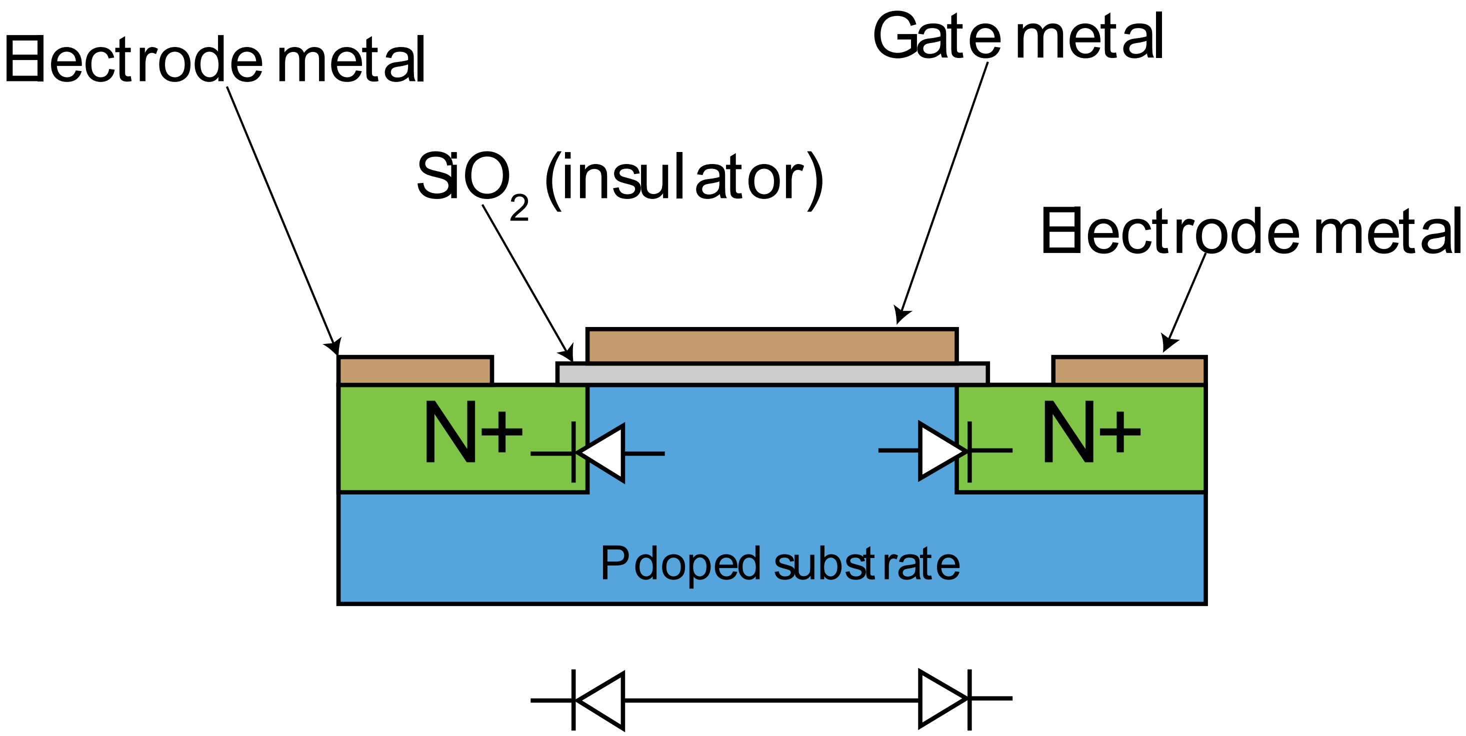
- A P-doped substrate,
- Two N-doped electrodes,
- A thin insulating dielectric layer, and
- A metal gate electrode.



Note: a so-called “Ohmic” contact between metal and semiconductor permits easy current flow across the interface. Metal is deposited on the semiconductor to allow packaging into an integrated circuit.

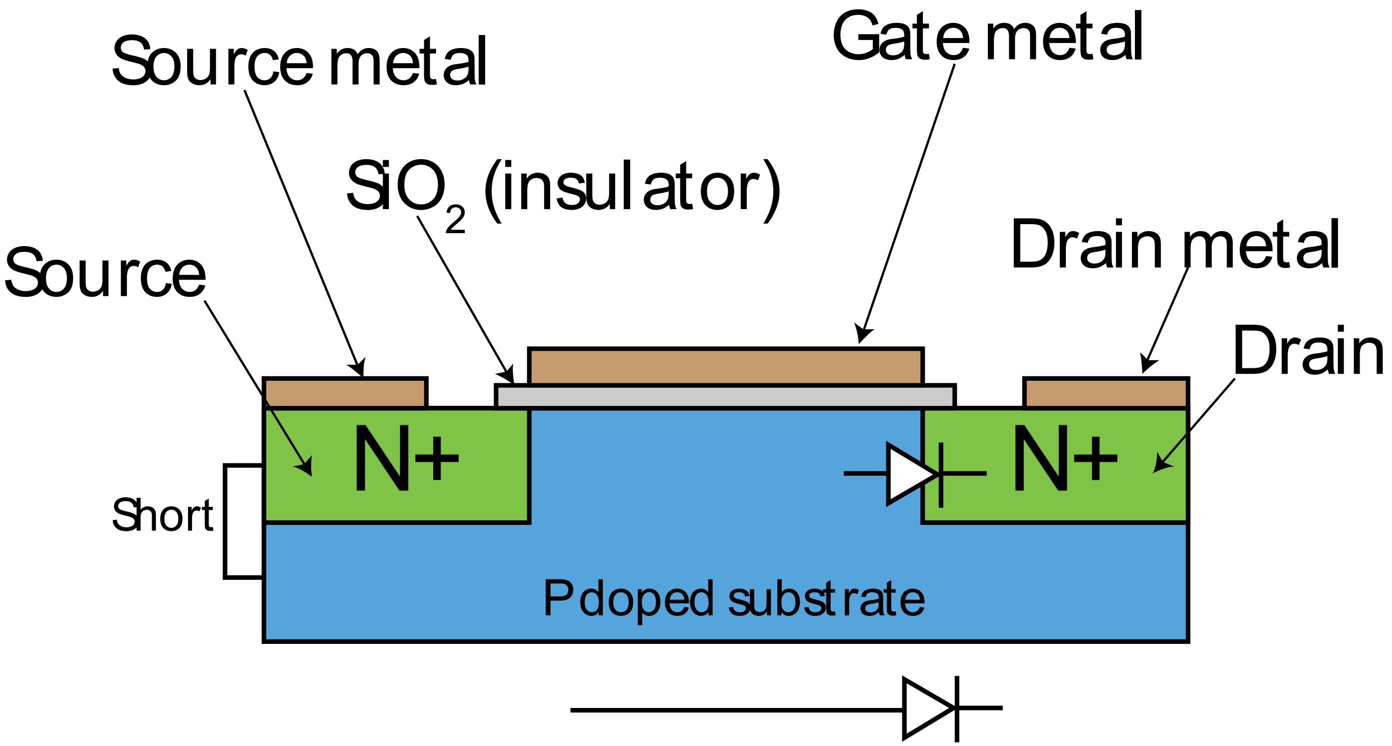
FET diodes

- There are back-to-back diodes!
- No current will flow.



Turn the 4-terminal FET into a 3-terminal FET

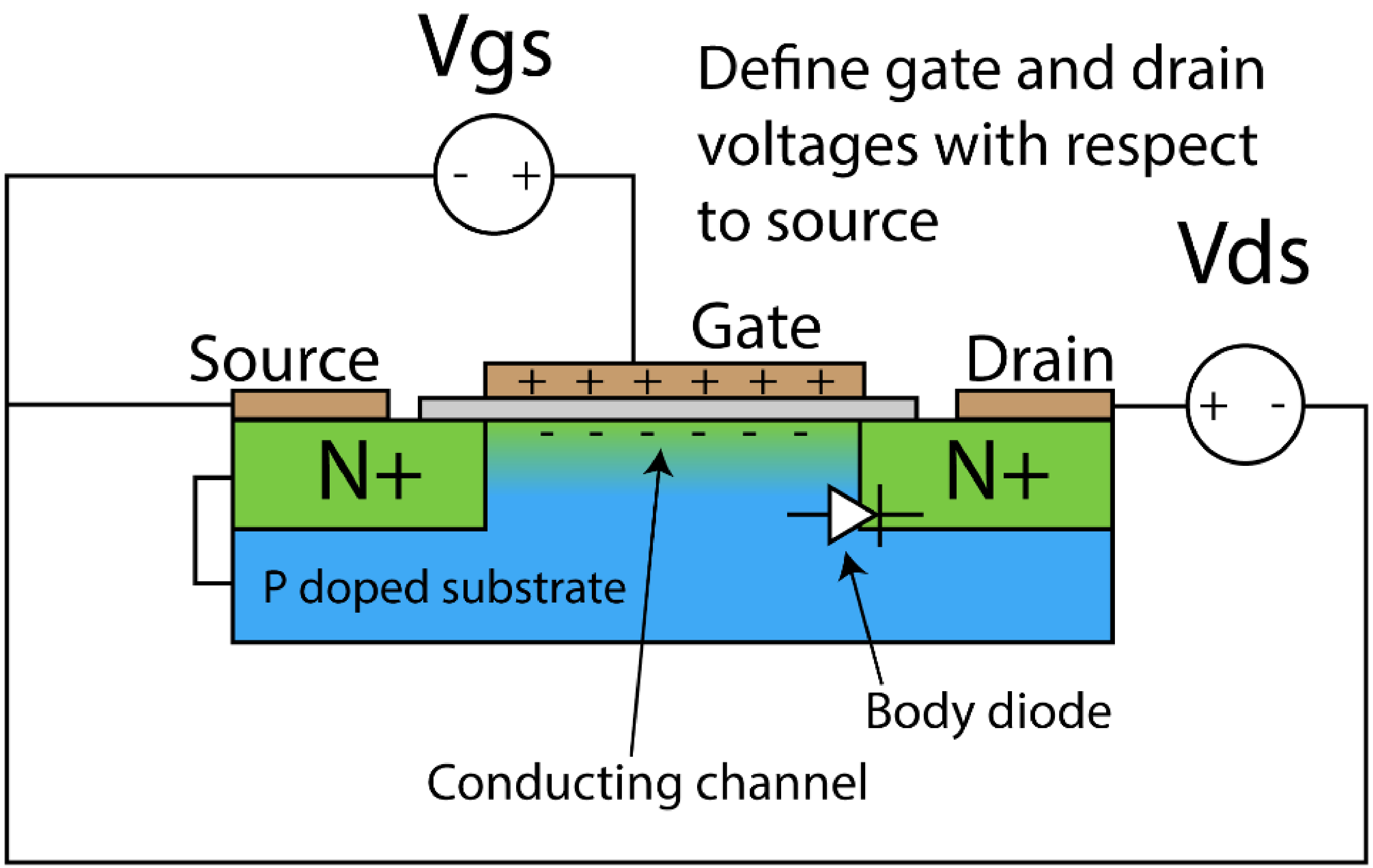
- On the semiconductor die, **short one of the terminals to the body.**
- There is now an asymmetry between electrodes.
- They are named **source** and **drain**.
  - The naming will become clear later.



