EE-557
Semiconductor devices I

Power semiconductor devices

Génie Electrique et Electronique
Master Program
Prof. Elison Matioli

Outline of the lecture

Basics of power devices

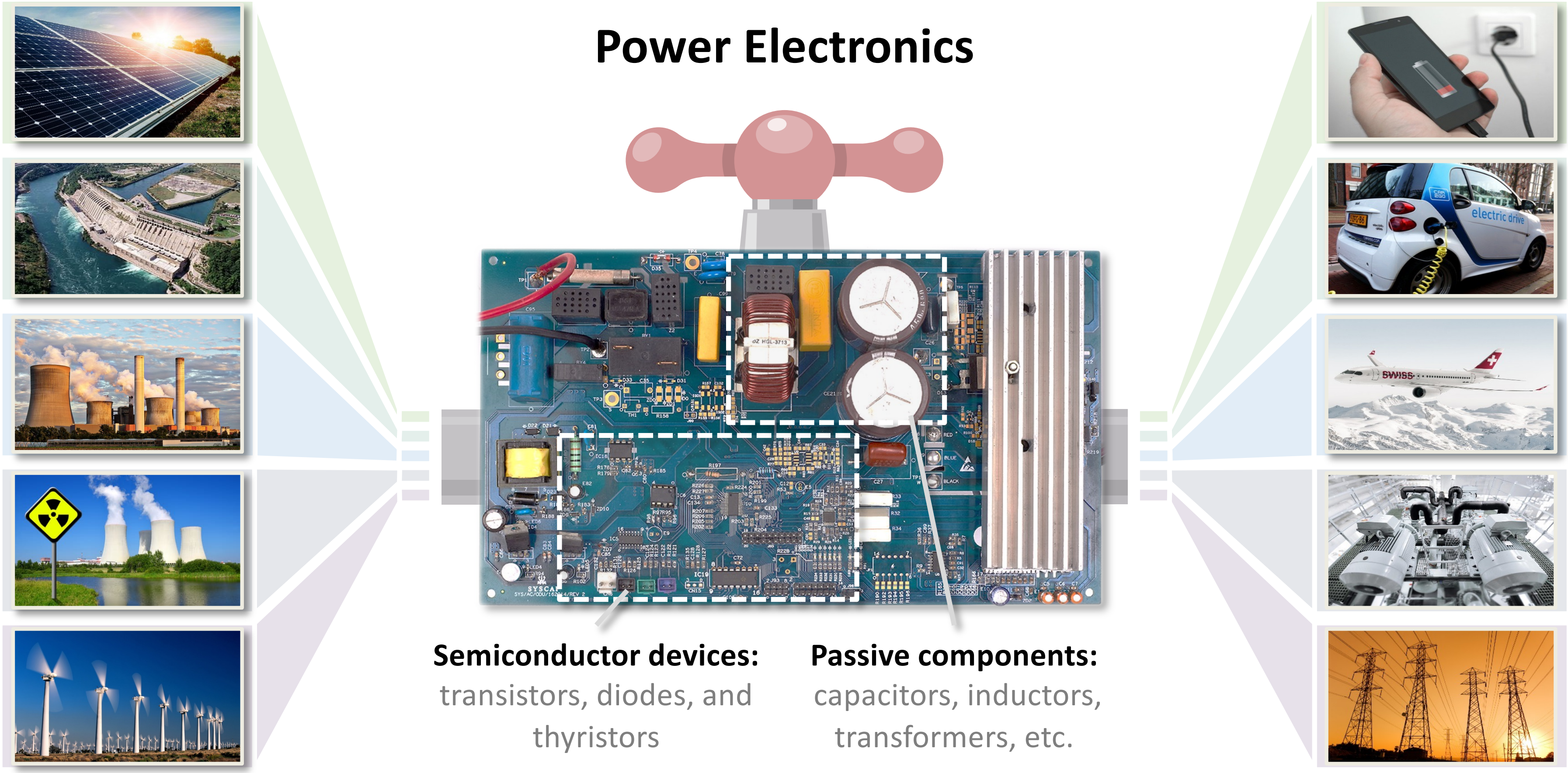
- Baliga's figure of merit
- Power diodes
- Power MOSFETs
- IGBTs

References:

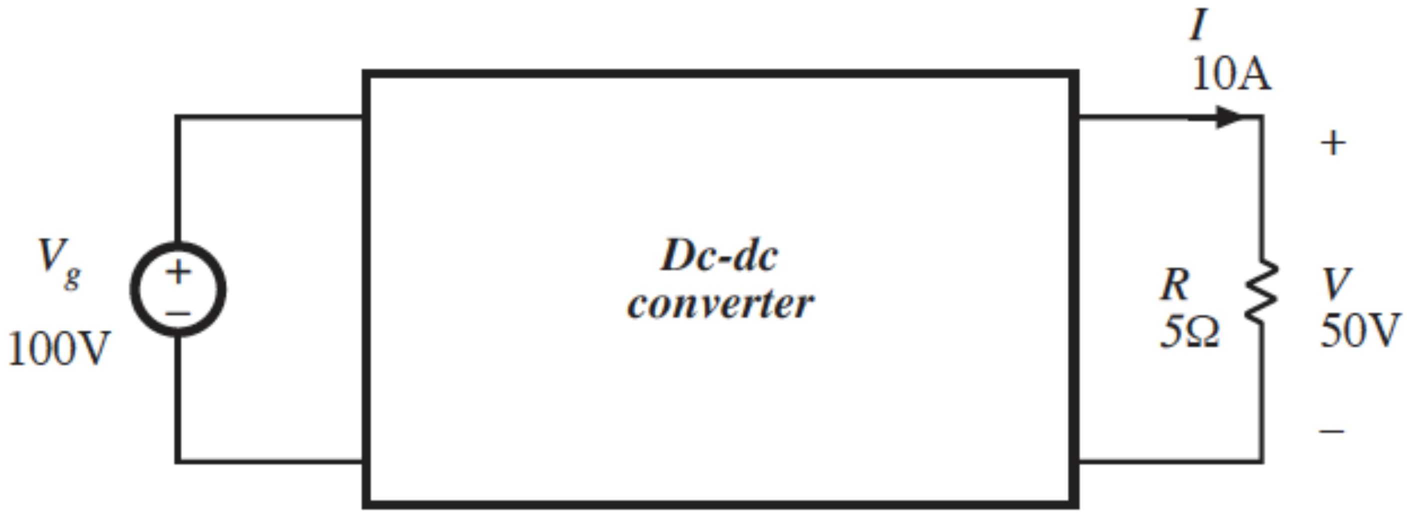
Chapter 4.2 of Fundamentals of Power Electronics – second edition – Robert W. Erickson and Dragan Maksimović, Kluwer Academic Publishers, 2004

Key questions

- How can semiconductor devices hold large voltages for power applications?
- How is the voltage related to the semiconductor properties?
- What are the different types of semiconductor power devices?

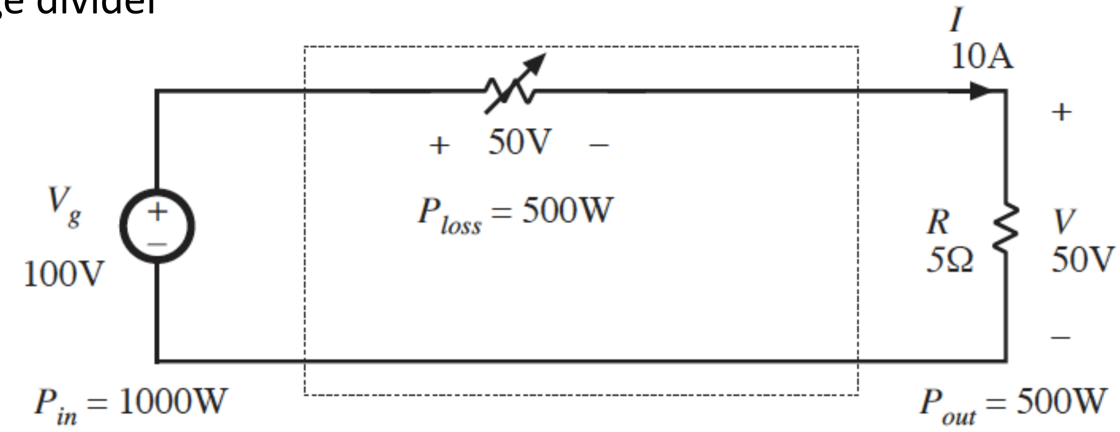

Power Electronics
Semiconductor devices:
transistors, diodes, and thyristors
Passive components:
capacitors, inductors, transformers, etc.
SWISS
electric drive

DC-DC converter

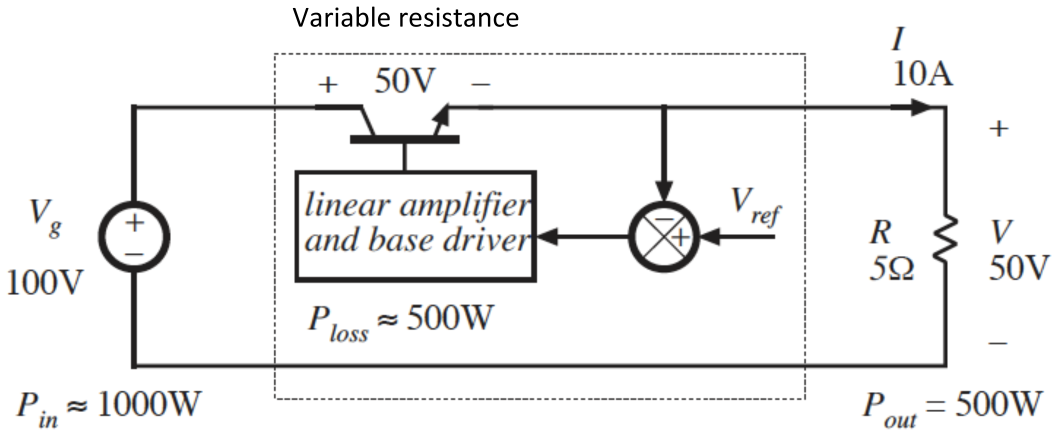


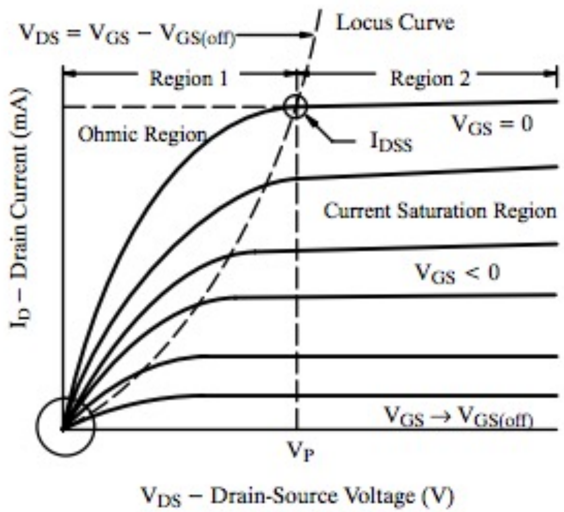
How can such converter be realised?

