EE-557
Semiconductor devices I

Power semiconductor devices

Génie Electrique et Electronique
Master Program
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Outline of the lecture

Basics of power devices
- Baliga's figure of merit
- Power diodes
- Power MOSFETs
- IGBTs

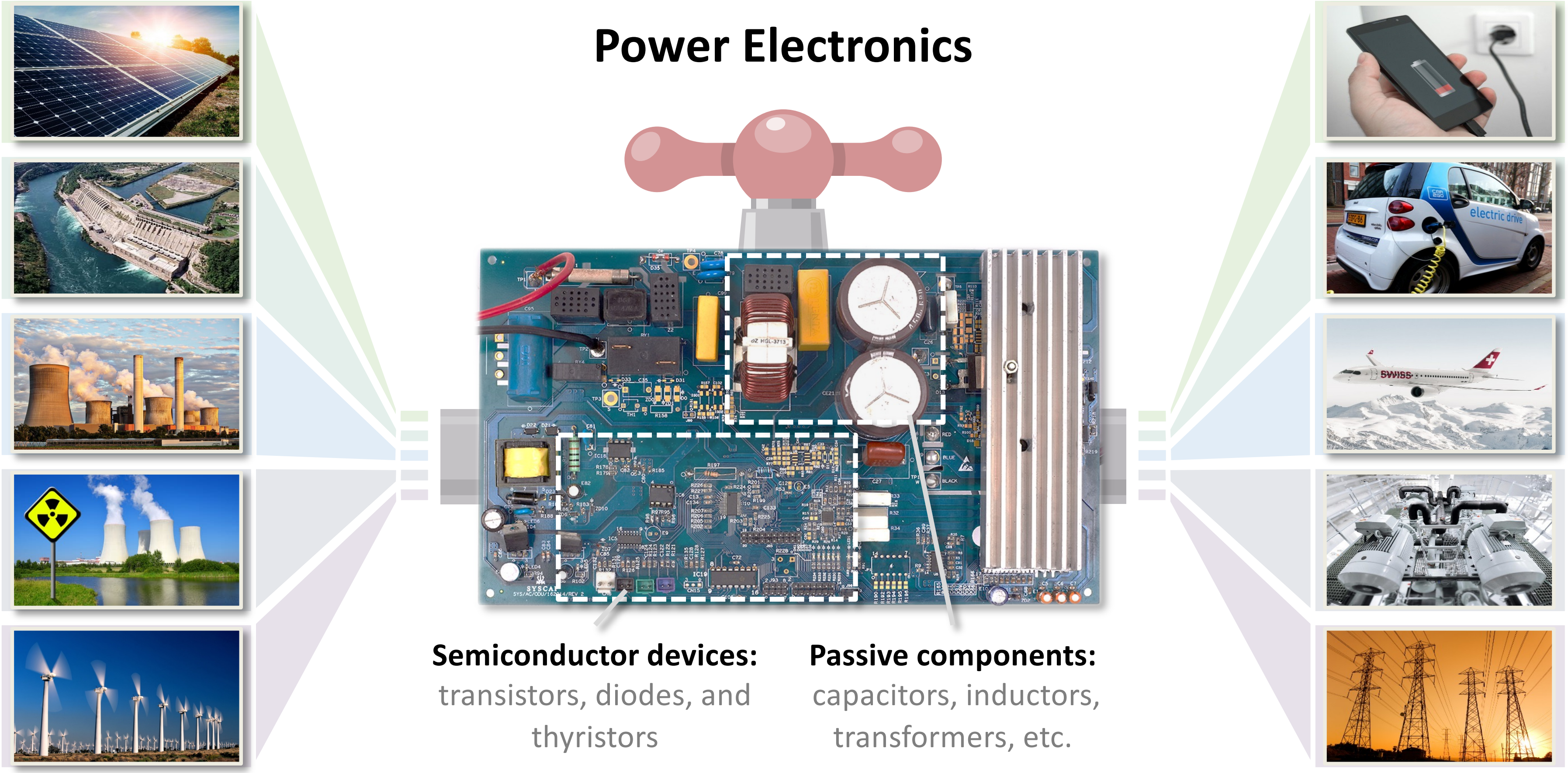
References:

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?