Terminology

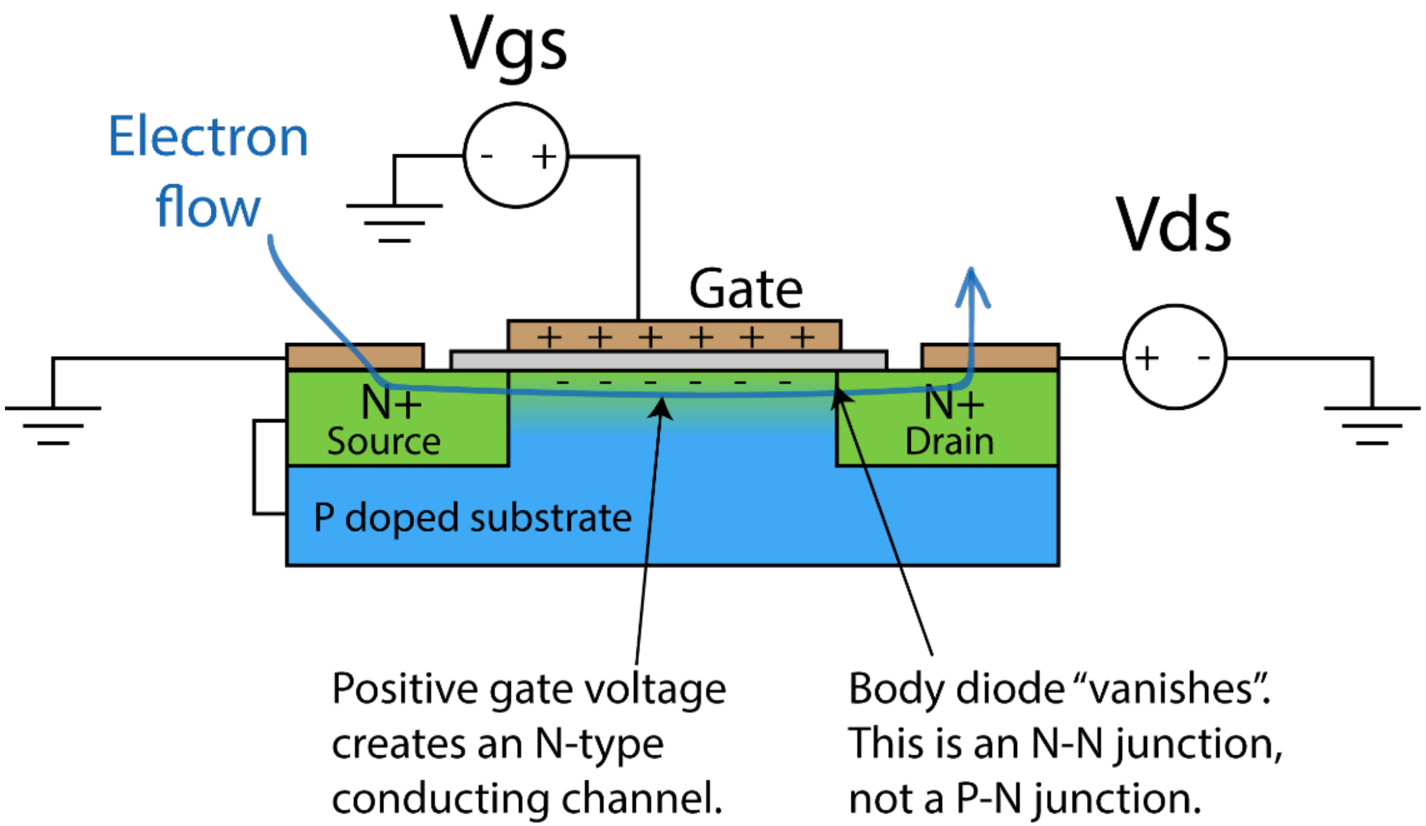
Vgs = voltage from gate to source.

Vds = voltage from drain to source.



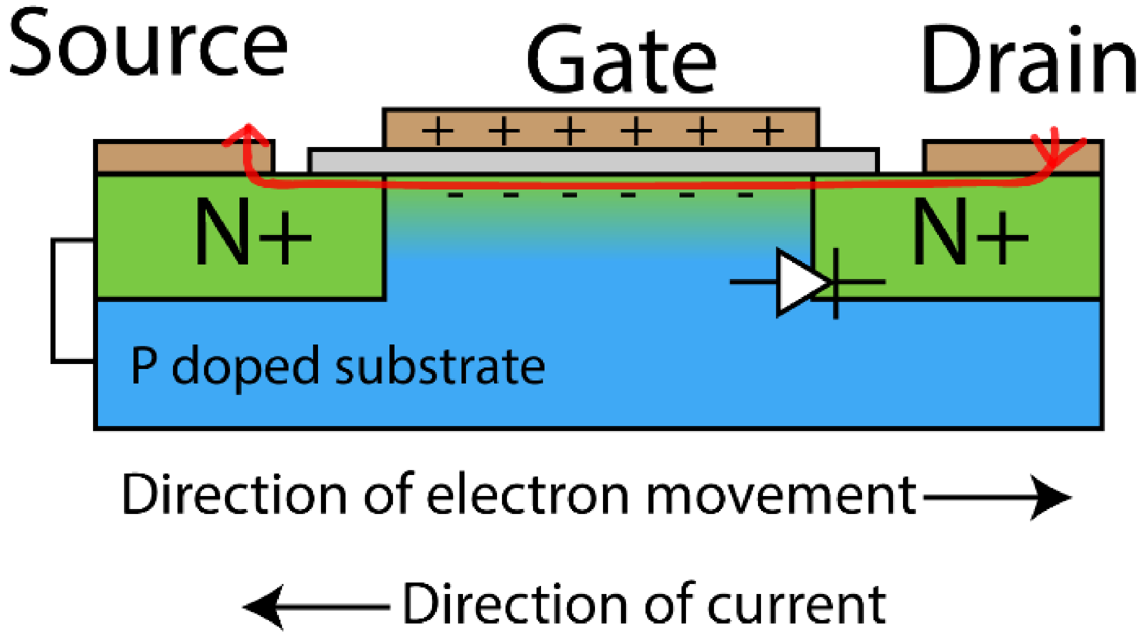
Apply a voltage to the gate

- The gate voltage will attract negative charges towards the dielectric layer.
- With enough negative charges, the material at the interface will **look like N-type.**
- **There will be no p-n junction and no diode!**