Solution 1: voltage divider



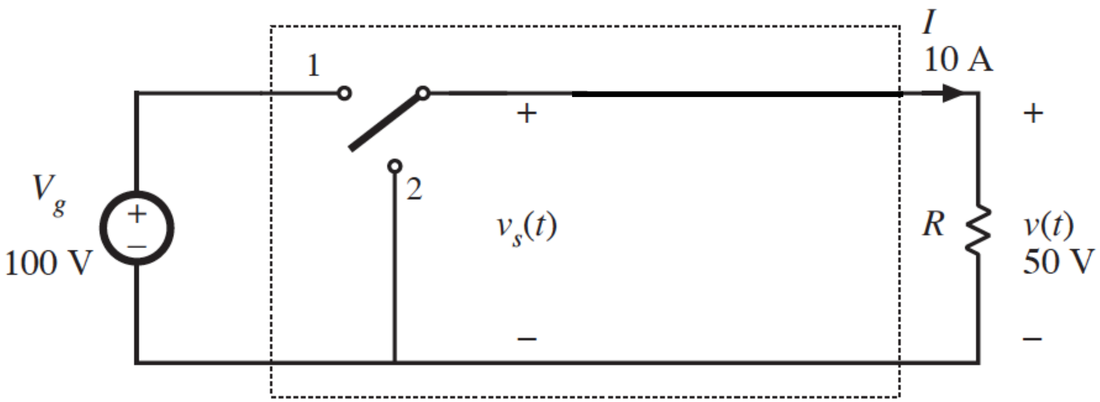
Solution 2: linear amplifier

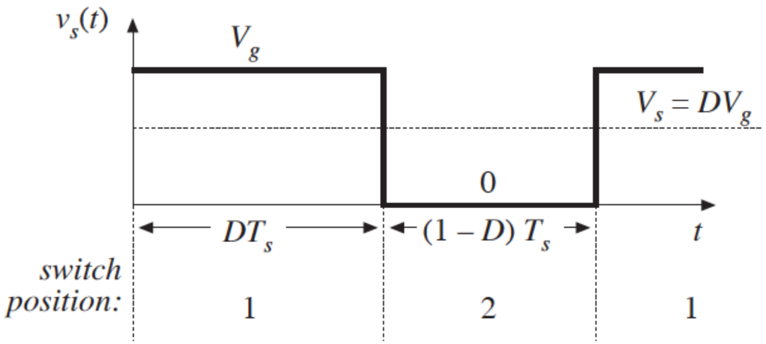




These are very inefficient solutions

Concept of switching





D = switch duty cycle

$0 \leq D \leq 1$

T_s = switching period

f_s = switching frequency

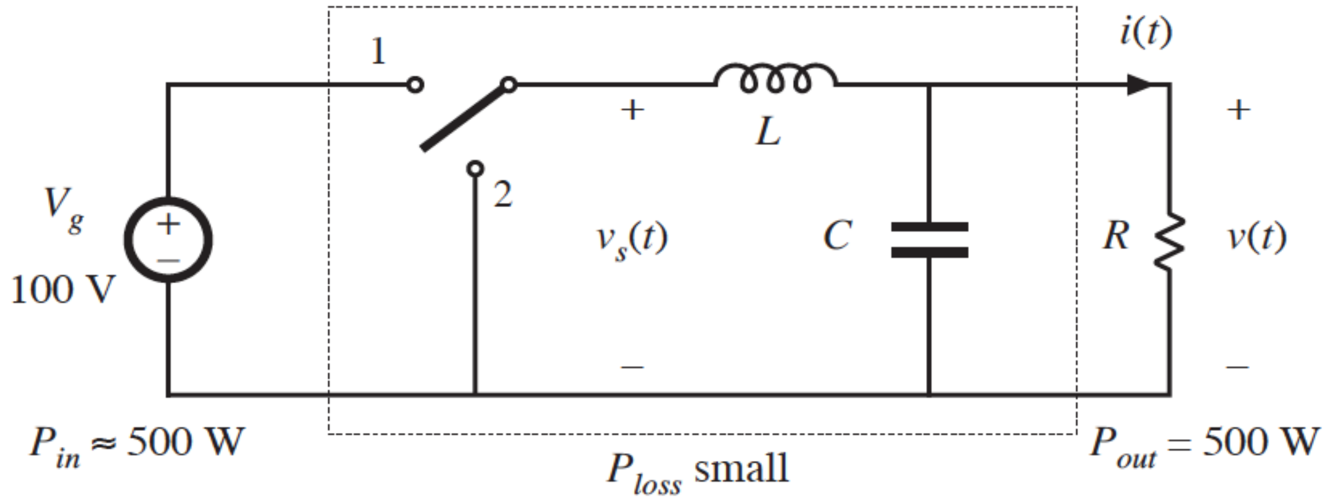
$= 1 / T_s$

DC component of $v_s(t)$ = average value:

$$V_s = \frac{1}{T_s} \int_0^{T_s} v_s(t)\, dt = DV_g$$

Fundamentals of Power Electronics, Robert W. Erickson, Dragan Maksimović

Addition of (ideally lossless) *L-C* low-pass filter, for removal of switching harmonics:

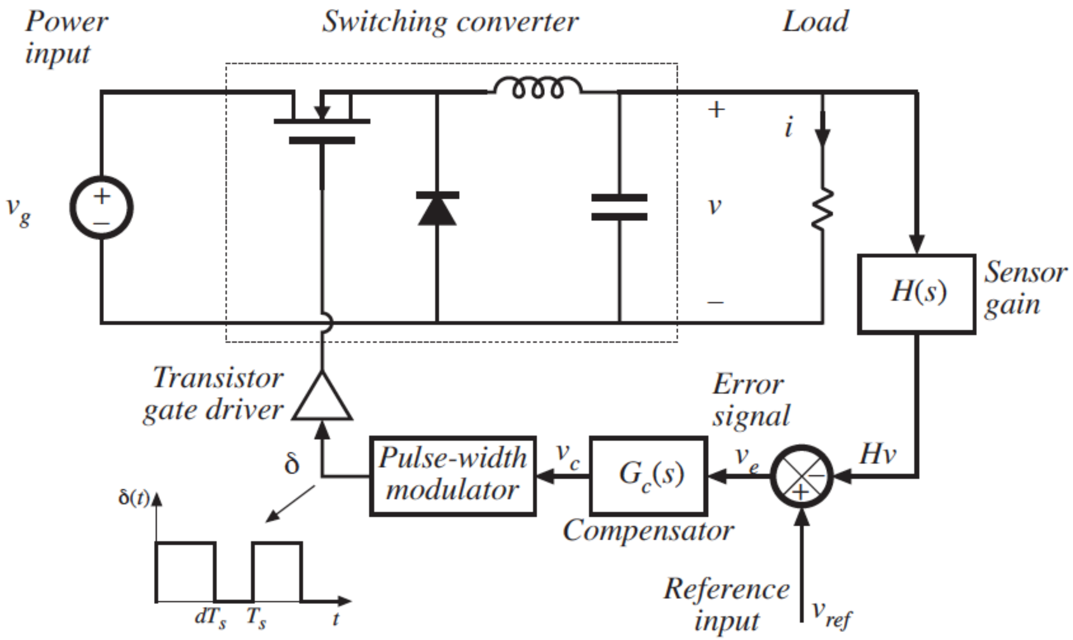


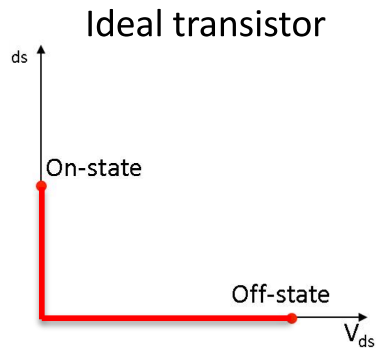
- Cut-off frequency of the filter must be much smaller that the switching frequency $\mathbf{f_0 << f_S}$
- This is called a **buck converter:** $\mathbf{V_{out} = DV_{in}}$

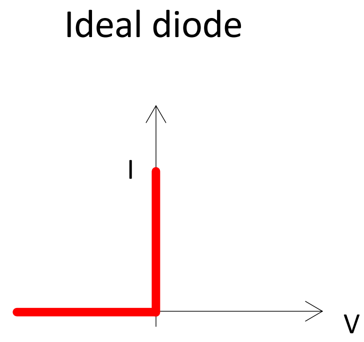
Fundamentals of Power Electronics, Robert W. Erickson, Dragan Maksimović

Realization of such circuit:

Power transistors + power diodes + filters + circuit de regulation







Product V x I must be as close as possible to zero

Power transistors and diodes are the heart of power converters

They are power switching devices, which:

Should **conduct with small losses**, **switch fast** with small losses, **hold large voltages**

Efficient conversion is the goal: what are the loss mechanisms?