Introduction to power electronics

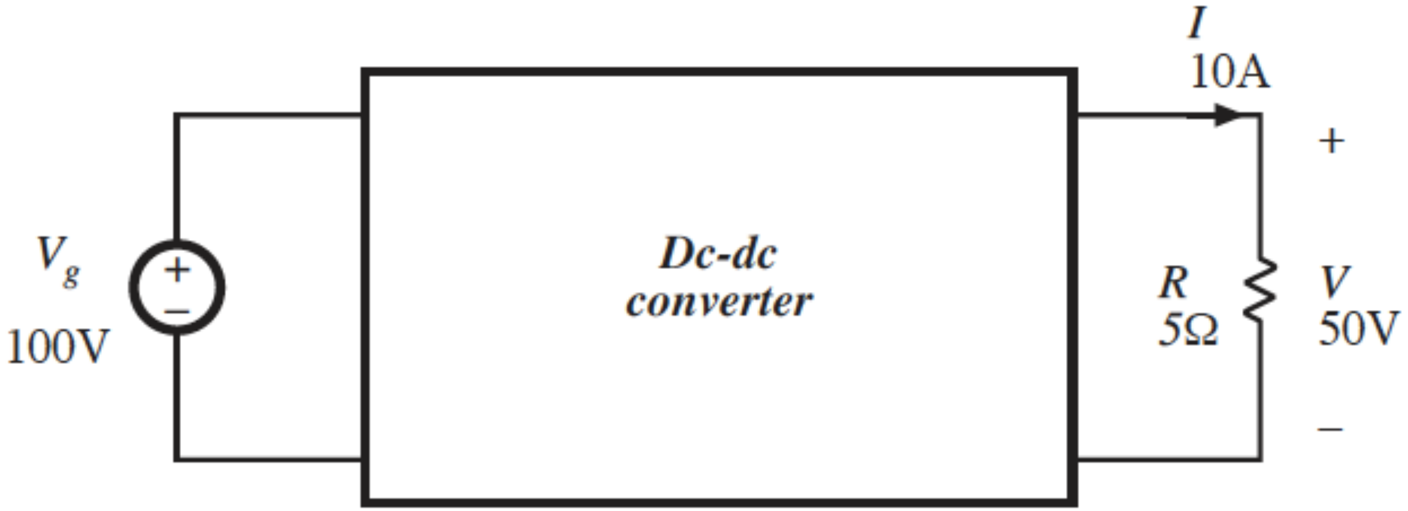


Power Electronics

Semiconductor devices: transistors, diodes, and thyristors

Passive components: capacitors, inductors, transformers, etc.

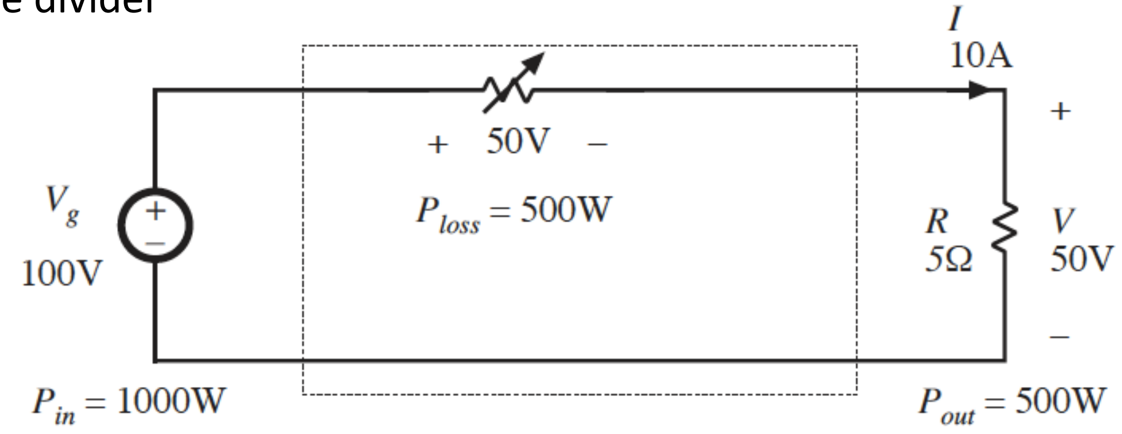
DC-DC converter



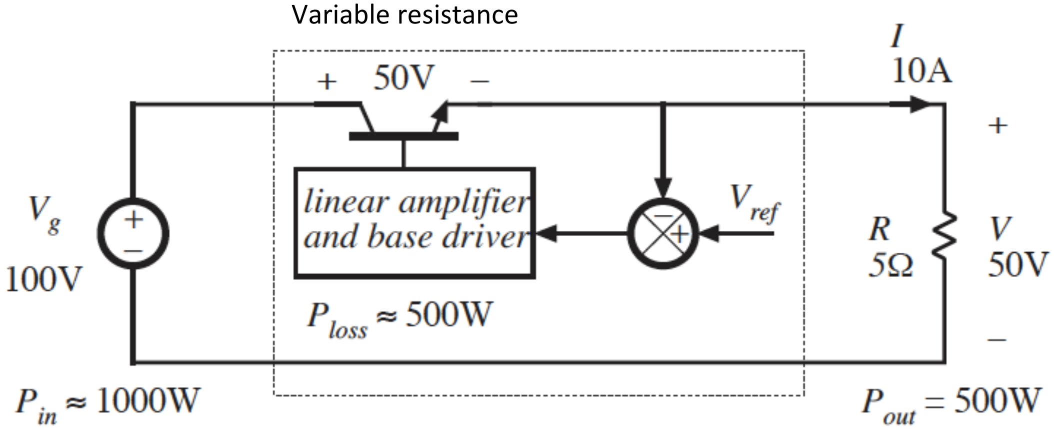
How can such converter be realised?