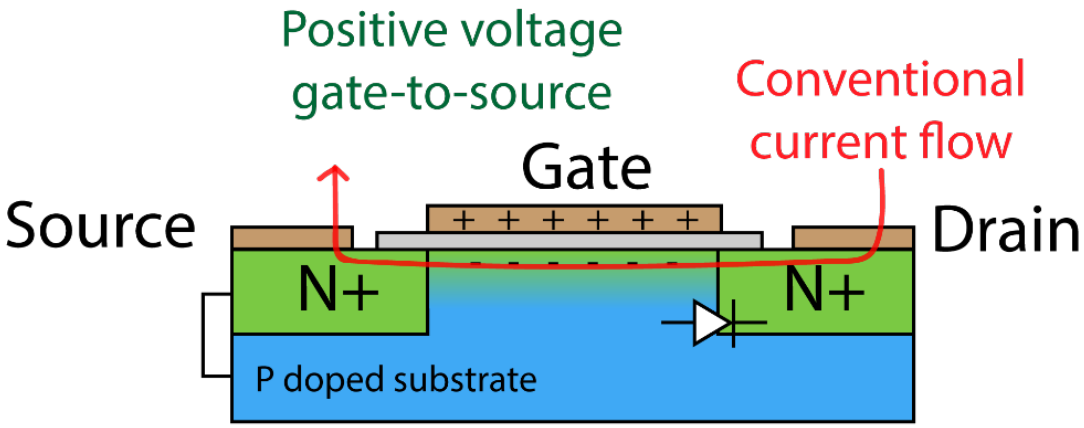


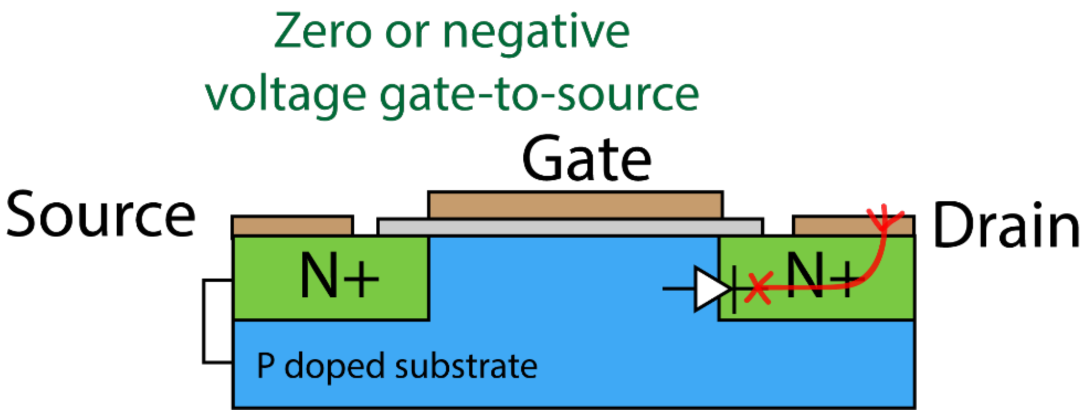
Naming of the terminals

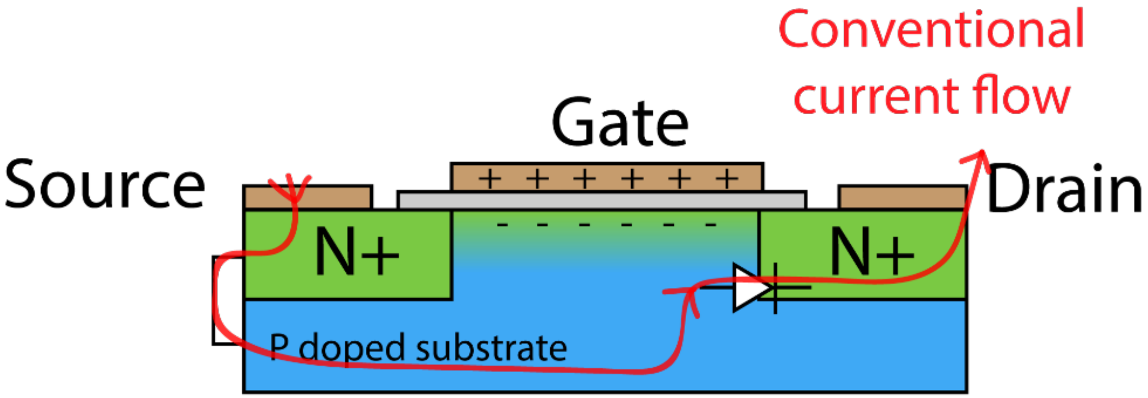
- In an **N type FET**, the charge carriers are electrons.
- Carriers enter at the **source**.
- Carriers leave at the **drain**.



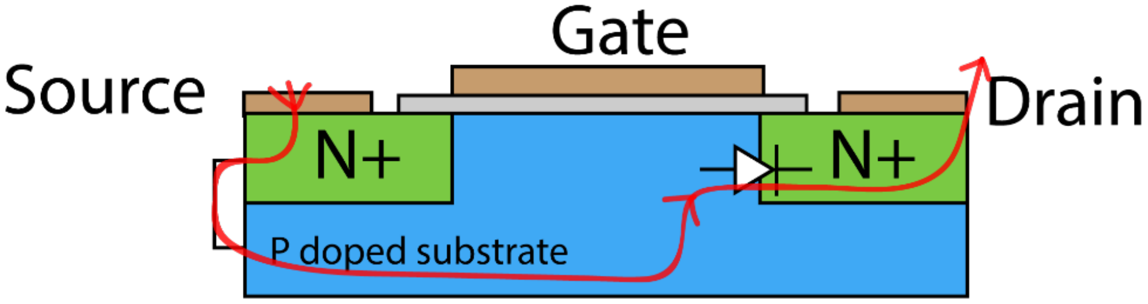
Overview of N-type FET behaviour





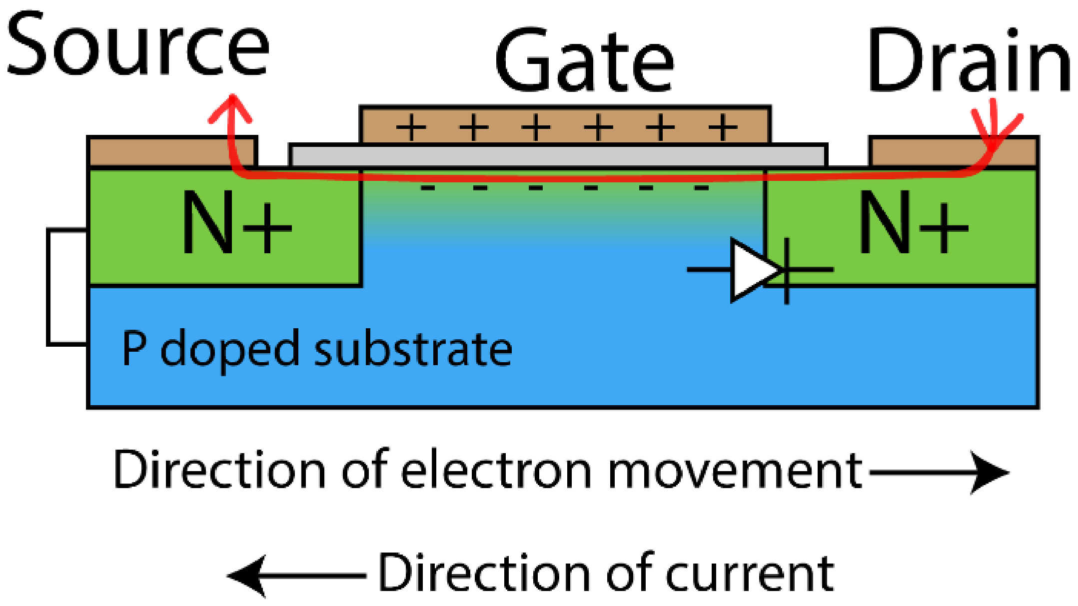


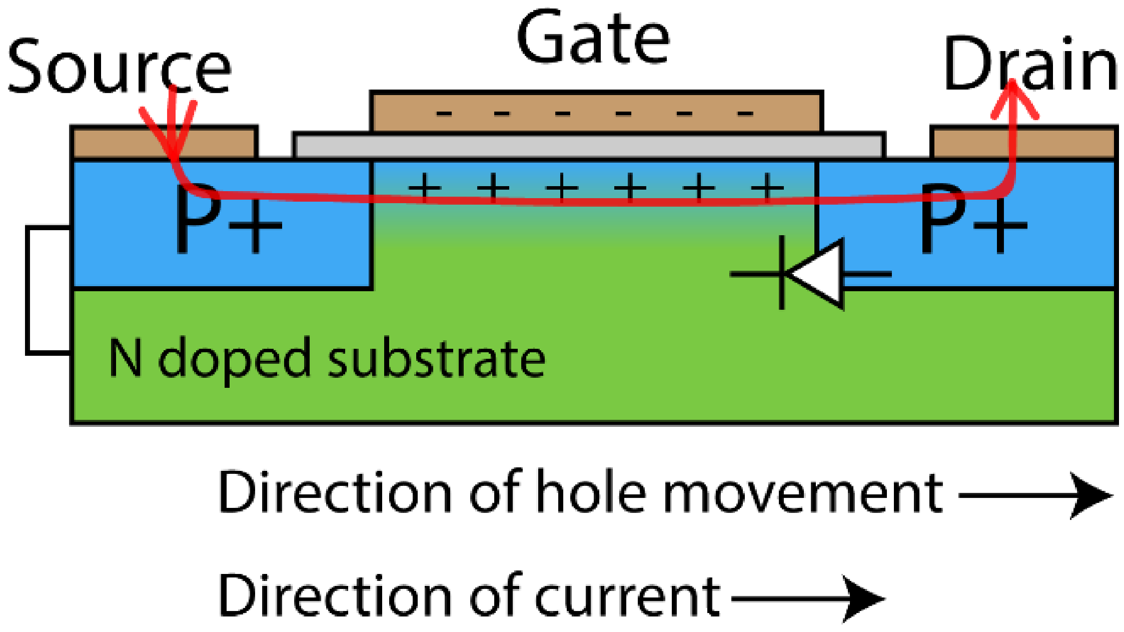
Varying gate voltage has no effect!



N-type FETs vs P-type FETs

- N-type conducts electrons when Vgs is **positive**
- P-type conducts holes when Vgs is **negative**