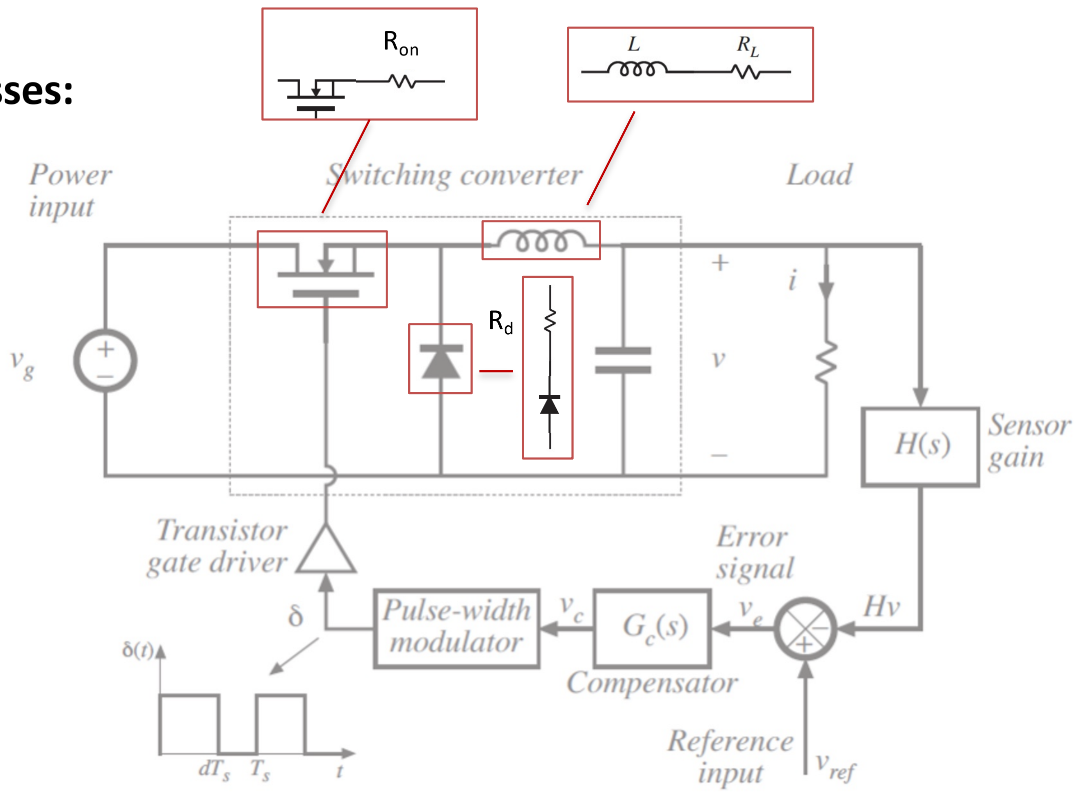
Fundamentals of Power Electronics, Robert W. Erickson, Dragan Maksimović

Two main loss mechanisms:

1. Conduction losses: when devices are conducting
- Semiconductor forward bias
- Parasitics: inductances, capacitances, resistances

2. Switching losses: when devices are switching

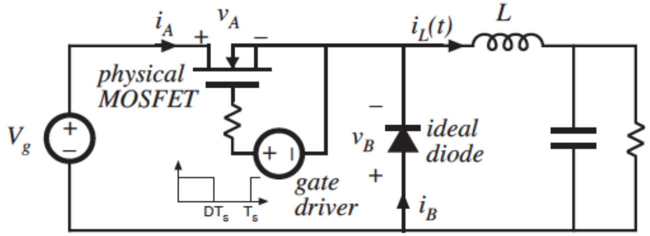
1. Conduction losses:



Dissipated power

$P_{conduction} = R_{on} I_{RMS}^2$

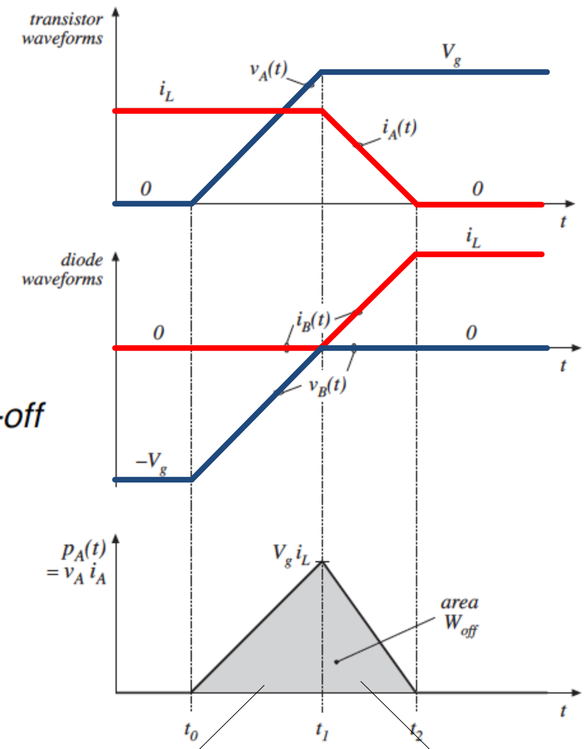
2. Switching losses:



Buck converter example

$$v_B(t) = v_A(t) - V_g$$
$$i_A(t) + i_B(t) = i_L$$

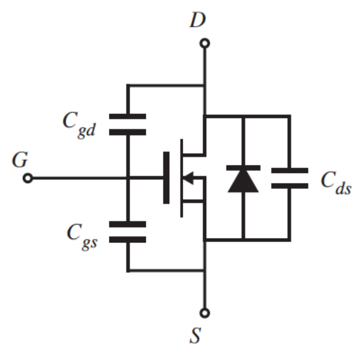
transistor turn-off transition



Charging time of C_{GD}

Discharging time of C_{GS}

Equivalent circuit



Energy lost during transistor turn-off transition:

$$W_{off} = \frac{1}{2} V_g i_L (t_2 - t_0)$$

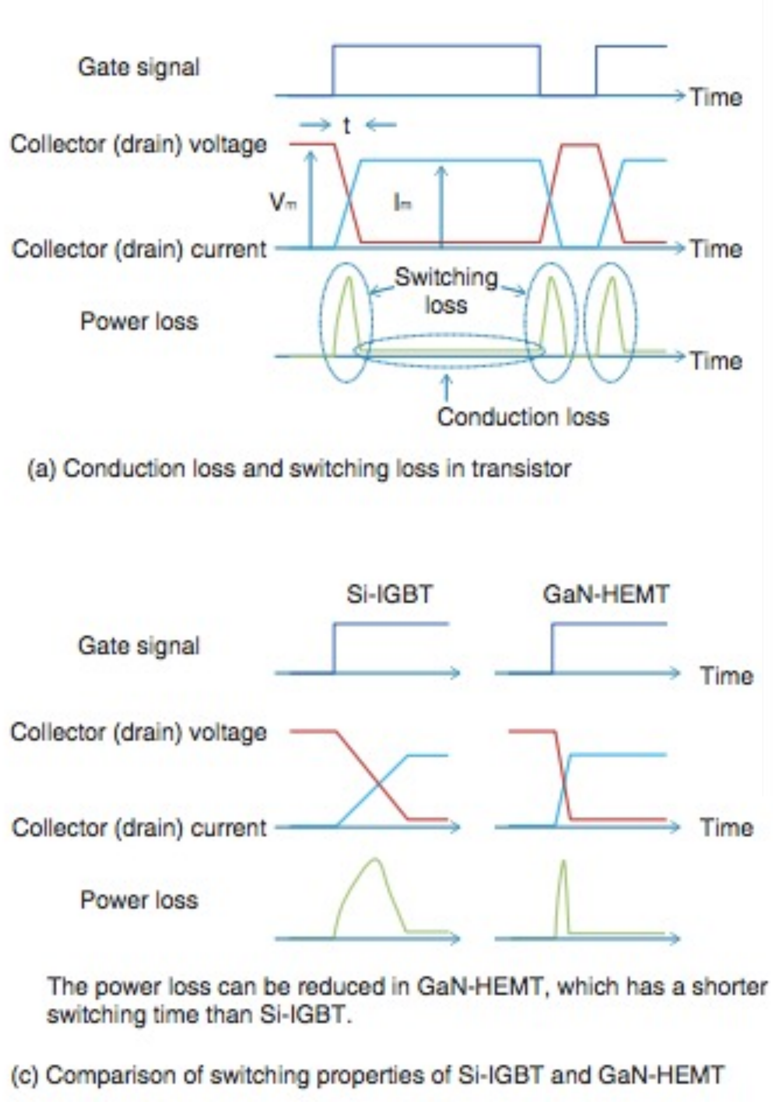
Similar result during transistor turn-on transition.
Average power loss:

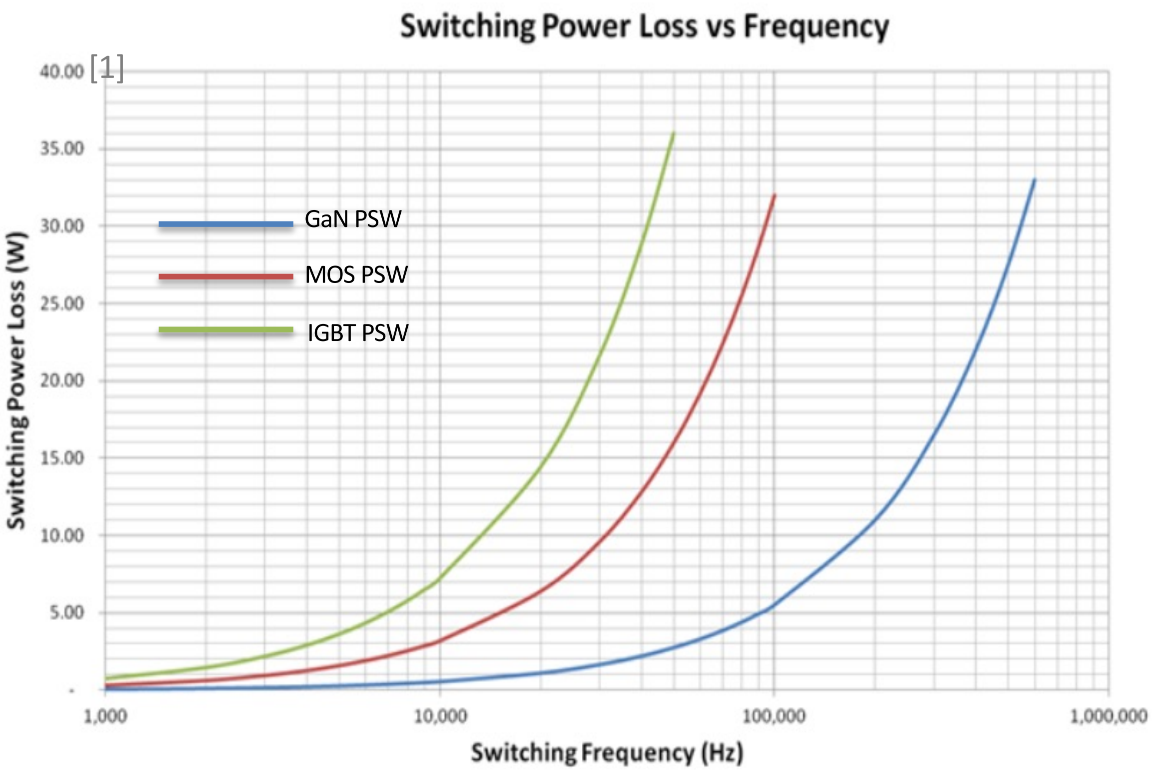
$$P_{sw} = \frac{1}{T_s} \int_{\substack{\text{switching}\\ \text{transitions}}} p_A(t)\, dt = (W_{on} + W_{off})\, f_s$$