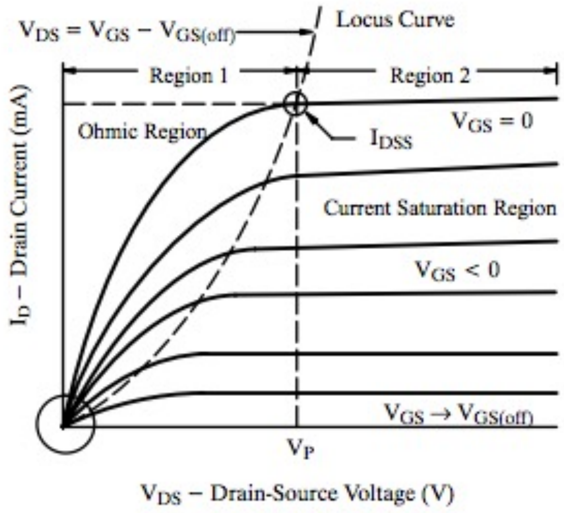
Principles of power conversion

Solution 1: voltage divider



Solution 2: linear amplifier

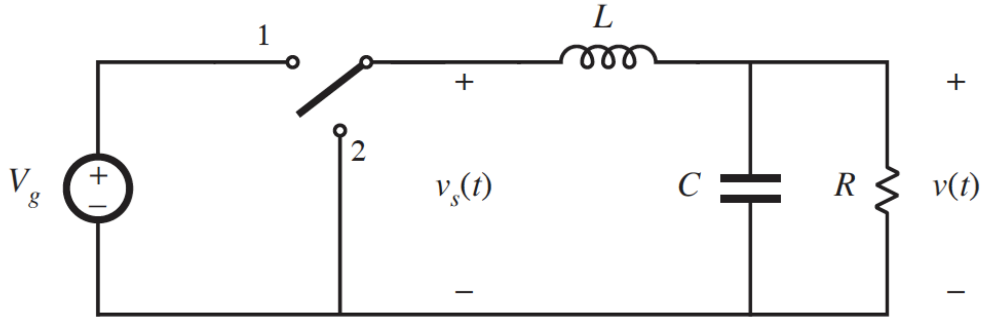


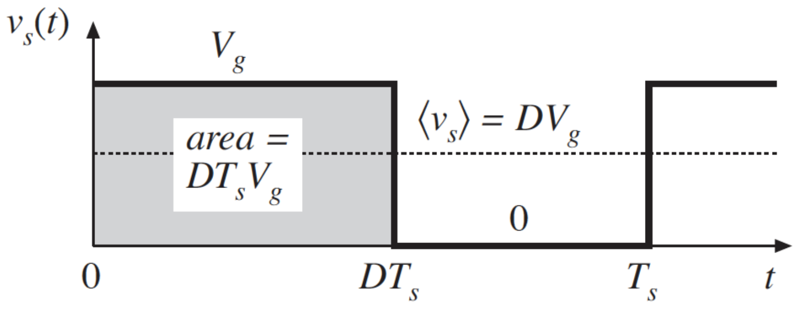


These are very inefficient solutions

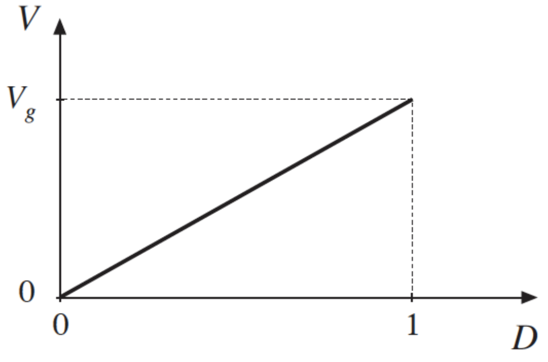
Concept of switching

DC-DC converter (buck converter)





$$v \approx \langle v_s \rangle = DV_g$$



Fourier analysis: Dc component = average value

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

$$\langle v_s \rangle = \frac{1}{T_s}(DT_sV_g) = DV_g$$

High frequency harmonics are filtered out by the LC filter:

- Cut-off frequency of the LC filter must be much smaller that the switching frequency **$f_0 << f_S$**

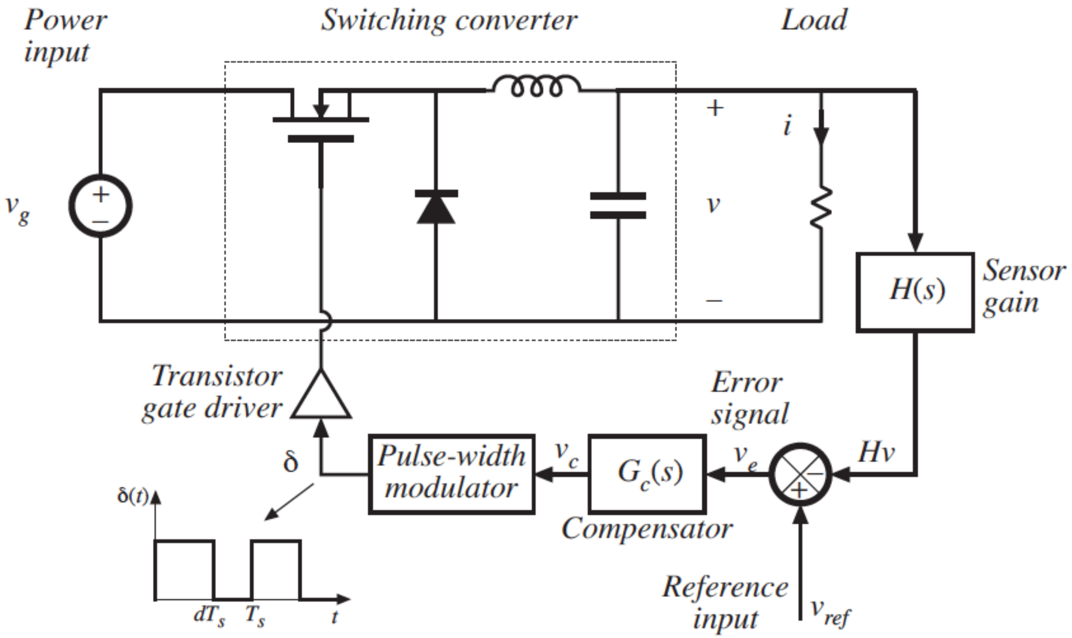
Only DC at the output: This is called a **buck converter: $V_{out} = DV_{in}$**