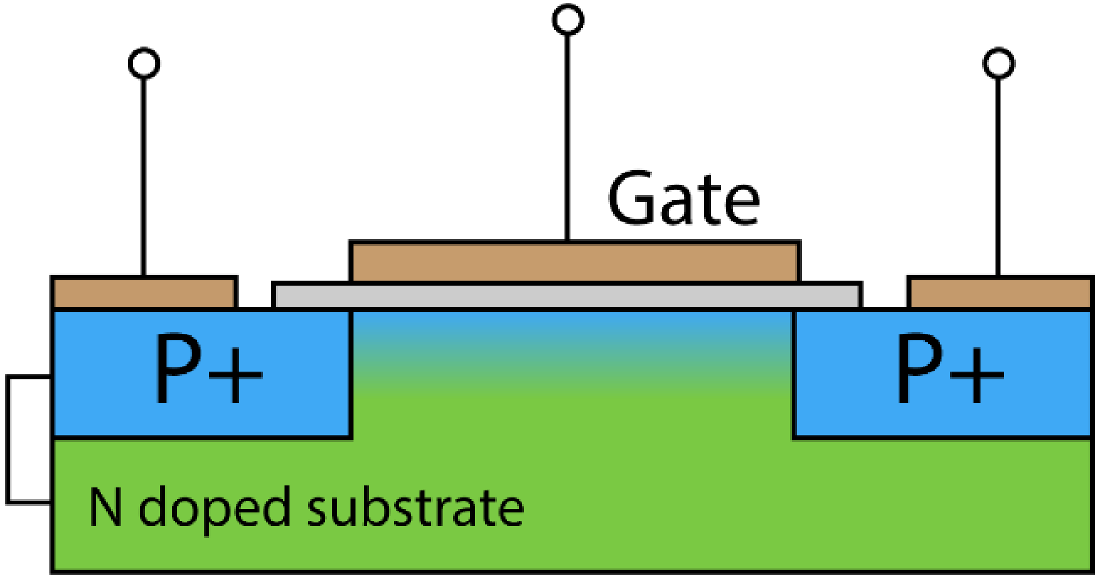




The gate terminal

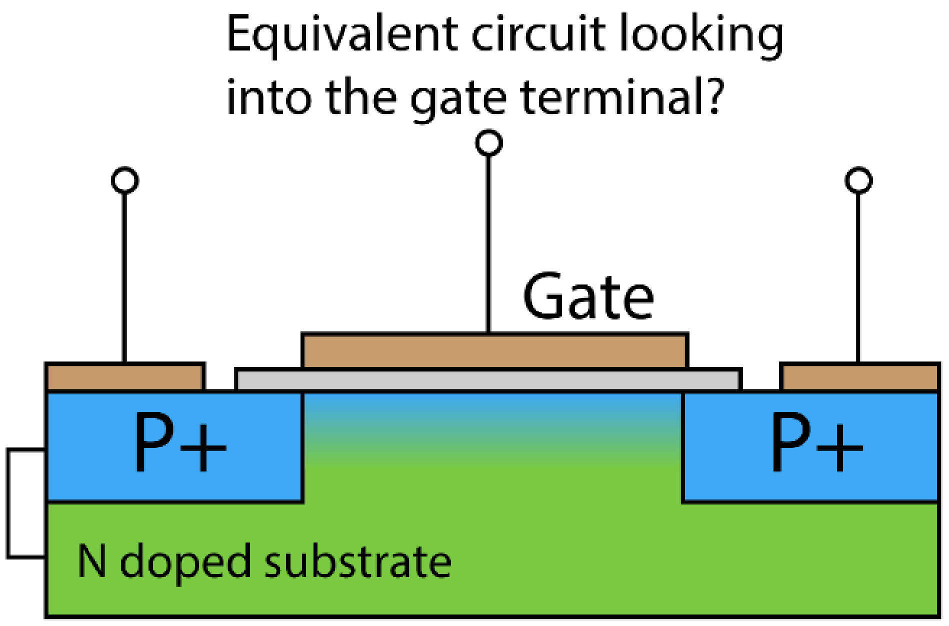
- Looking into the gate terminal, what is the equivalent circuit?

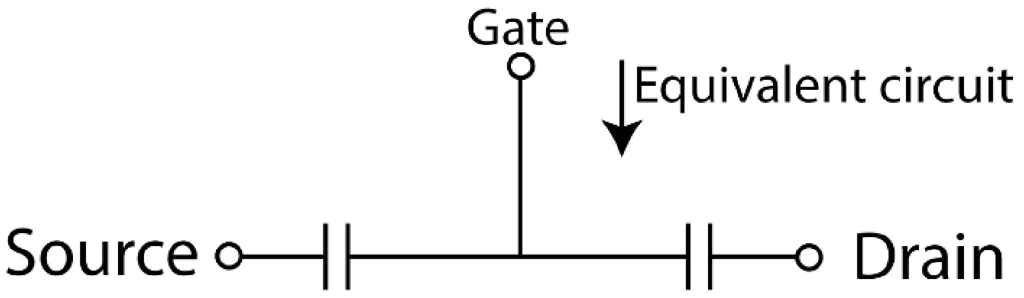
Equivalent circuit looking into the gate terminal?



The gate terminal

- Equivalent circuit looking into the gate is a **capacitance to source and a capacitance to drain**.
- In an ideal FET there is zero current entering the gate.
- In real devices there is a small leakage current of the order of 100 nA.
- Therefore FETs are very efficient.



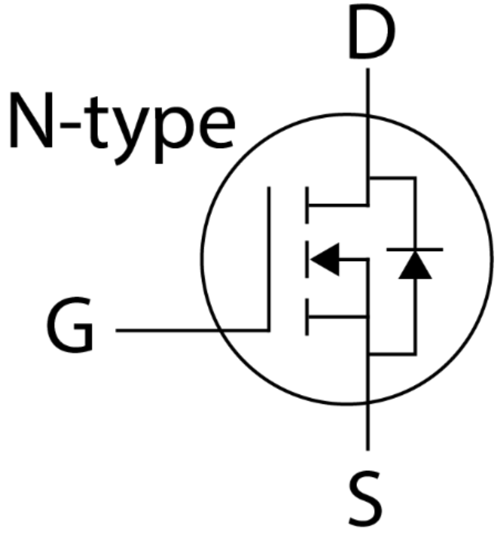


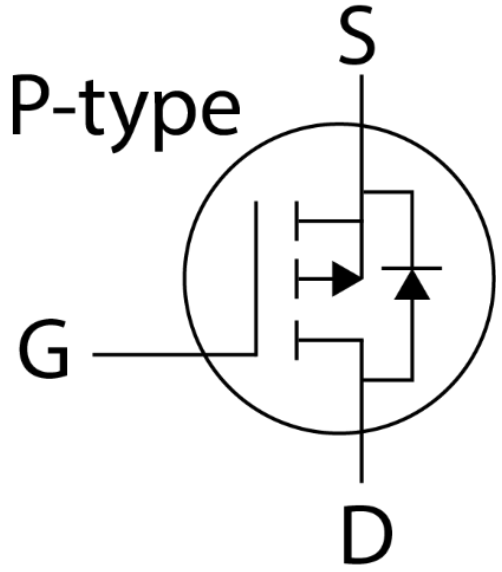
FET circuit symbols

How to read a FET symbol:

The arrow points from P to N. (Just like a diode).

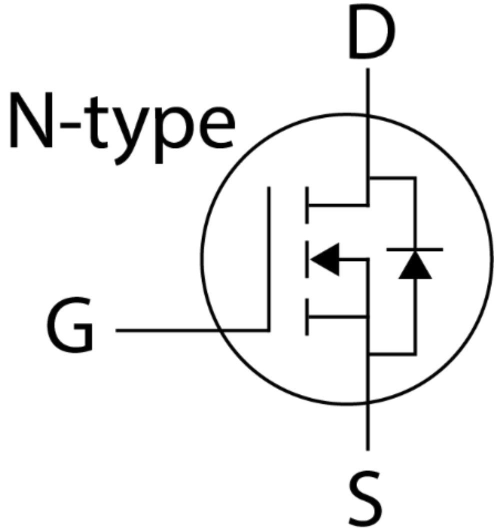
- Pointing ‘inwards’ means the N-type is at the interface, i.e. N channel.
- Pointing ‘outwards’ means the N-type is in the body, i.e. the channel must be P.

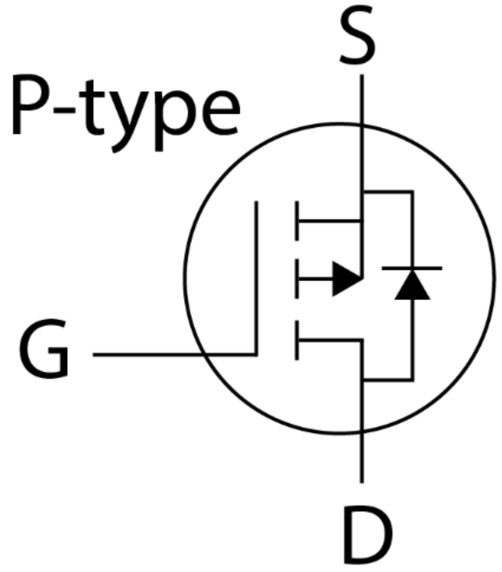




FET circuit symbols

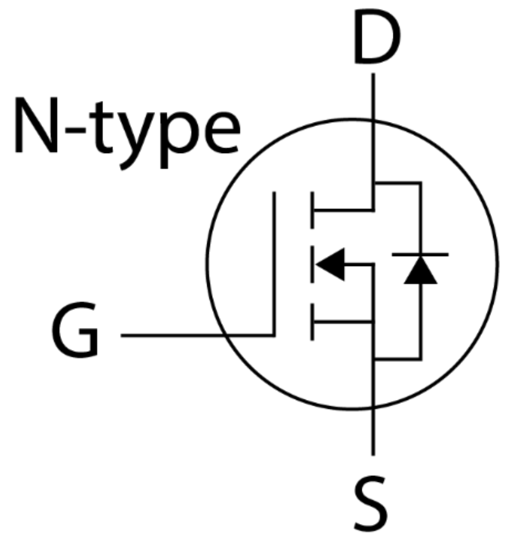
- The **source** has a line connecting to the centre arrow.
- This indicates that the source is shorted to the body.
- Usually (but not always) the source and drain are arranged such that the flow of current that can be switched is down the page.