Switching losses are proportional to the switching frequency…

…while conduction losses are fixed

Switching losses



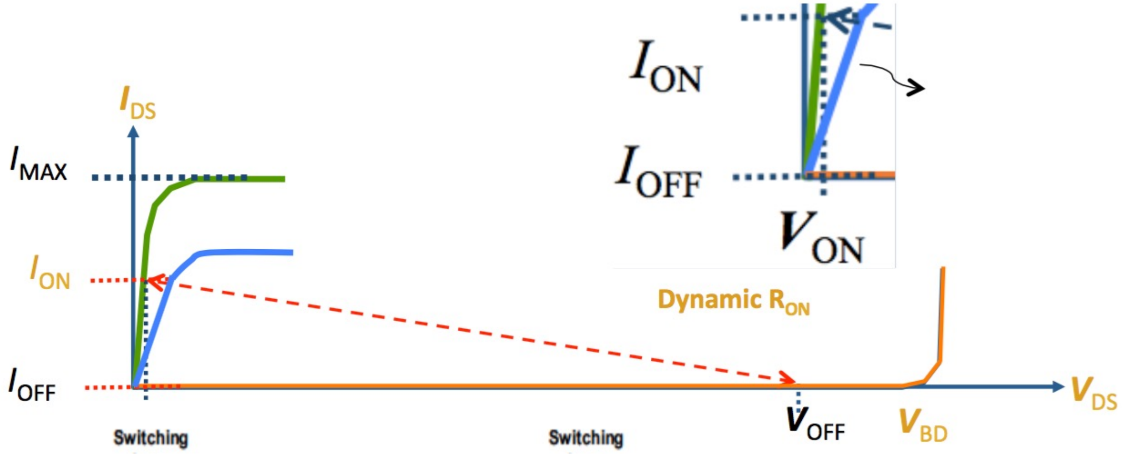


Switching losses are proportional to the switching frequency: Fast devices are required!

[1] http://pi-innovo.com/content/uploads/2016/03/Figure-2.png

Requirements for efficient power electronic devices

Power switch:

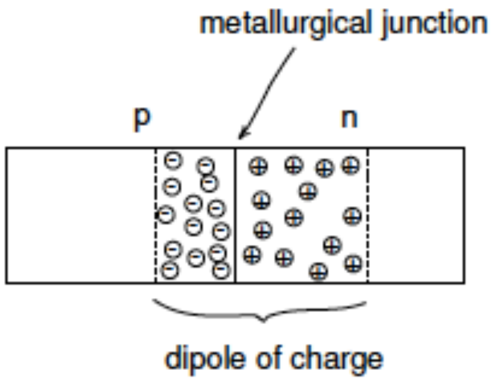


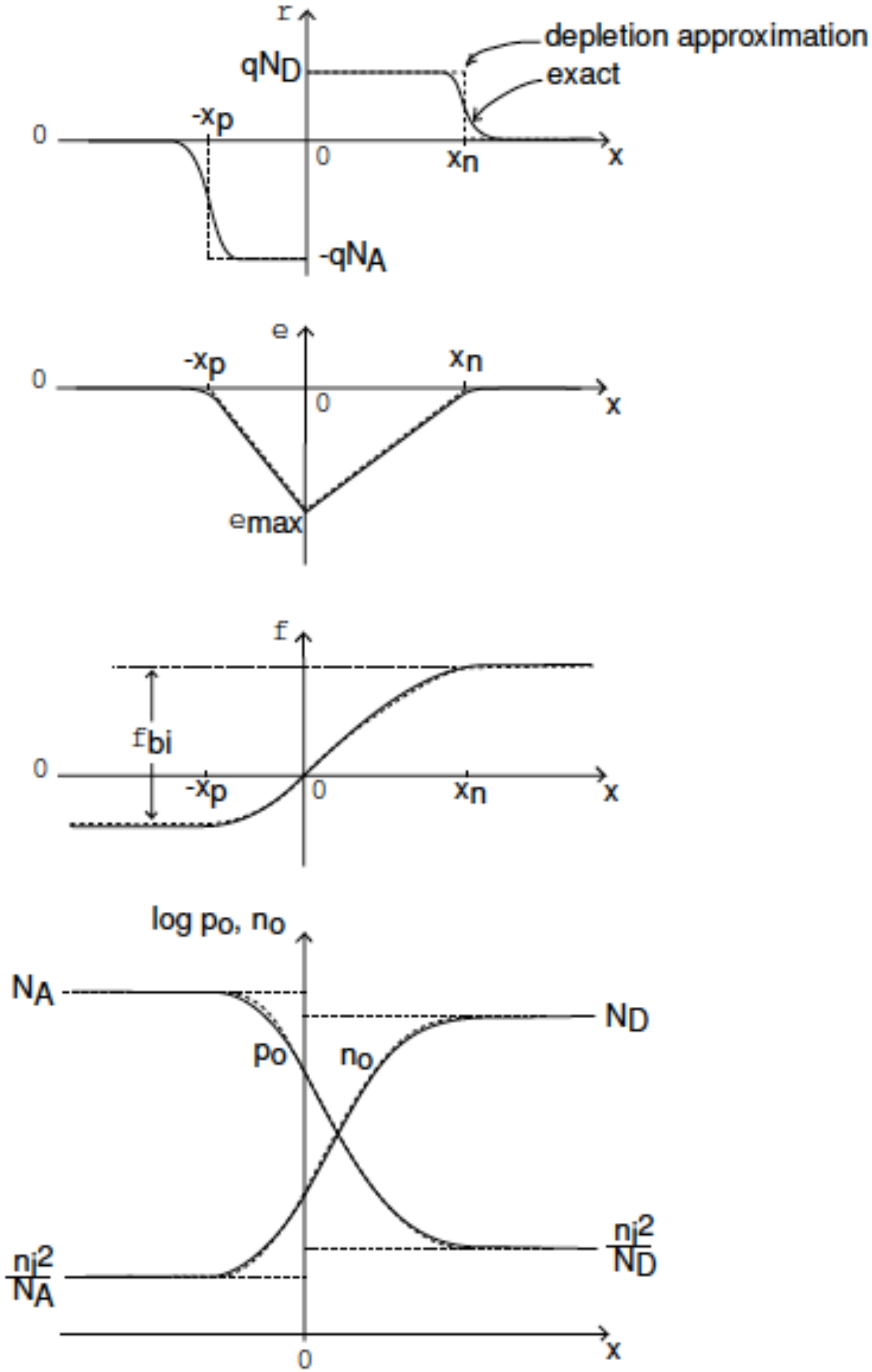
It operates in two regimes:
ON: Low voltage, high current
OFF: High voltage, low current

- High breakdown voltage
- Low on-resistance: Small on-state power dissipation: $I_{rms}^2 x R_{on}$
- High maximum current
- Low leakage current at breakdown voltage: Small off-state power dissipation: $I_{off}\, x V_{br}$

How to get large breakdown voltages?

Back to pn junctions





Distinct regions:

Around metallurgical junction:
space charge region (SCR)

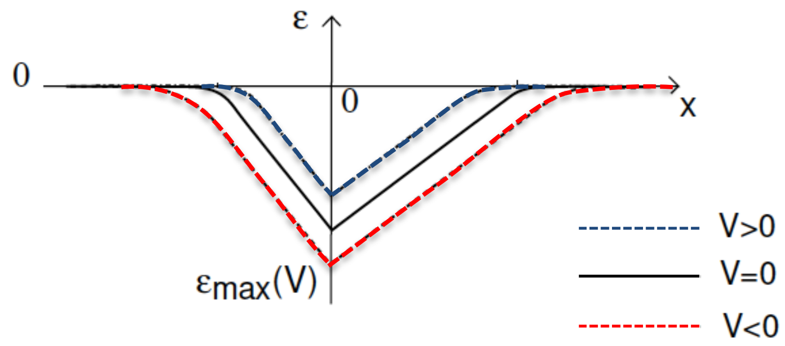
Far from junction:
quasi-neutral regions (QNR)
$\rho \sim 0$

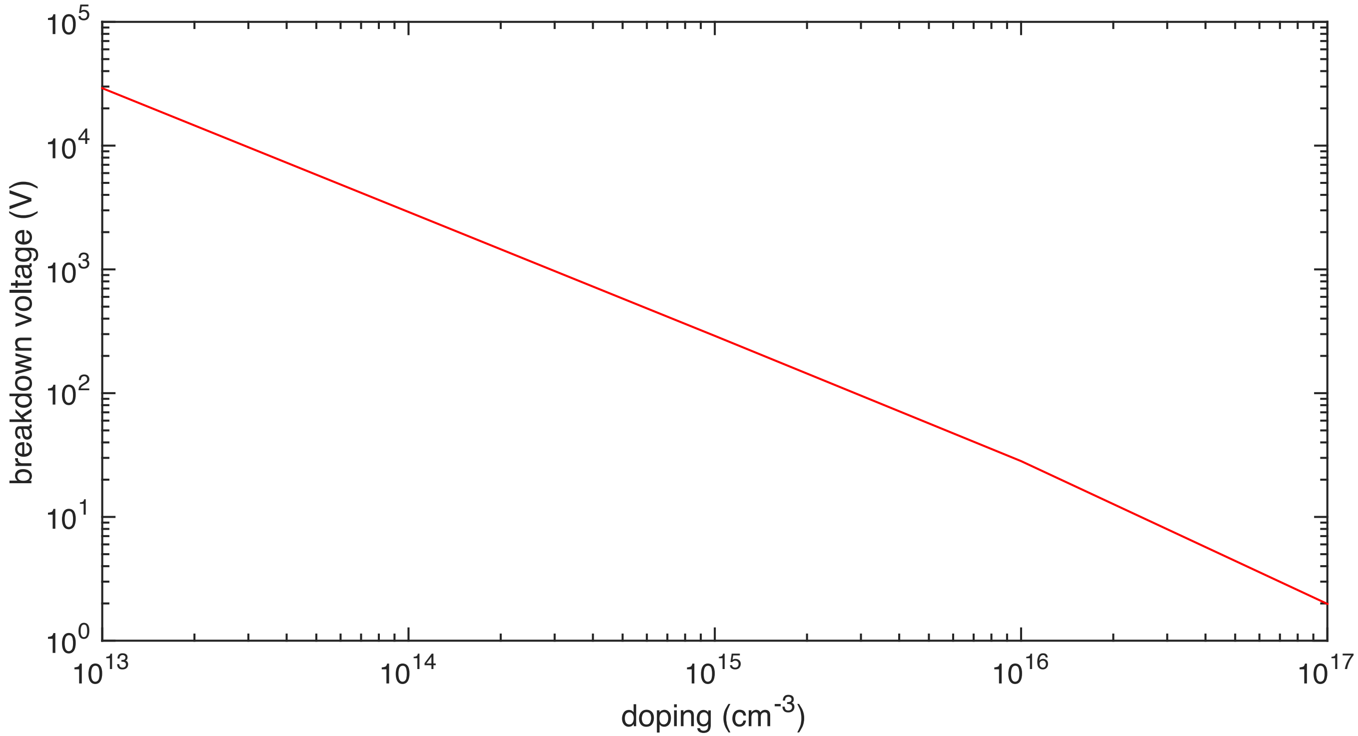
Electric field is constant and equal to zero

Ideal p-n junction out of equilibrium

Peak electric field:

$$|\mathcal{E}_{max}(V)| = \sqrt{\frac{2qN_AN_D(\phi_{bi} - V)}{\epsilon(N_D + N_A)}} = |\mathcal{E}_{max}(V = 0)|\sqrt{1 - \frac{V}{\phi_{bi}}}$$





How to make a power device?