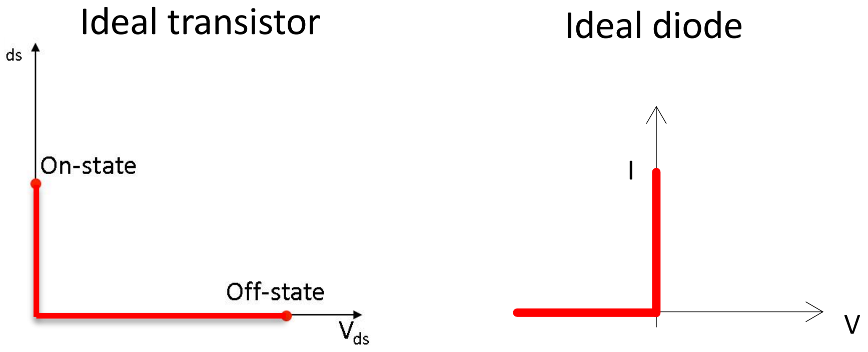
Fundamentals of Power Electronics, Robert W. Erickson, Dragan Maksimović

Principles of power conversion

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

Efficiency

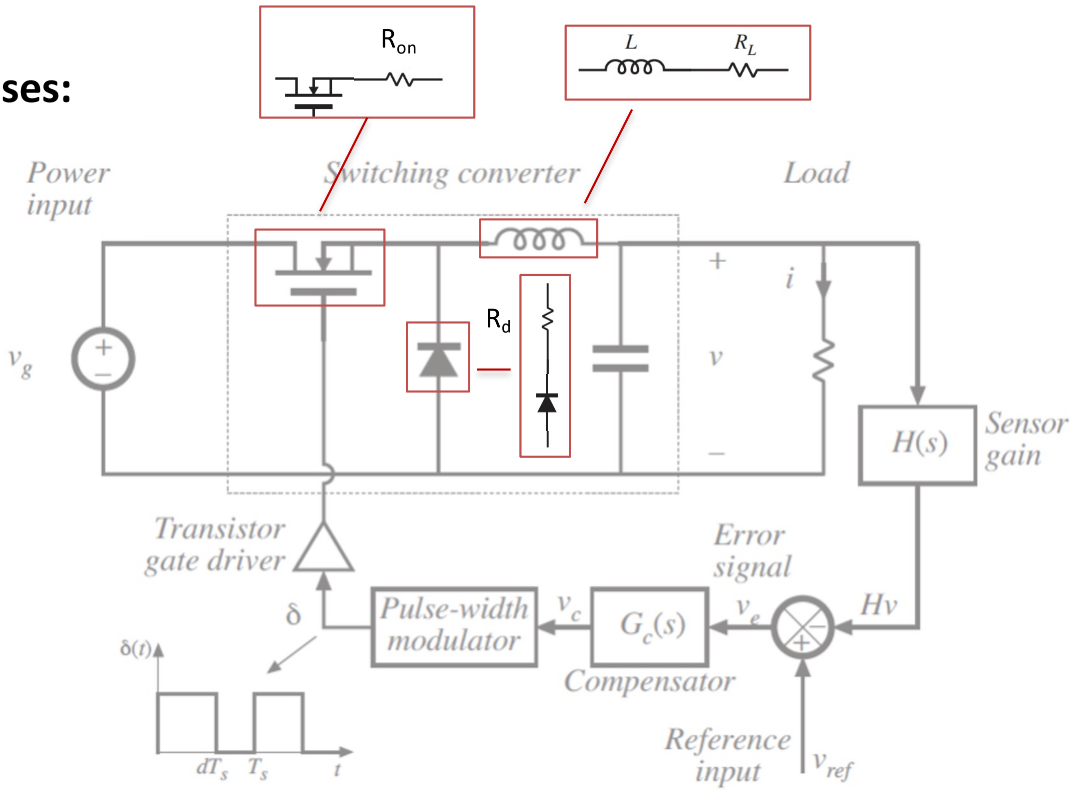
Two main loss mechanisms:

1. Conduction losses: when devices are conducting

- Semiconductor forward bias
- Parasitics: inductances, capacitances, resistances

2. Switching losses: when devices are switching

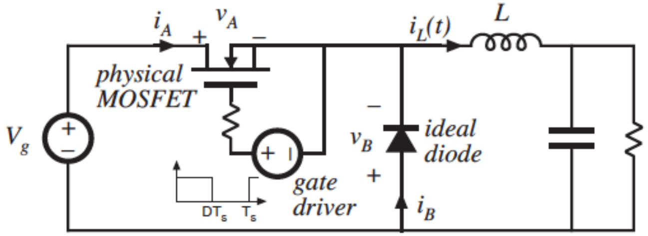
1. Conduction losses:



Dissipated power

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

2. Switching losses:



Buck converter example

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

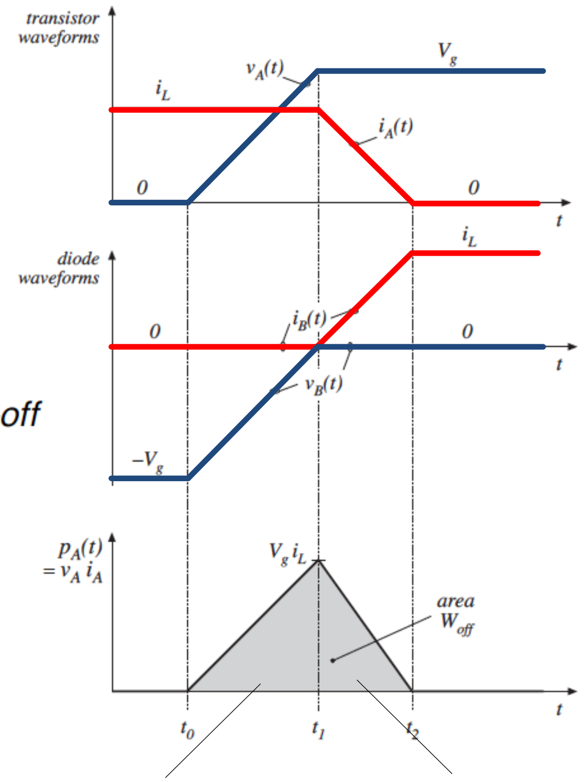
transistor turn-off transition

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:

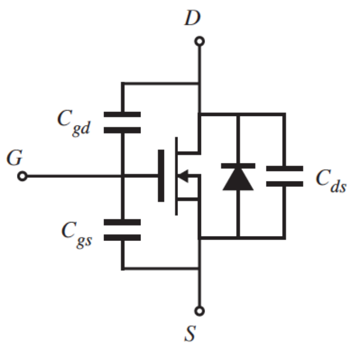
$$P_{sw} = \frac{1}{T_s} \int_{\substack{switching\\transitions}} p_A(t)\, dt = (W_{on} + W_{off})\, f_s$$



Charging time of C_{GD}

Discharging time of C_{GS}

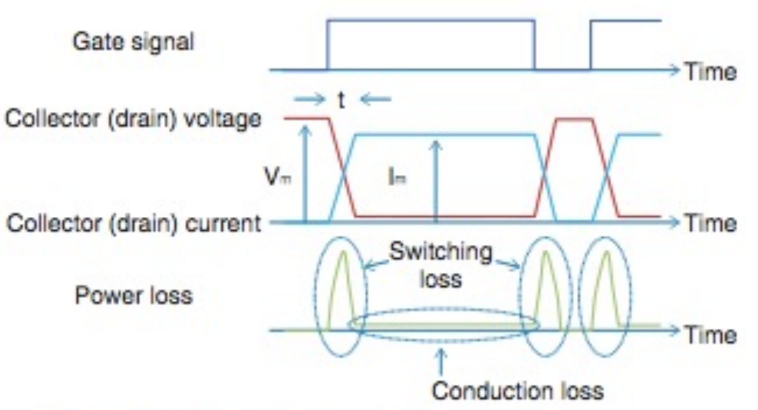
Equivalent circuit



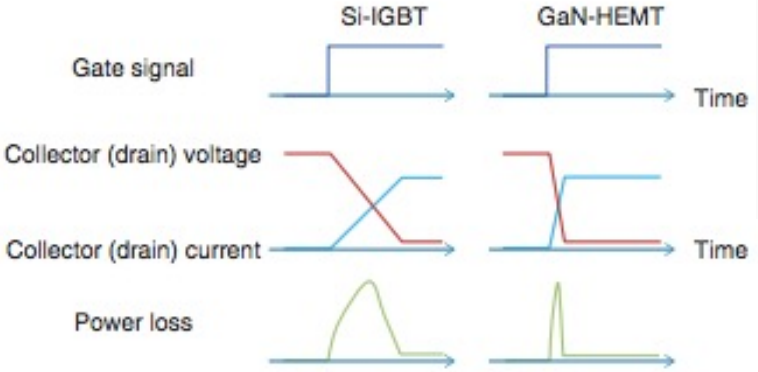
Switching losses are proportional to the switching frequency…