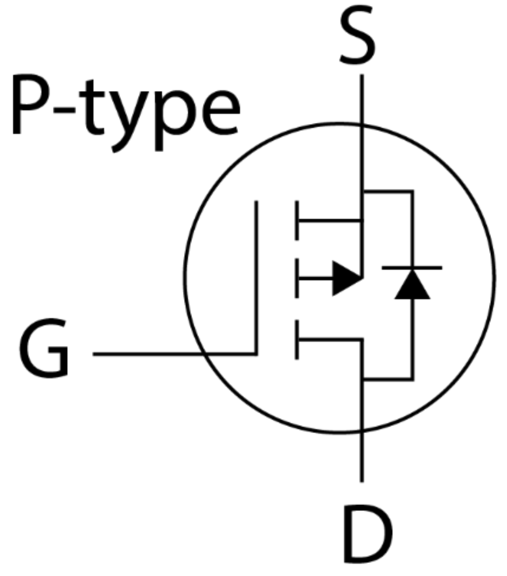




FET circuit symbols

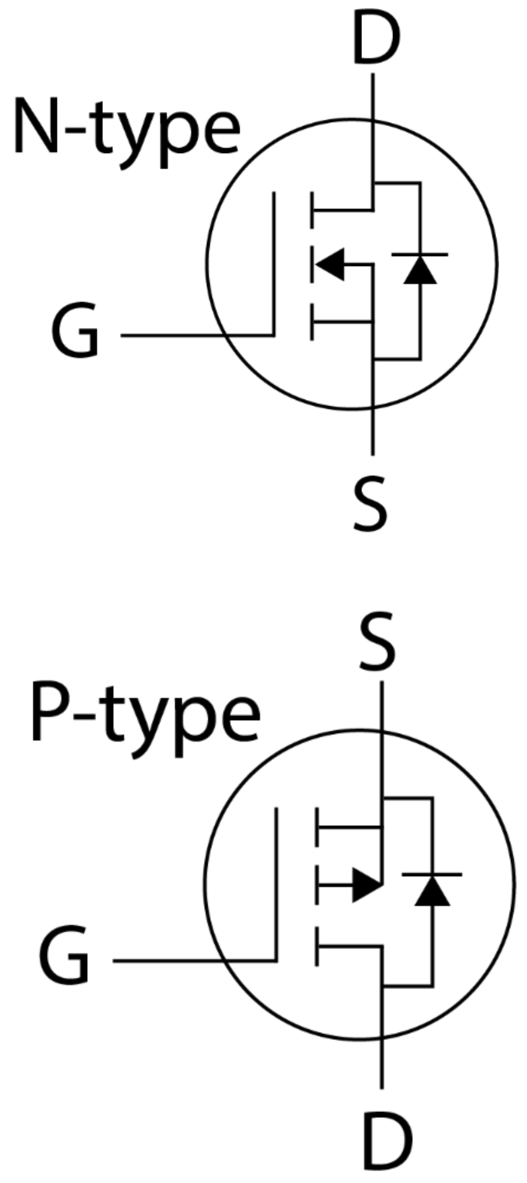
- **Broken lines** indicate **enhancement mode** (i.e. a voltage must be applied to turn the transistor on).
- A solid line would indicate **depletion mode** (i.e. a voltage must be applied to turn the transistor off).





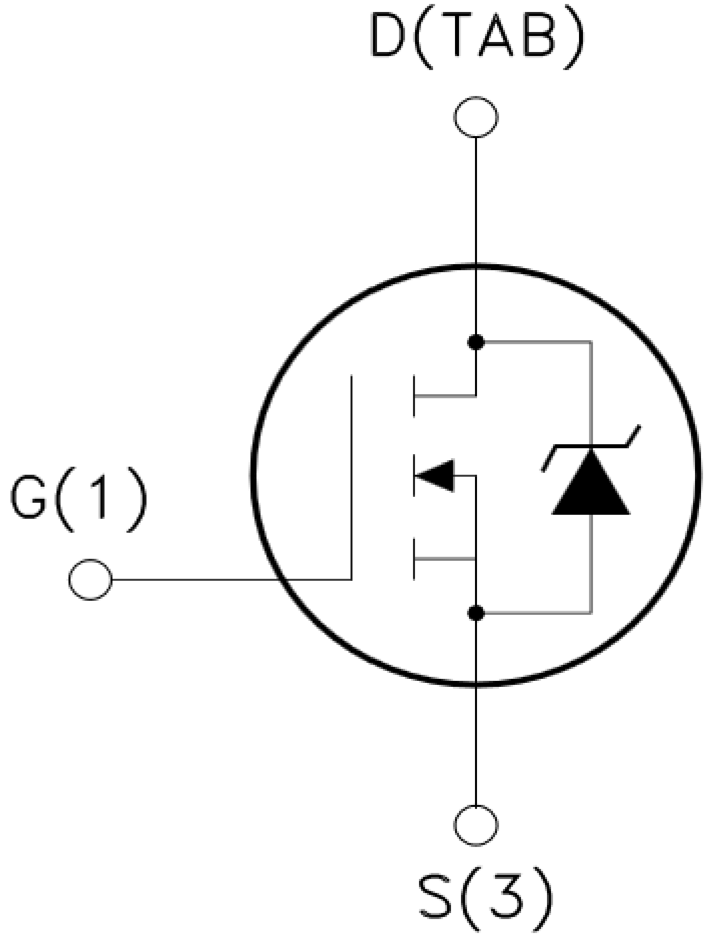
The body diode

- Recall a diode is formed by the p-n junction between substrate and drain.
- The body diode indicates that current in that direction will always conduct regardless of the gate voltage.



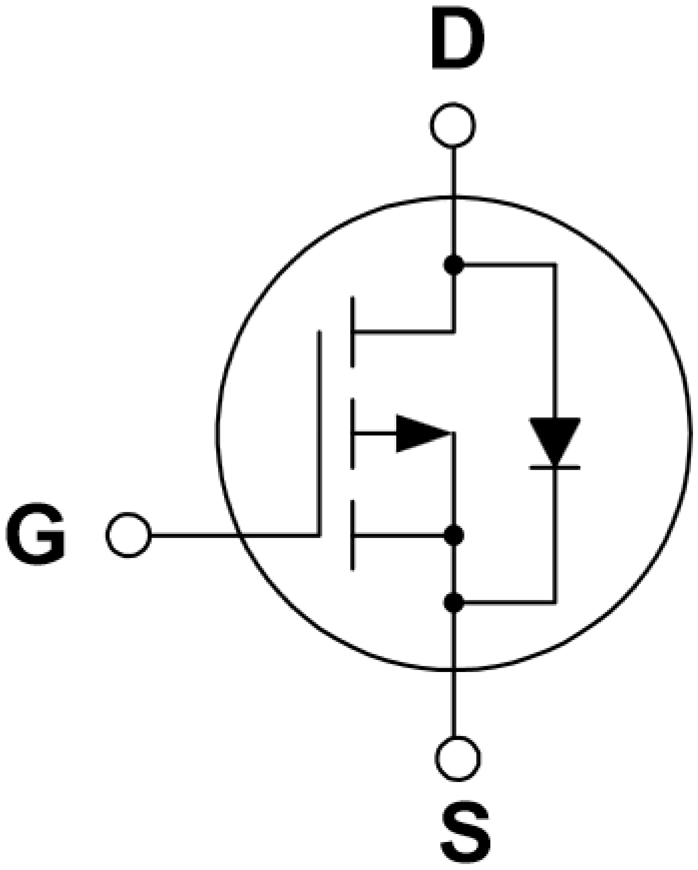
N-channel MOSFETs

- The device on the right is a **N-channel** MOSFET.
- Therefore, the conducting carriers are **electrons**.
- Therefore, turn on the transistor when the gate voltage is **positive** with respect to the source (so that electrons are drawn towards the channel).
- **Electrons** flow from source to drain (so current flows the **opposite** direction)



P-channel MOSFETs

- The device on the right is a **P-channel** MOSFET.
- Therefore, the conducting carriers are **holes**.
- Therefore, turn on the transistor when the gate voltage is **negative** with respect to the source (so that holes are drawn towards the channel).
- **Holes** flow from source to drain (so current flows the **same** direction)



Practical considerations

Everything else being equal:

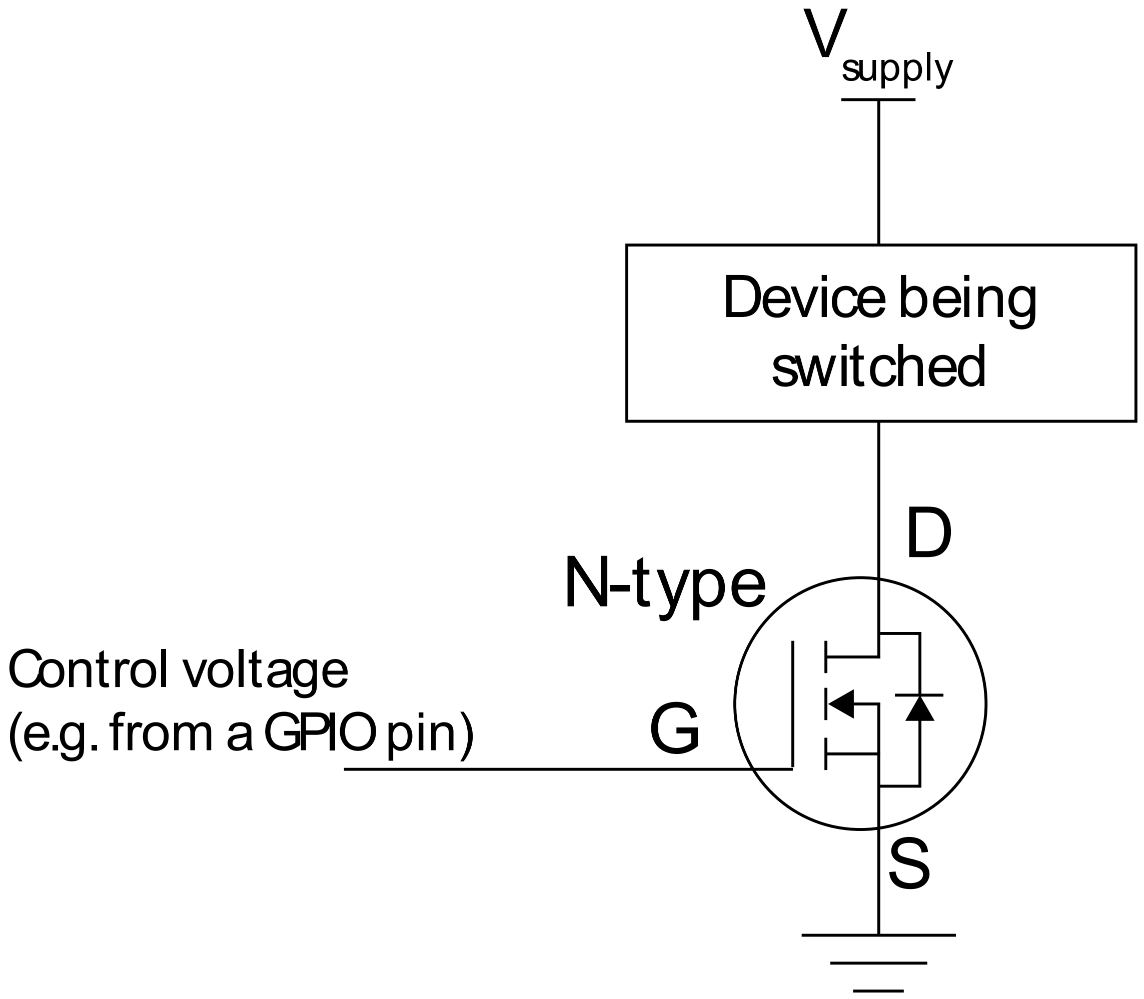
- N-channel MOSFETs usually have a lower resistance (= lower losses and less heat) than P-channel MOSFETs.
  - In silicon, electrons have a higher mobility than holes (i.e. they move faster).
- N channel devices often switch faster than P channel devices.
- N channel MOSFETs are more desirable, but there's a catch that we will see later.