Power diodes

Goal:

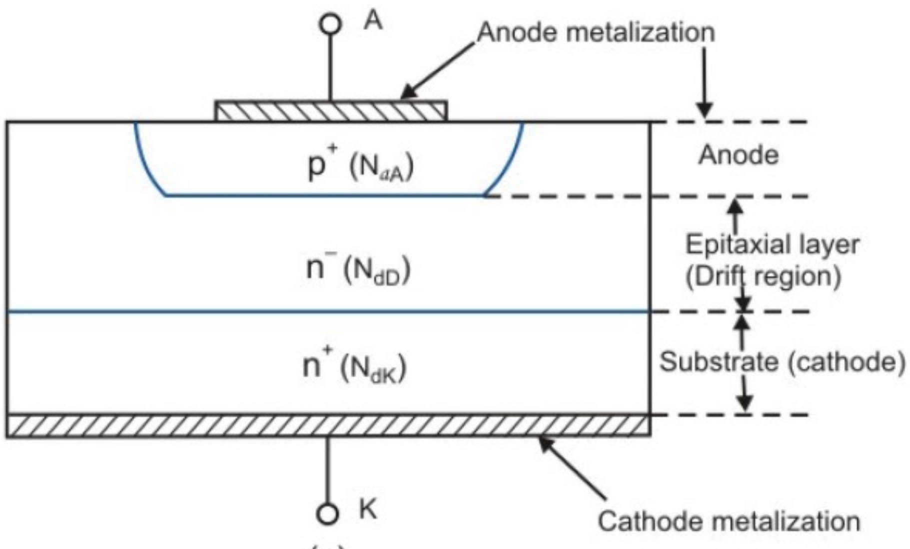
Conduct **several kilo amps** of current in the forward direction with very **little power loss** while blocking **several kilo volts** in the reverse direction.

Large blocking voltage requires **wide depletion layer** in order to restrict the maximum electric field strength below the breakdown voltage (impact ionization level).

Space **charge density in the depletion layer should also be low** in order to yield a wide depletion layer for a given **maximum electric field strength**.

This is satisfied in a **lightly doped p-n junction** diode **of sufficient width** to accommodate the required depletion layer.

PIN diode



(c)

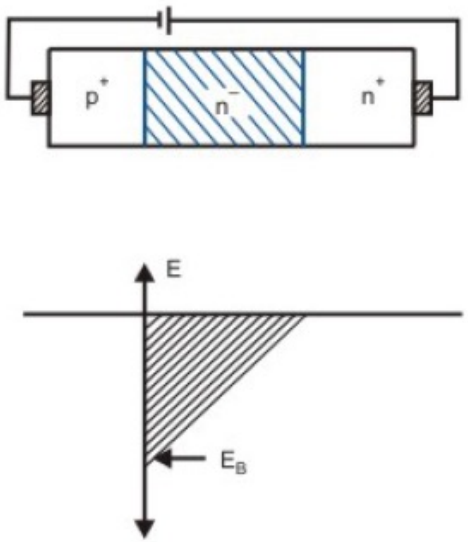
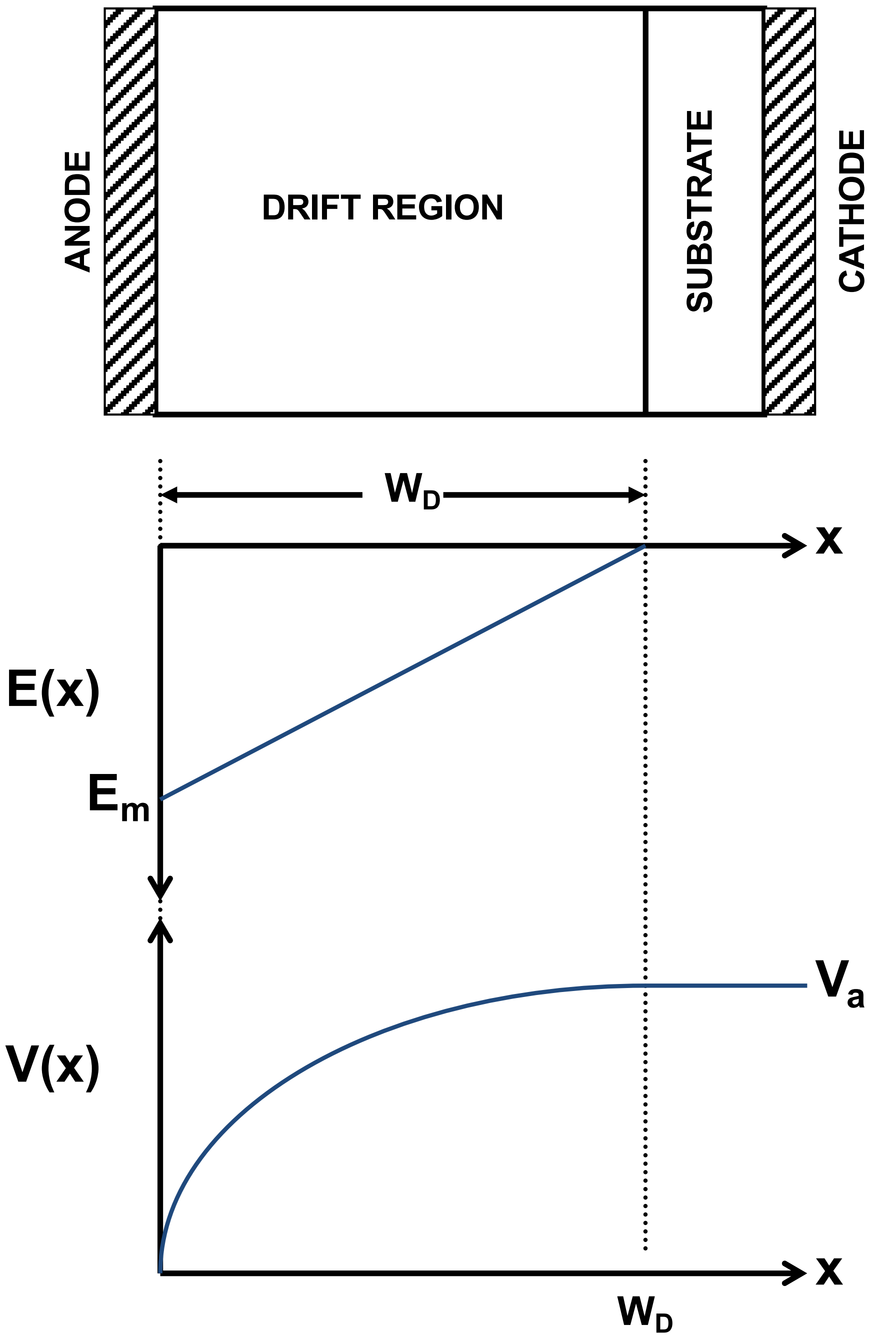


Figure of merit: how to compare different semiconductors



Specific on-resistance (Ωcm^2)

$$R_{ON,SP} = \frac{W_D}{qN_D\mu_n}$$

$$V = \frac{E_m W_D}{2} \quad \text{thus} \quad \boxed{W_D = \frac{2BV}{E_C}}$$

Poisson's Equation:

$$\frac{d^2V}{dx^2} = -\frac{dE}{dx} = -\frac{Q(x)}{\varepsilon_S} = -\frac{qN_D}{\varepsilon_S}$$

$$E(x) = -\frac{qN_D}{\varepsilon_S}(W_D - x)$$

$$V(x) = \frac{qN_D}{\varepsilon_S}(W_D x - \frac{x^2}{2})$$

$$V_a = \frac{qN_D W_D^2}{2\varepsilon_S}$$

$$\boxed{N_D = \frac{\varepsilon_S E_C^2}{2qBV}}$$

Figure of merit: how to compare different semiconductors

Ideal Specific On-Resistance ($R_{ON,SP}$):

$$W_D = \frac{2BV}{E_C} \quad \text{and} \quad N_D = \frac{\varepsilon_S E_C^2}{2qBV}$$

$$R_{ON,SP} = \frac{W_D}{q\mu_n N_D}$$

$$R_{ON,SP} = \frac{4BV^2}{\varepsilon_S \mu_n E_C^3}$$

$R_{on,sp}$ is related to material properties

Baliga's figure of merit

$$BFOM = \varepsilon_S \mu_n E_C^3 = \frac{4BV^2}{R_{ON,SP}}$$

Critical electric field E_c is very important, followed by mobility in the drift layer