…while conduction losses are fixed

Switching losses

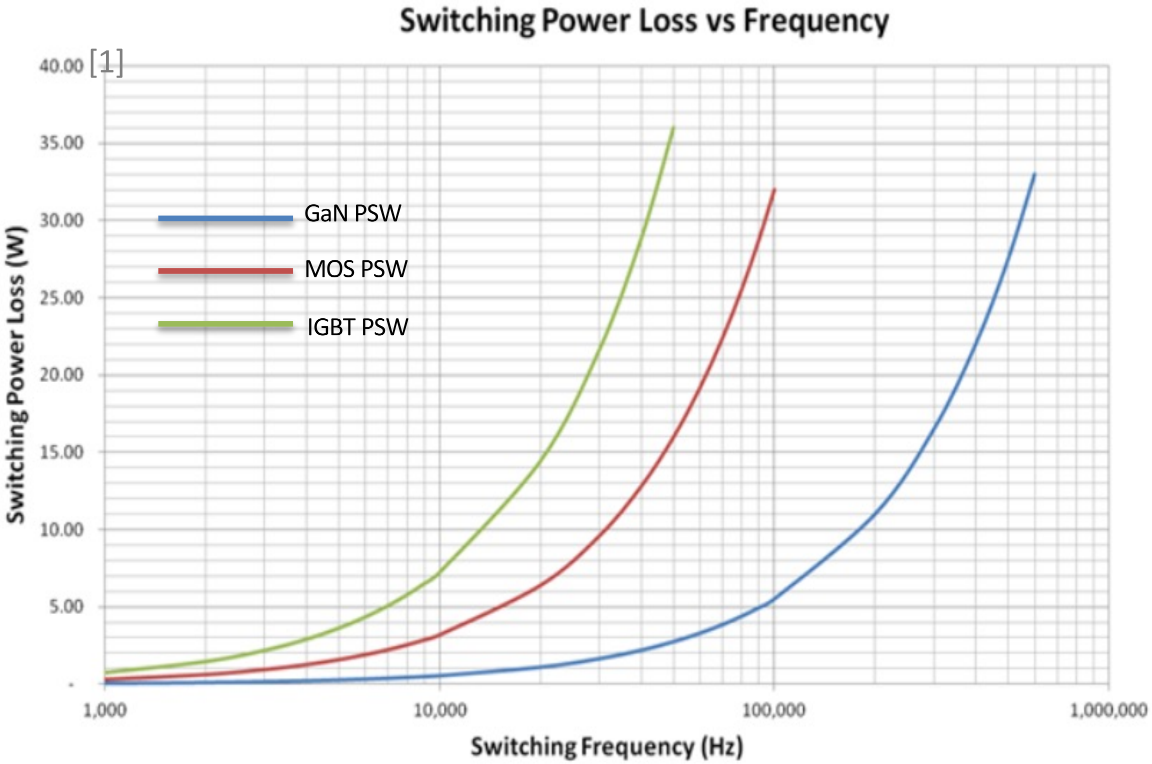


(a) Conduction loss and switching loss in transistor



The power loss can be reduced in GaN-HEMT, which has a shorter switching time than Si-IGBT.

(c) Comparison of switching properties of Si-IGBT and GaN-HEMT



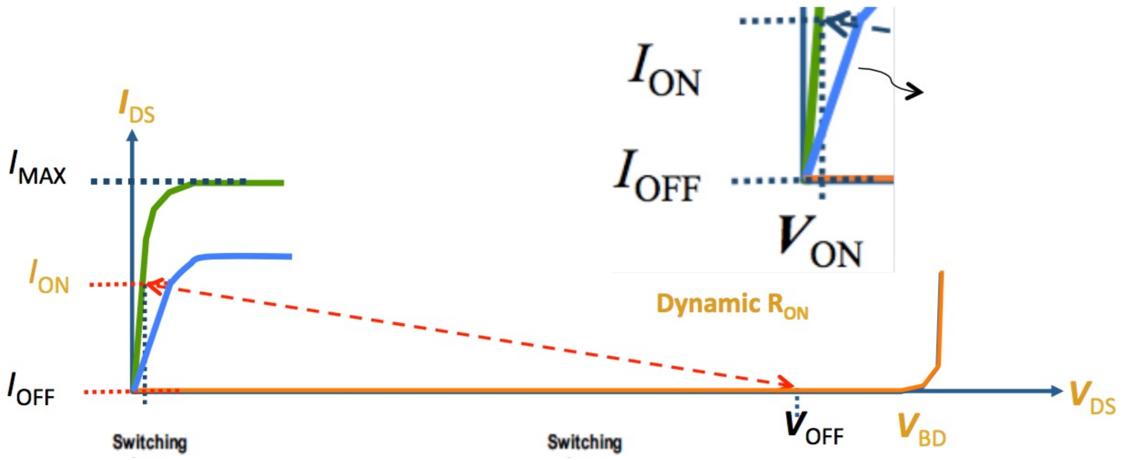
[1]

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:

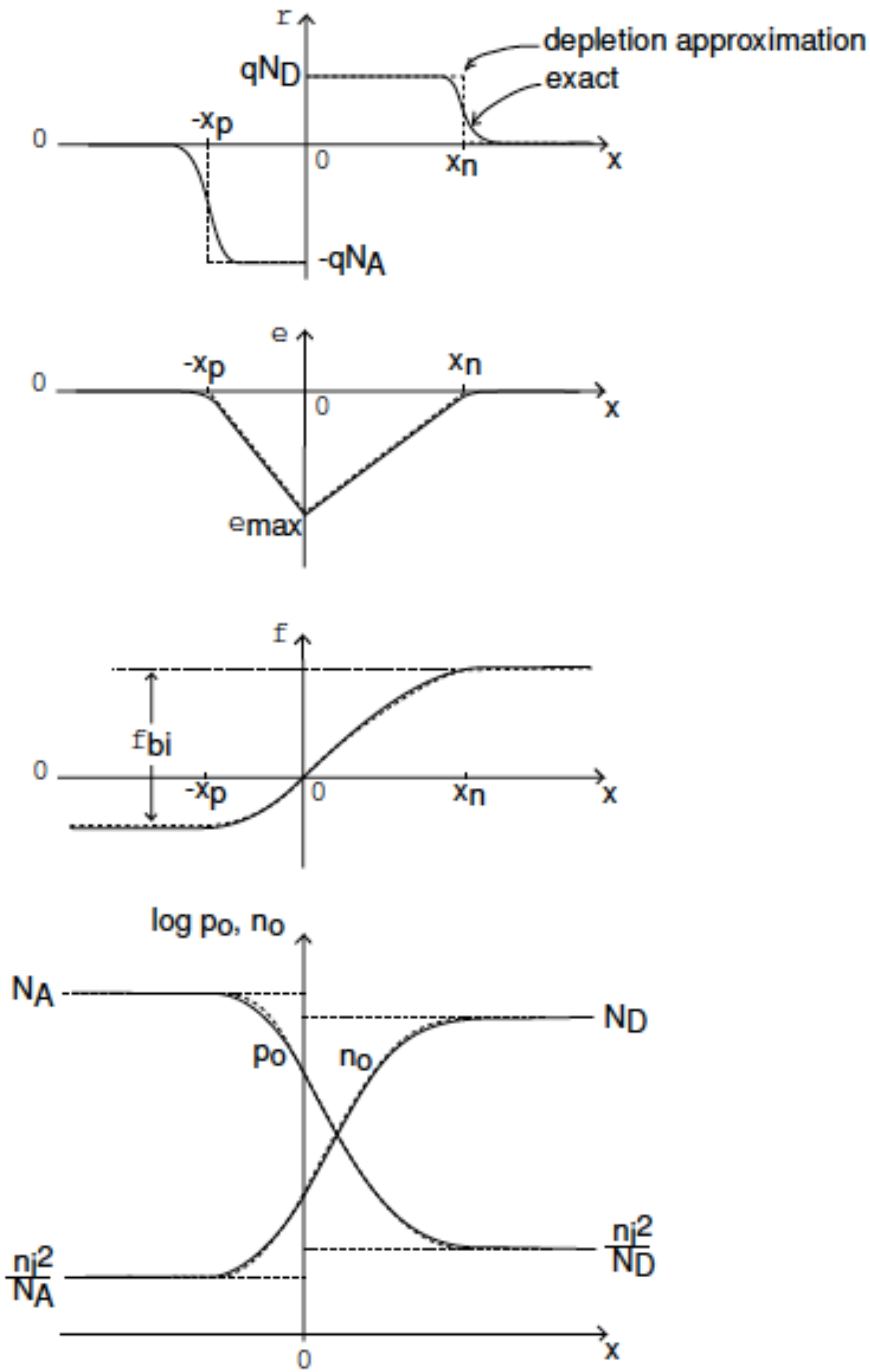


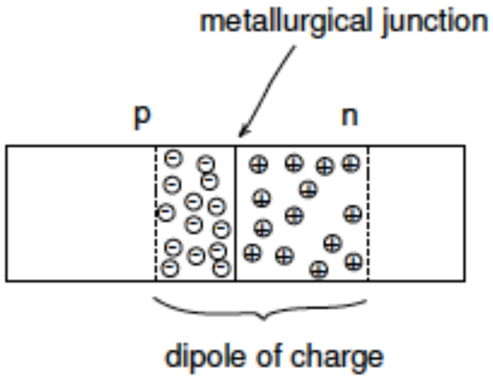
It operates in two regimes:
ON: Low voltage, high current
OFF: High voltage, low current

- 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)