MOSFET data sheets

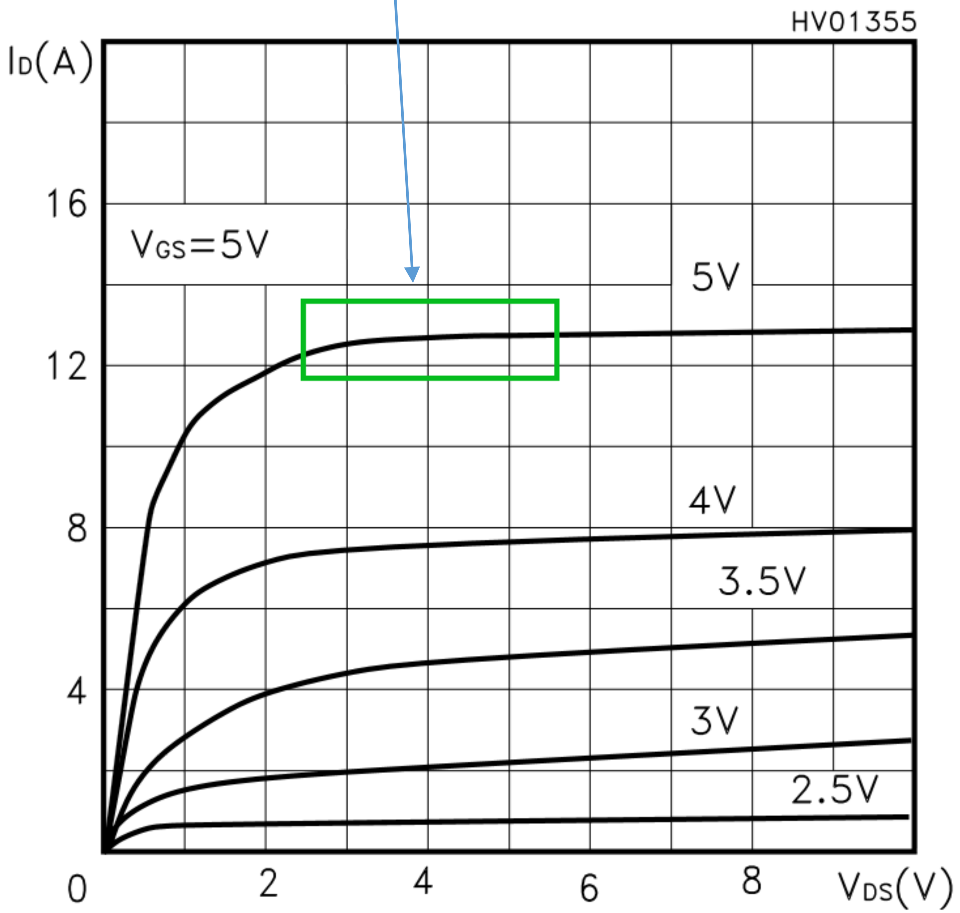
- Steady-state transistor performance is defined by two graphs:

1. The output characteristic (I_d vs V_{ds} at varying V_{gs})
2. The transfer characteristic (I_d vs V_{gs} at varying V_{ds})

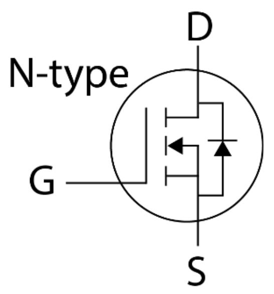
Using a FET as a switch



Operate in the green box to turn on the device

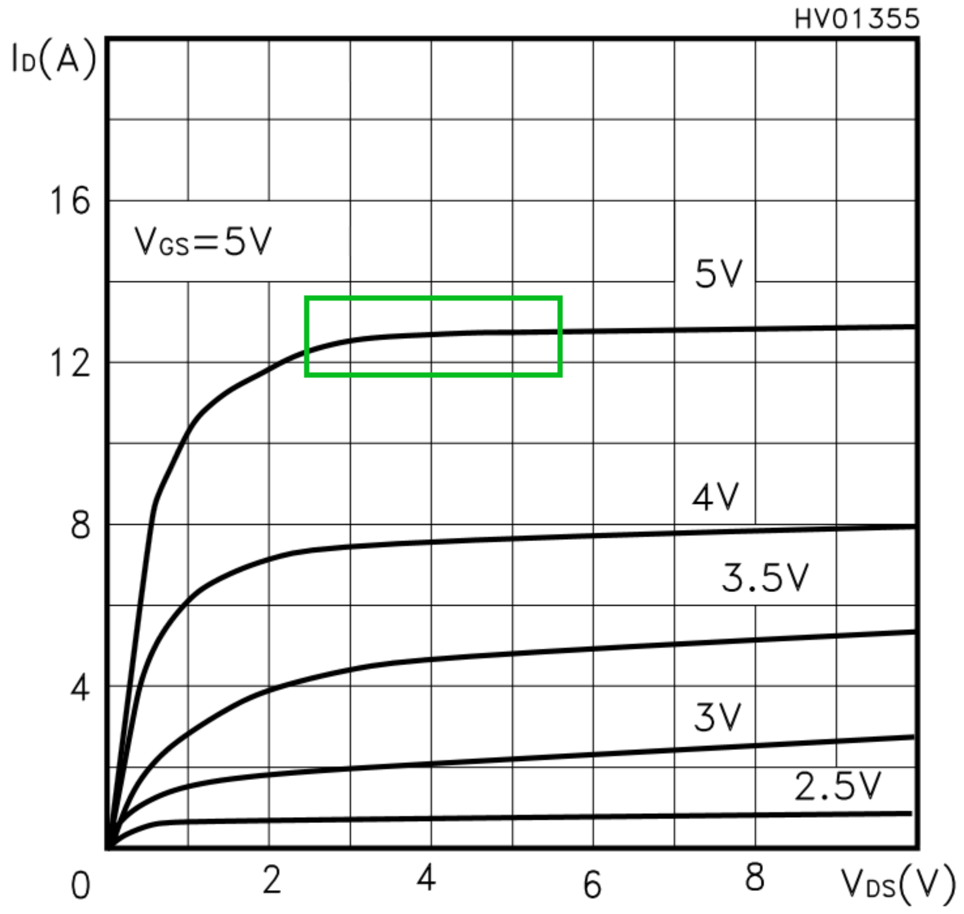


Example output characteristic

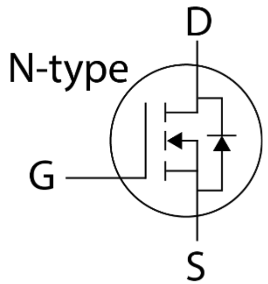


For this device:

- Apply Vgs=5V to allow approx. 12 A of current to flow.
    - The voltage dropped across the MOSFET Vds will be ~ 3 V.
- Vgs = 5 V is ideal.
- 3.3 V logic levels cannot give a high current.