B.J. Baliga, *Fundamentals of Power Semiconductor Devices*, Springer 2008

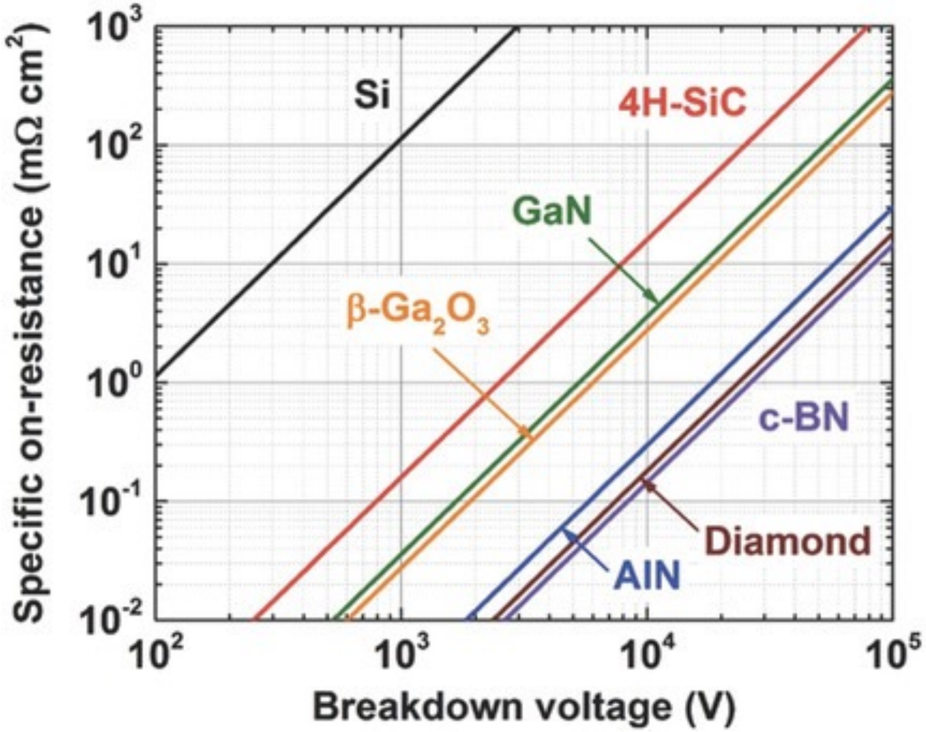
Wide-band-gap materials

$$R_{ON,SP} = \frac{4BV^2}{\varepsilon_S \mu_n E_C^3}$$

$R_{on,sp}$ is related to material properties

Baliga's figure of merit

$$BFOM = \varepsilon_S \mu_n E_C^3 = \frac{4BV^2}{R_{ON,SP}}$$



Parameter	Silicon	4H-SiC	GaN	Diamond
E_g, eV	1.12	3.26	3.39	5.47
E_{crit}, MV/cm	0.23	2.2	3.3	5.6
ε_r	11.8	9.7	9.0	5.7
μ_n, cm^2/V·s	1400	950	800/1700[b]	1800
BFoM[a] relative to Si	1	500	1300/2700[b]	9000
n_i, cm^{-3}	$1 \cdot 10^{10}$	$8 \cdot 10^{-9}$	$2 \cdot 10^{-10}$	$1 \cdot 10^{-20}$
λ, W/cm·K	1.5	3.8	1.3/3[c]	20

B.J. Baliga, *Fundamentals of Power Semiconductor Devices*, Springer 2008

Influence of material properties

Parameter	Silicon	4H-SiC	GaN	Diamond
E_g, eV	1.12	3.26	3.39	5.47
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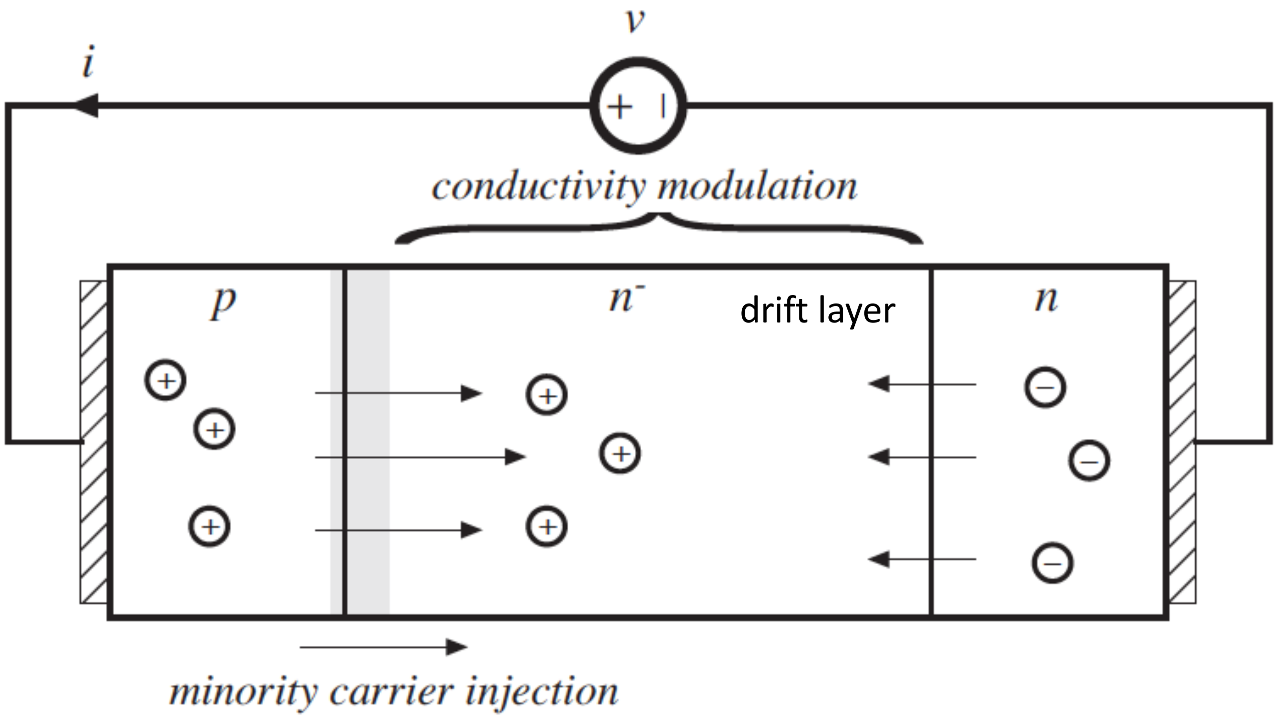
n_i, cm^{-3}	$1{\cdot}10^{10}$	$8{\cdot}10^{-9}$	$2{\cdot}10^{-10}$	$1{\cdot}10^{-20}$
λ, W/cm·K	1.5	3.8	1.3/3[c]	20

Desired properties, found in some of these wide band-gap materials:

- Higher breakdown strength: same breakdown voltage with less material
- Higher switching speed: lower switching losses
- Lower losses: enables significantly reduced volume and decreased cooling requirements
- Higher frequency: smaller passive components (inductors and capacitors)