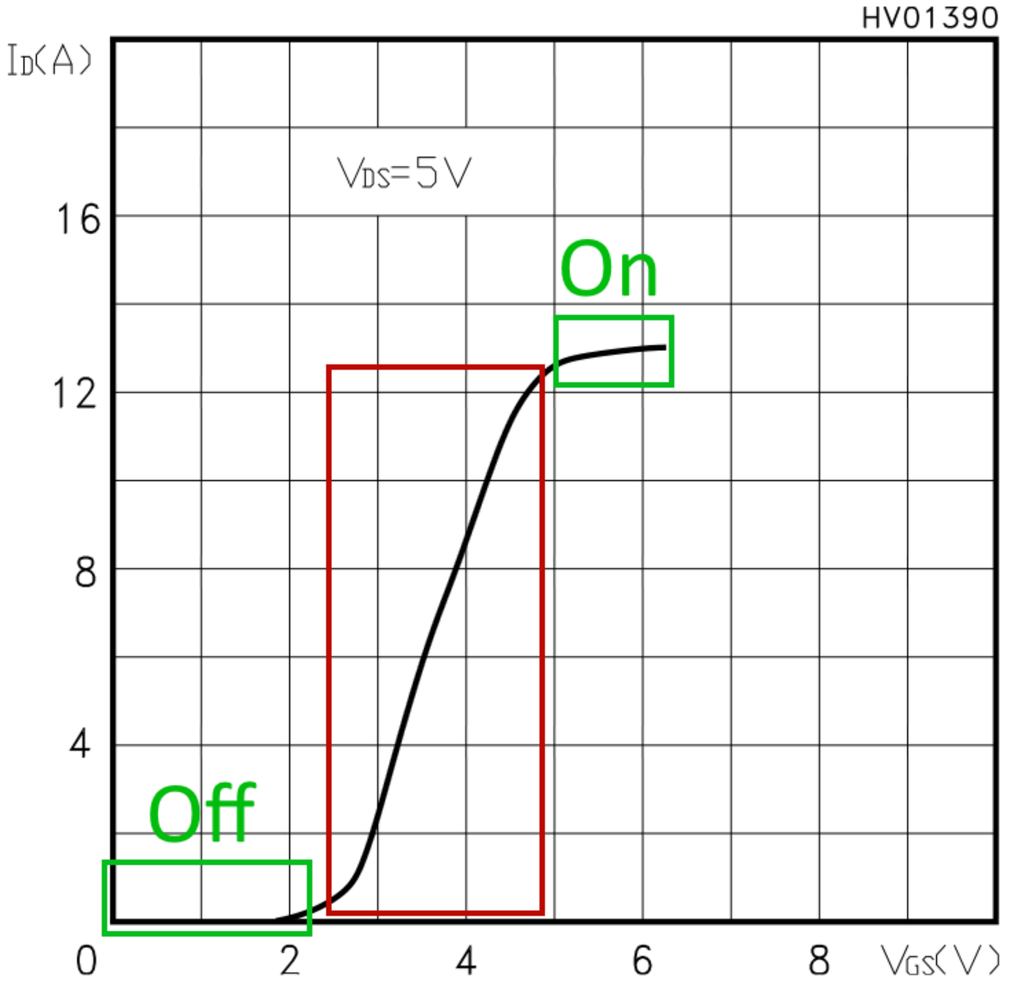


Example transfer characteristic



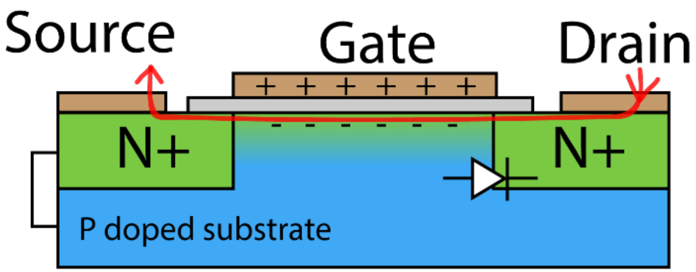
- To turn the transistor off, reduce Vgs below 2 V.
- To turn the transistor on, increase Vgs above 5 V.

- In the intermediate regime, the FET resistance increases and it may overheat.



Realistic MOSFET designs

- For simplicity of understanding, our toy MOSFET model (top right) had source and drain on the top of the substrate.
- **A more realistic design is the planar MOSFET** (bottom right)**.** Source and drain are on opposite sides of the substrate.
- The metal source electrode touches both the source semiconductor (N+ doped region) and the P doped body.
  - The N type epitaxial layer is grown on top of the N+ substrate, then P and N+ regions are formed by diffusion of impurity ions under high temperature.



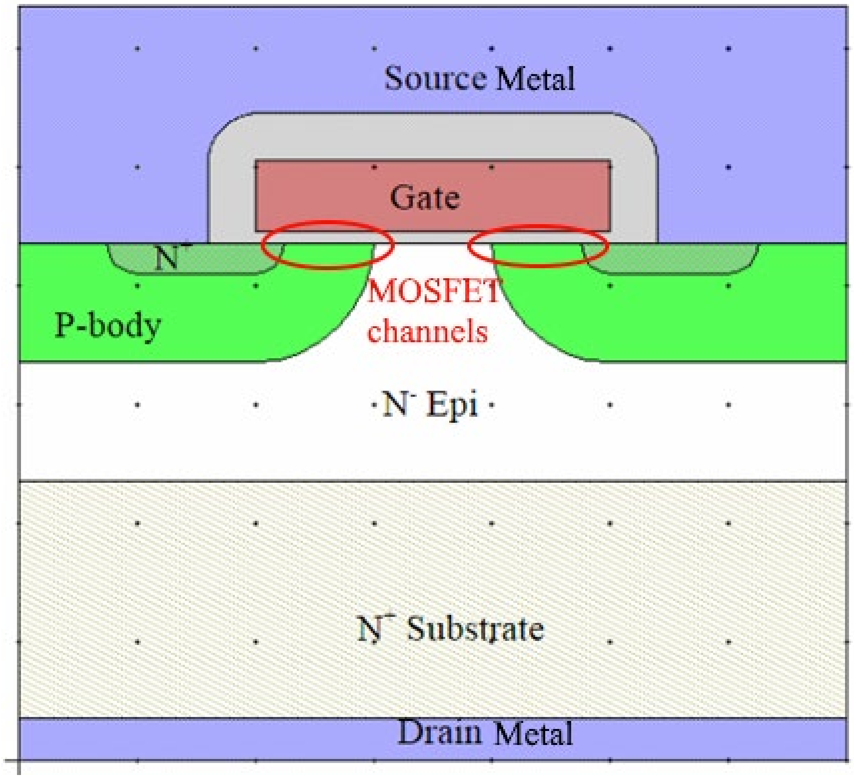
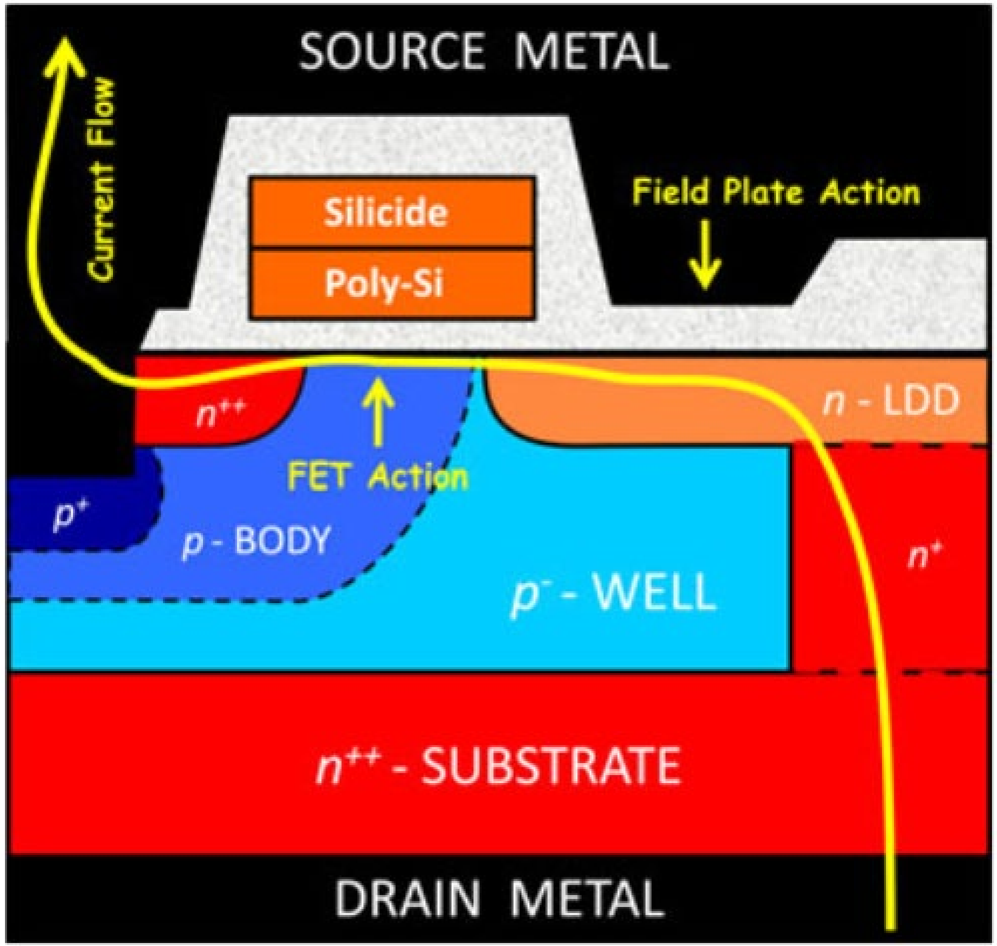


Image from Power MOSFET Basics by Alpha & Omega Semiconductor

Modern MOSFET example “NexFET” by Texas Instruments



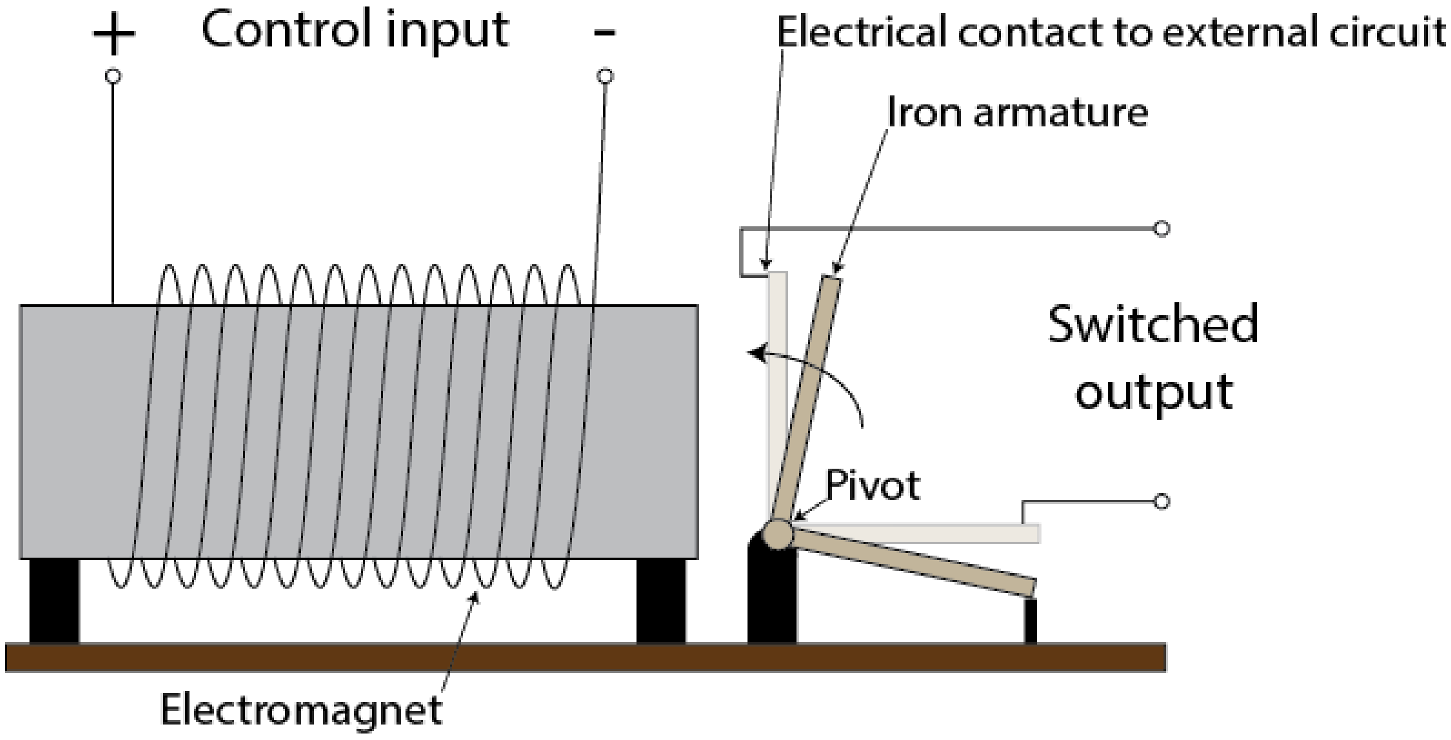
N type carriers move against the direction of current flow:

1. Enter the n++ highly doped source
2. Pass through the channel
3. Enter the lightly doped drain (LDD) region
4. Finally exit through the highly conductive n+ and n++ regions.

Image from Yang *et al*, IEEE Trans. on Power Electronics, vol 28, no. 9, page 4202, 2013.

Another way to switch large currents

- An **electromechanical relay** (or simply a relay) physically moves a switch using an electromagnet.

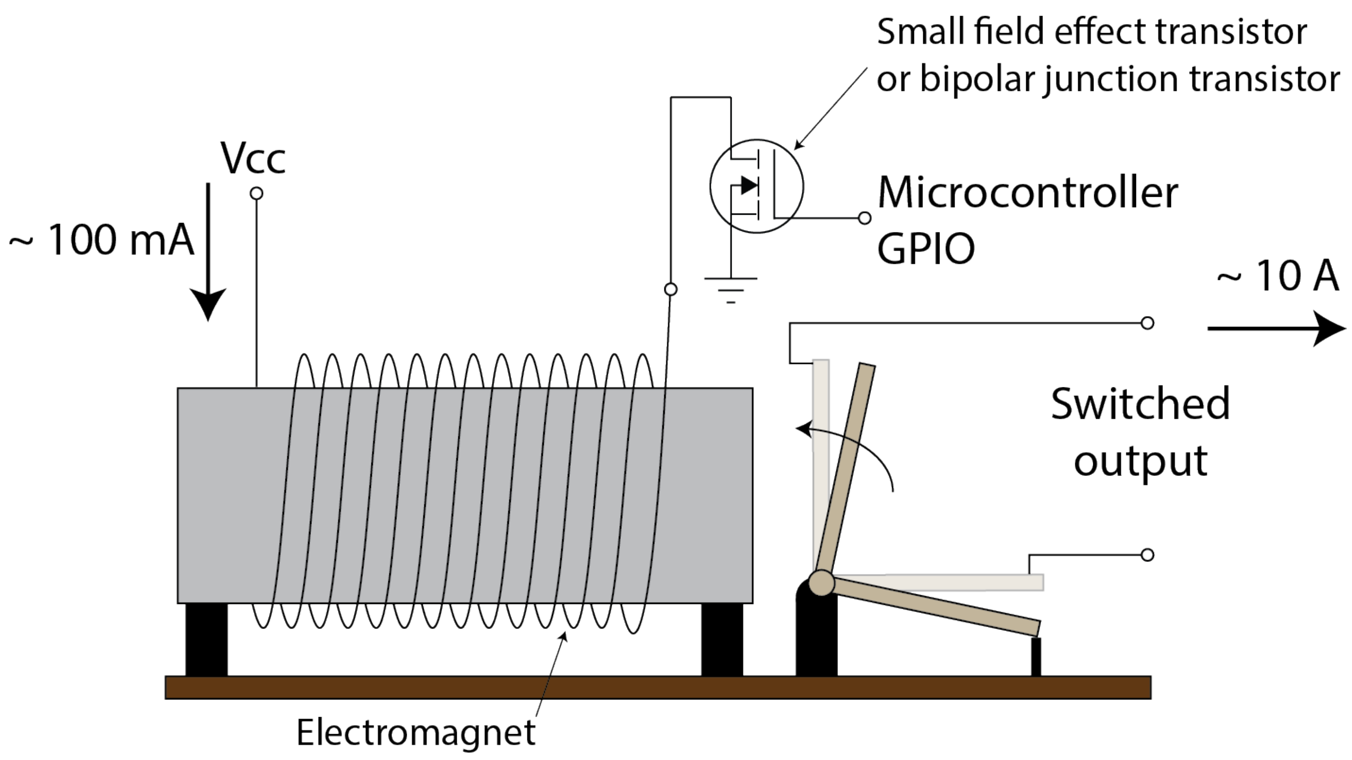


Properties of relays

- Relays are **robust** and easily handle large voltage spikes.
- Can switch **alternating current (AC) or direct current (DC)**.
- Typical devices designed to switch **tens - hundreds of amps**.
- Produce a **clicking noise** when switched because of the physical movement of the armature.
- Suitable for **low speed switching** (e.g. maximum tens of Hz).

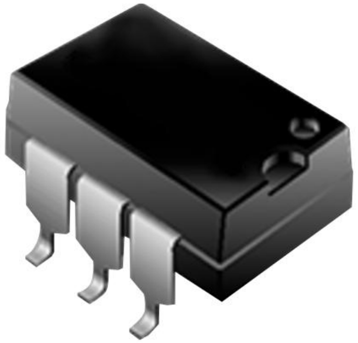
Controlling relays

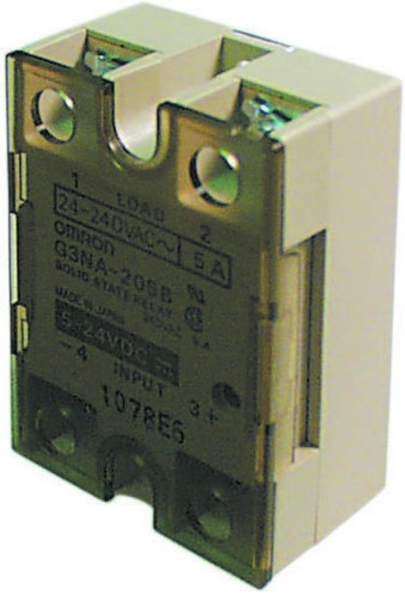
- Small relays typically need approx. 100 mA in the coil.
- **Can't drive relays directly from a microcontroller.**
- Need to use a small transistor to provide enough current to run the relay.

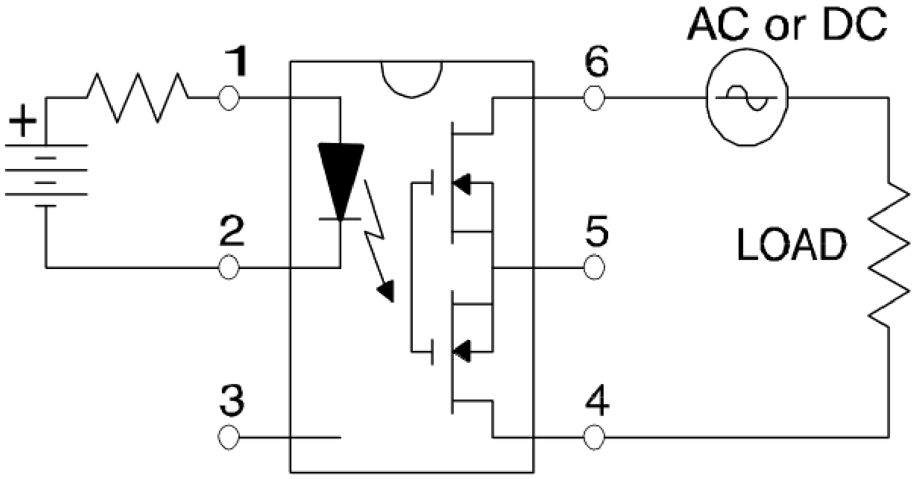


Solid State Relays

- An alternative to mechanical relays are “solid state relays” made from semiconductors.
  - These are technically not relays but borrowed the terminology.
- These are often chosen for higher switching speeds and improved reliability over mechanical relays.
- Available for PCB mounting or panel mounting.







Solid state vs electromechanical relays

Solid state relay	Electromechanical relay
Often built to switch only at the zero crossing of an AC waveform, resulting in less electrical noise.	Will produce an arc during switching (therefore not suitable for use near explosive gases).
Responds very quickly (sub-millisecond switching time).	Responds slowly (likely 50 – 100 milliseconds).
Robust against vibration and shock.	Subject to external forces such as vibration.
Larger power dissipation due to semiconducting switches. May require heatsinks / fans.	Smaller power dissipation due to all-metal contacts.
Higher cost.	Lower cost.

Summary

- Relays and FETs can be used to switch large currents.
- FETs are voltage-controlled switches ideal for embedded systems.

- Next lecture: how to use MOSFETs in motor control applications.