diode PIN

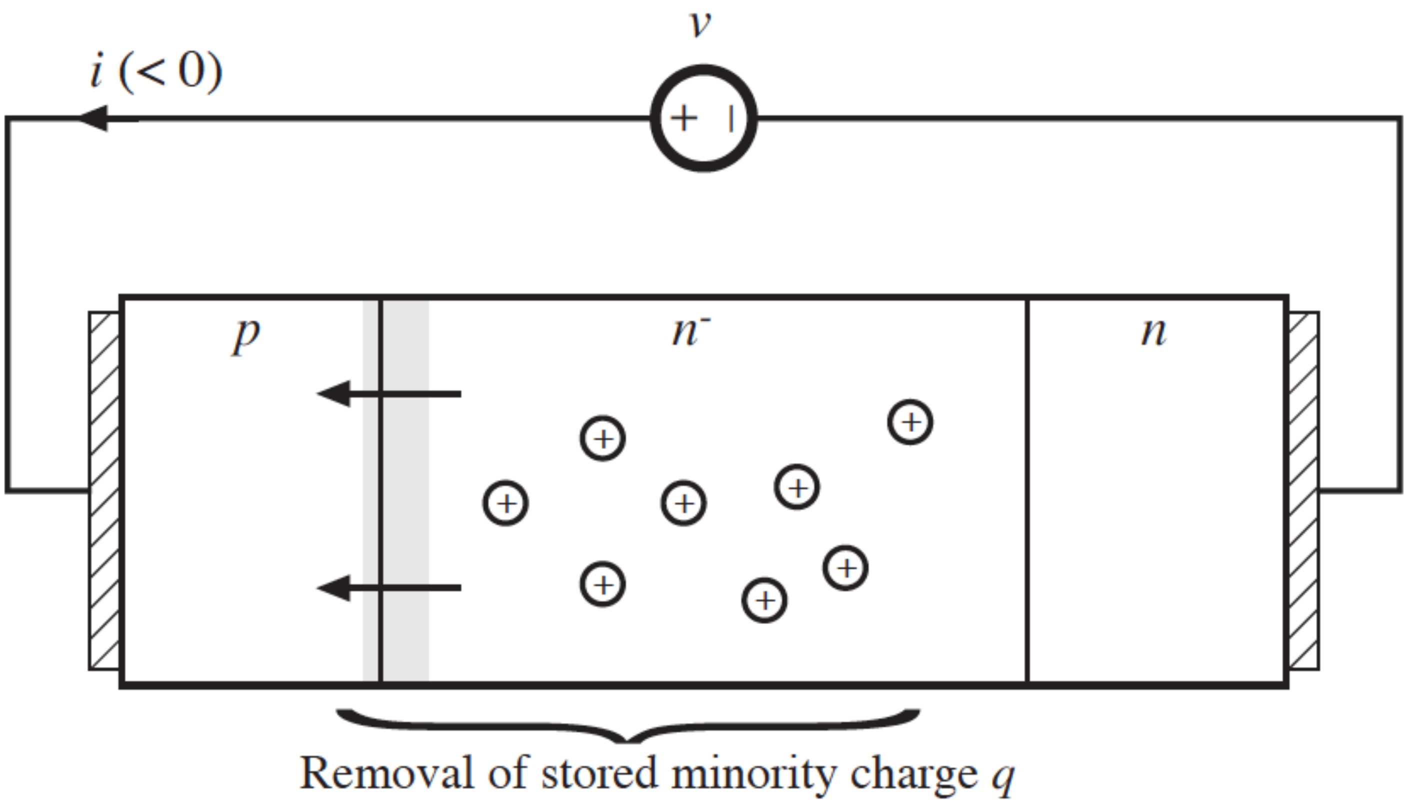
Forward polarization



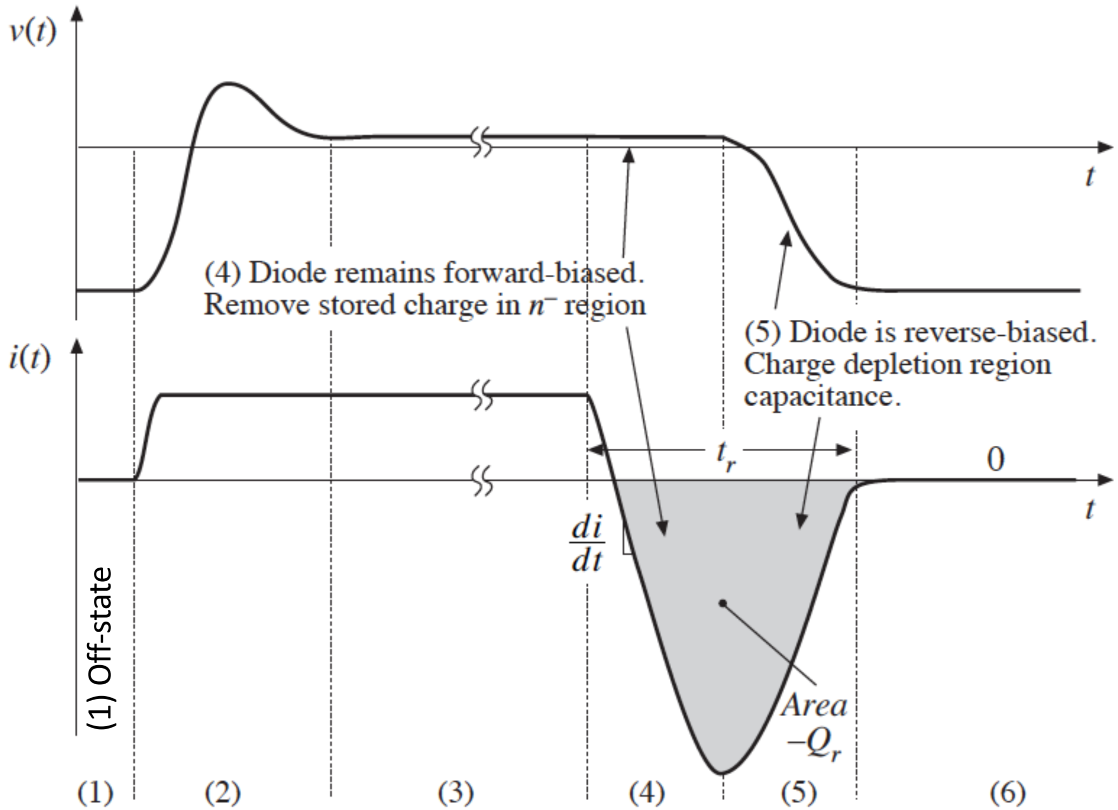
Forward polarization:

- Injection of minority carriers in the drift layer: conductivity modulation
- Charges are accumulated in the region «i»:
    - Resistance is reduced
    - But slows down the device
- Minority carrier device

Turn-off transient



Power diodes



(4) Reduction of the stored minority charge can be accomplished either by active means, via **negative terminal current**, or by passive means, via **recombination**. Normally, both mechanisms occur simultaneously.

The charge contained in the negative portion of the diode turn-off current waveform is called the **recovered charge**.

Minority charges are actively-removed during interval (4).

At the end of interval (4), the stored minority charge in the vicinity of the **junction has been removed**, such that the diode junction becomes **reverse-biased** and is able to **block negative voltage.**

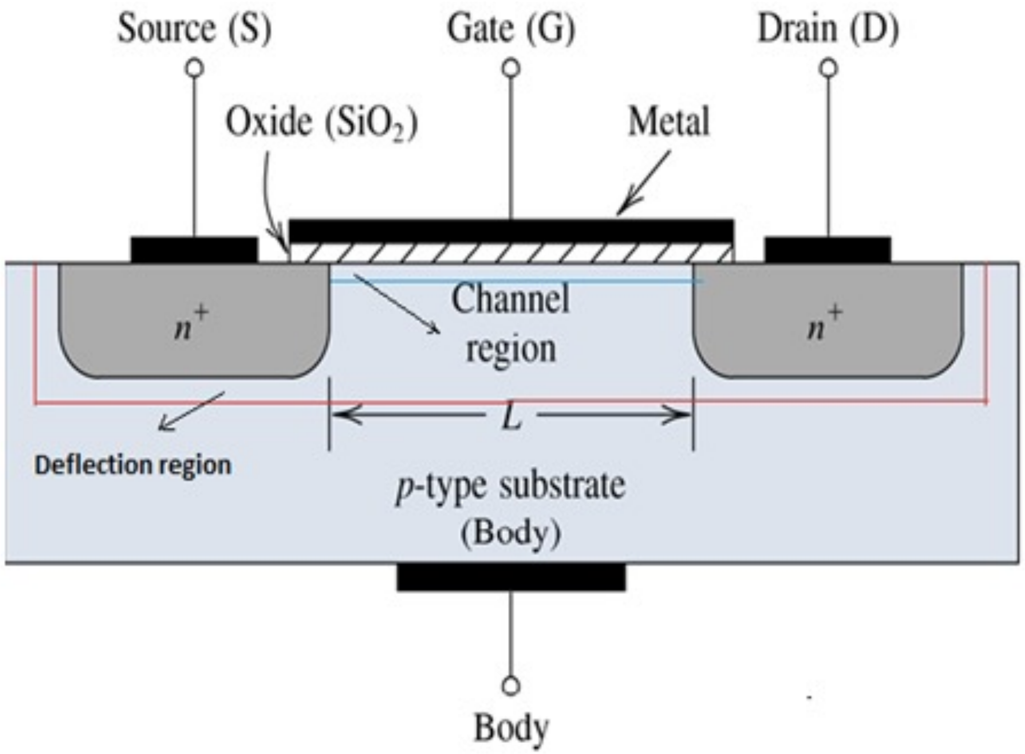
The depletion region **effective capacitance is then charged** during interval (5) to the negative off-state voltage.

The portion of Q during interval (5) is **charge supplied to the depletion region**, as well as minority charge that is actively removed from remote areas of the diode.

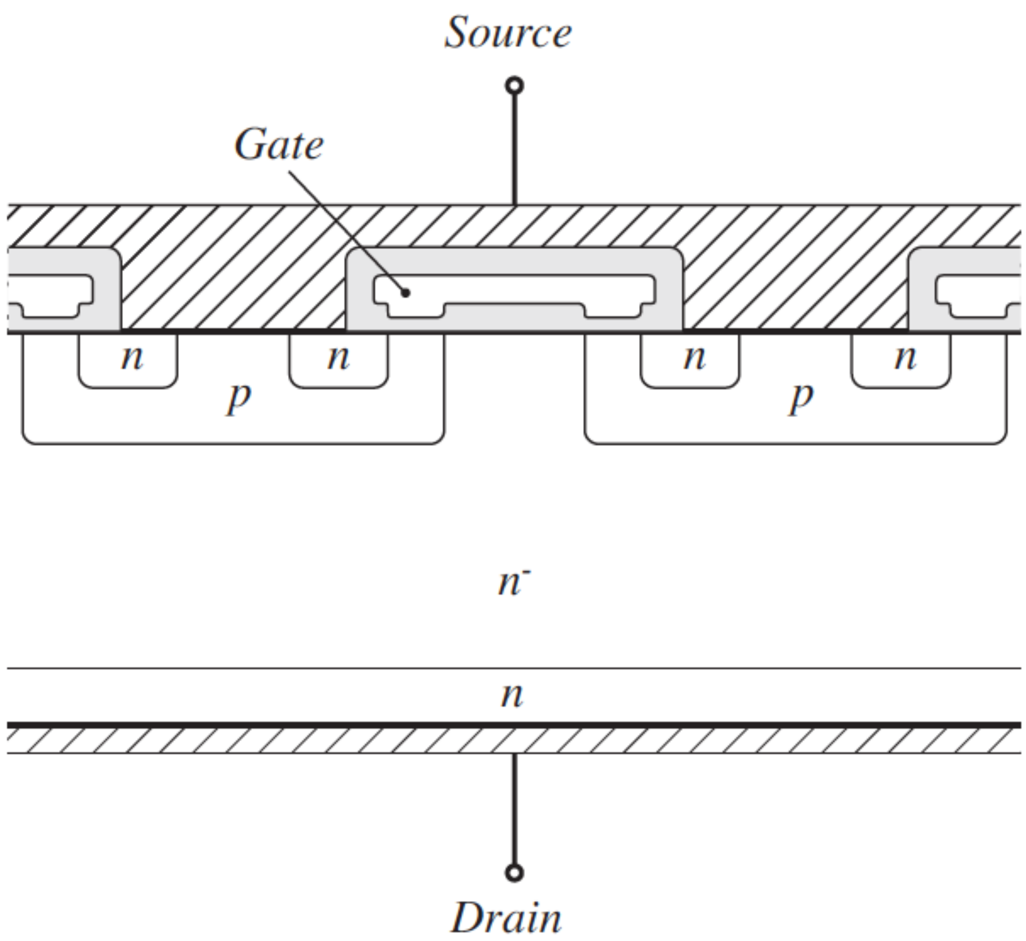
At **the end of interval** (5), the diode is able **to block the entire applied reverse voltage**.

The length of intervals (4) and (5) is the **reverse recovery time t_r**

Q_r: reverse recovery charges: diode is very slow!



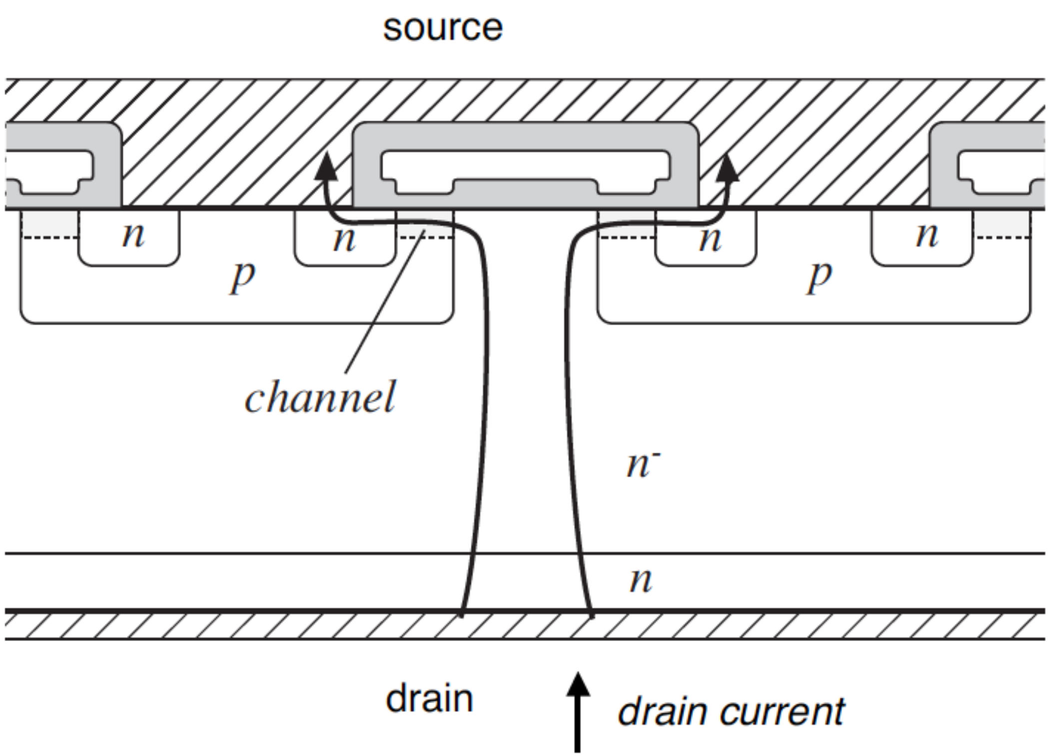
How to make a power MOSFET?



- Gate lengths approaching one micron
- Consists of many small enhancement-mode parallel-connected MOSFET cells, covering the surface of the silicon wafer
- Vertical current flow
- n-channel device is shown

Fundamentals of Power Electronics, Robert W. Erickson, Dragan Maksimović

Forward polarization: $V_{gs} > 0$



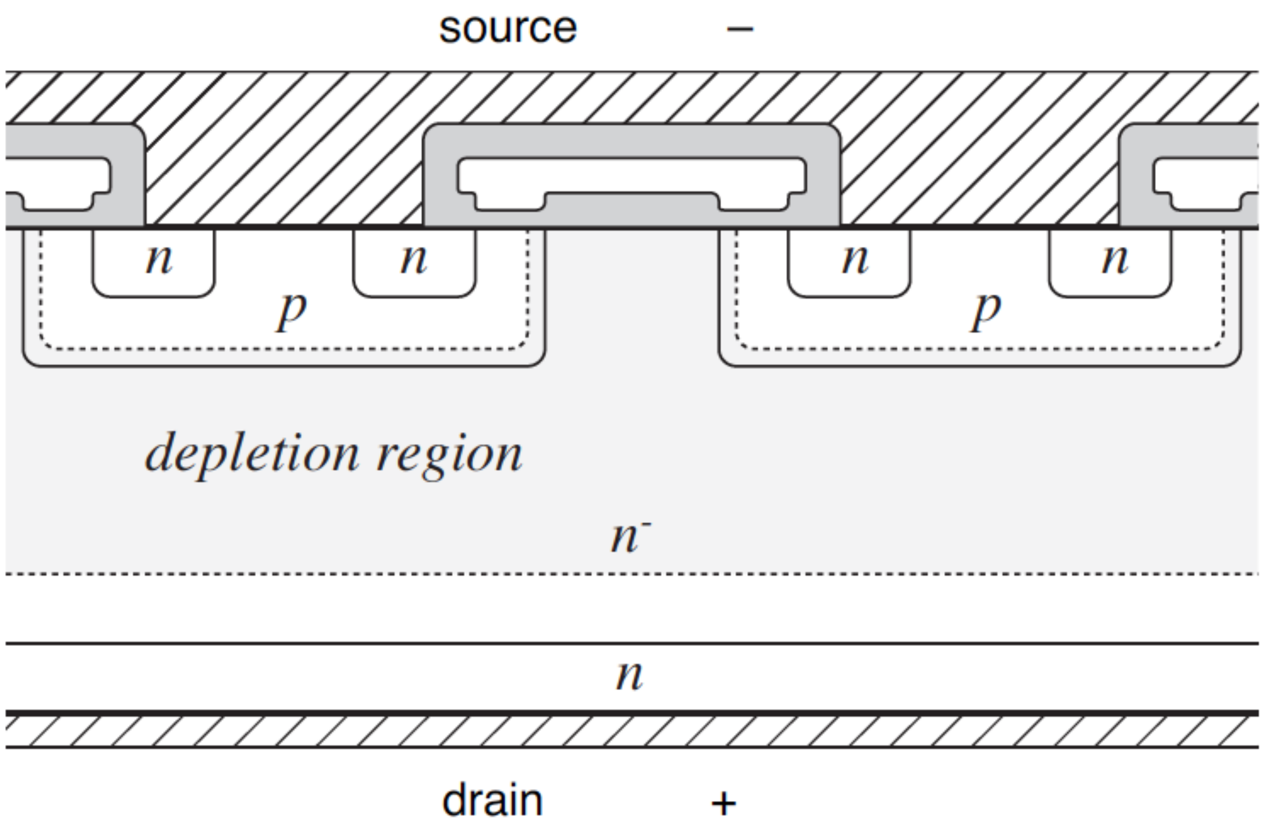
- *p-n⁻* junction is slightly reverse-biased
- positive gate voltage induces conducting channel
- drain current flows through n^- region and conducting channel
- on resistance = total resistances of n^- region, conducting channel, source and drain contacts, etc.

There are no minority carriers to cause conductivity modulation: **MOSFETs are majority carrier devices**

- Breakdown voltage is increased
- On-resistance dominated by resistance of n^- region.

Fundamentals of Power Electronics, Robert W. Erickson, Dragan Maksimović

Reverse polarization: $V_{gs} < 0$

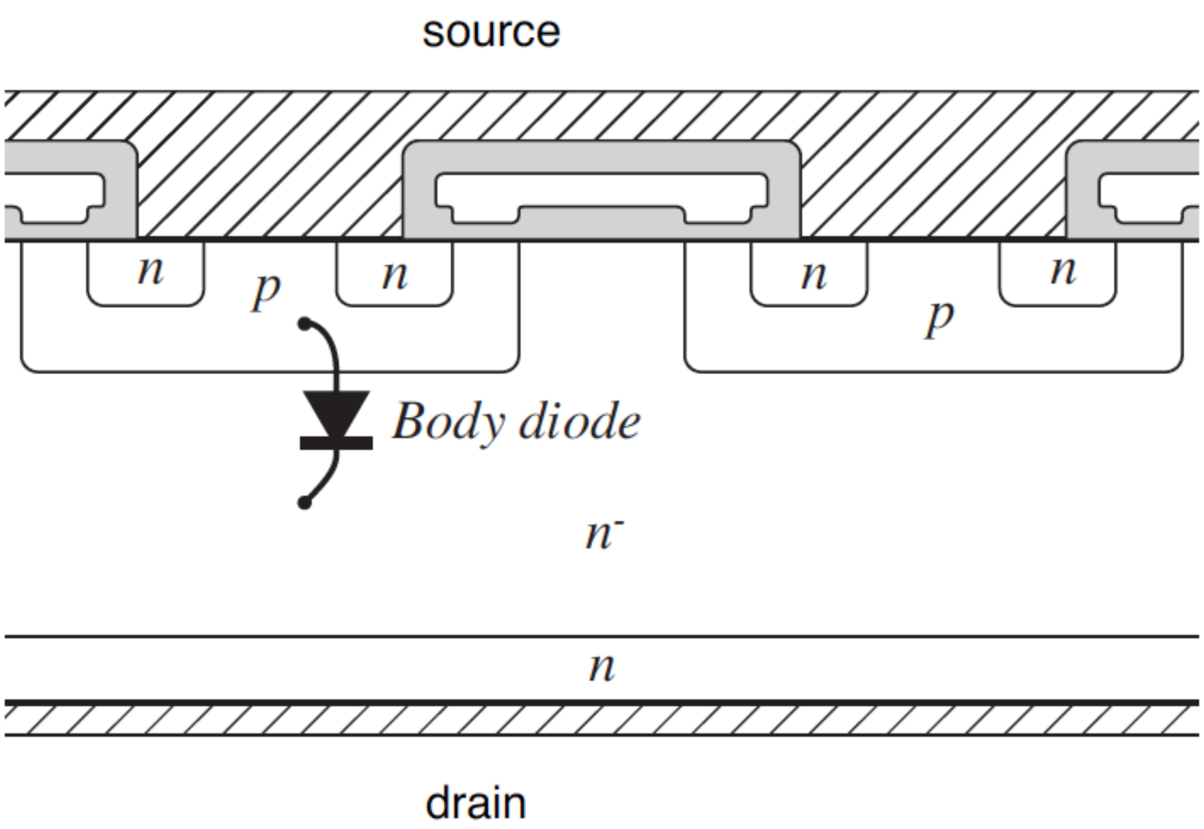


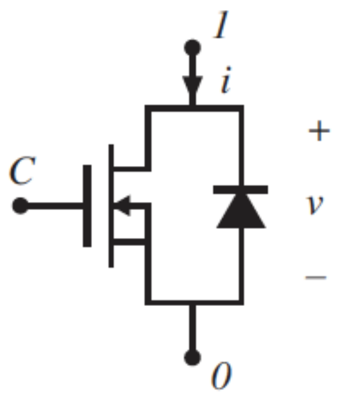
- p-n^- junction is reverse-biased
- off-state voltage appears across n^- region

Polarisation reverse:

p-n and p-n^- reverse-biased: voltage drops across n^- region

MOSFET: body-diode

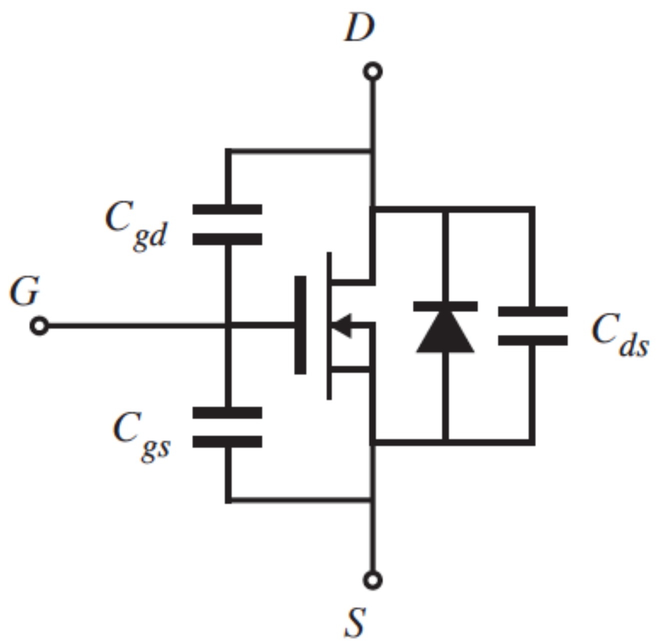




Power MOSFET, and its integral body diode

- *p-n⁻* junction forms an effective diode, in parallel with the channel
- negative drain-to-source voltage can forward-bias the body diode
- diode can conduct the full MOSFET rated current
- diode switching speed not optimized —body diode is slow, Q_r is large

MOSFET: equivalent circuit



- C_{gs} : large, essentially constant
- C_{gd} : small, highly nonlinear
- C_{ds} : intermediate in value, highly nonlinear
- switching times determined by rate at which gate driver charges/discharges C_{gs} and C_{gd}

$$C_{ds}(v_{ds}) = \frac{C_0}{\sqrt{1 + \frac{v_{ds}}{V_0}}} \qquad C_{ds}(v_{ds}) \approx C_0 \sqrt{\frac{V_0}{v_{ds}}} = \frac{C_0^{'}}{\sqrt{v_{ds}}}$$

C_{gd} is small but the voltage is large: so a lot of charges stored