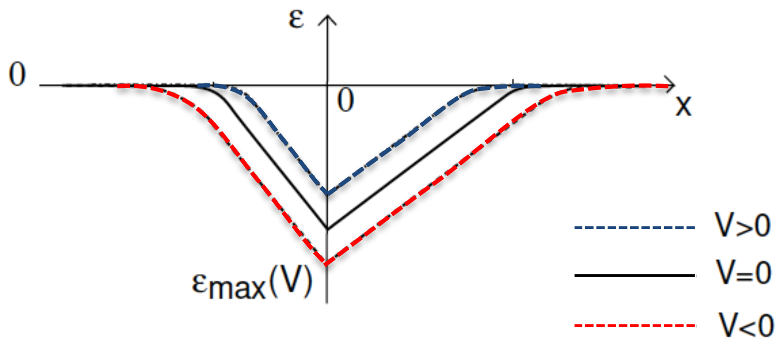
$\rho \sim 0$

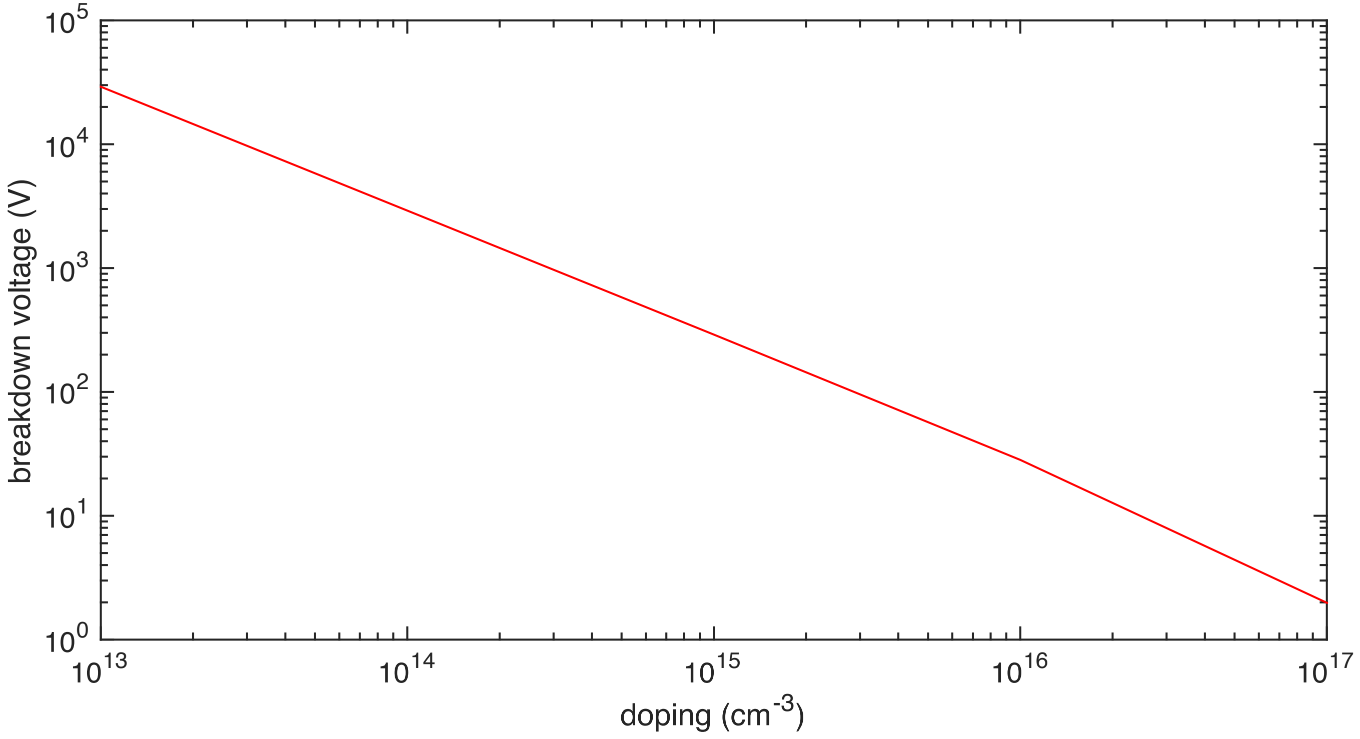
Electric field is constant and equal to zero

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:

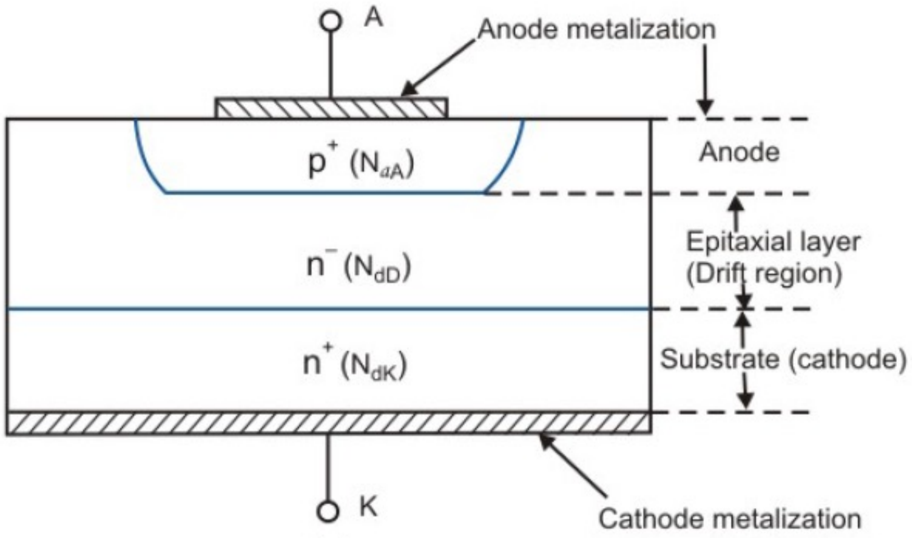
Conduct **several kilo amps** of current in the forward direction with very **little power loss** while blocking **several kilo volts** in the reverse direction.

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)

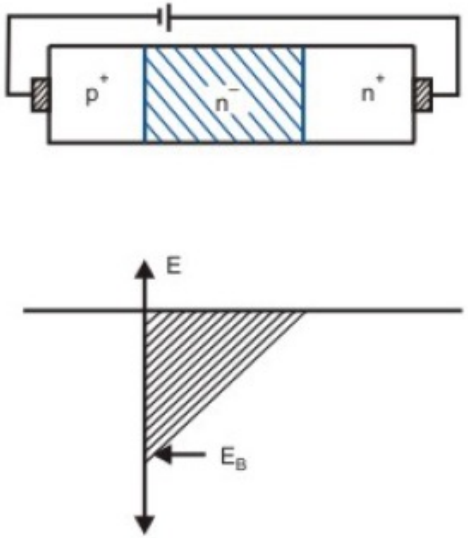
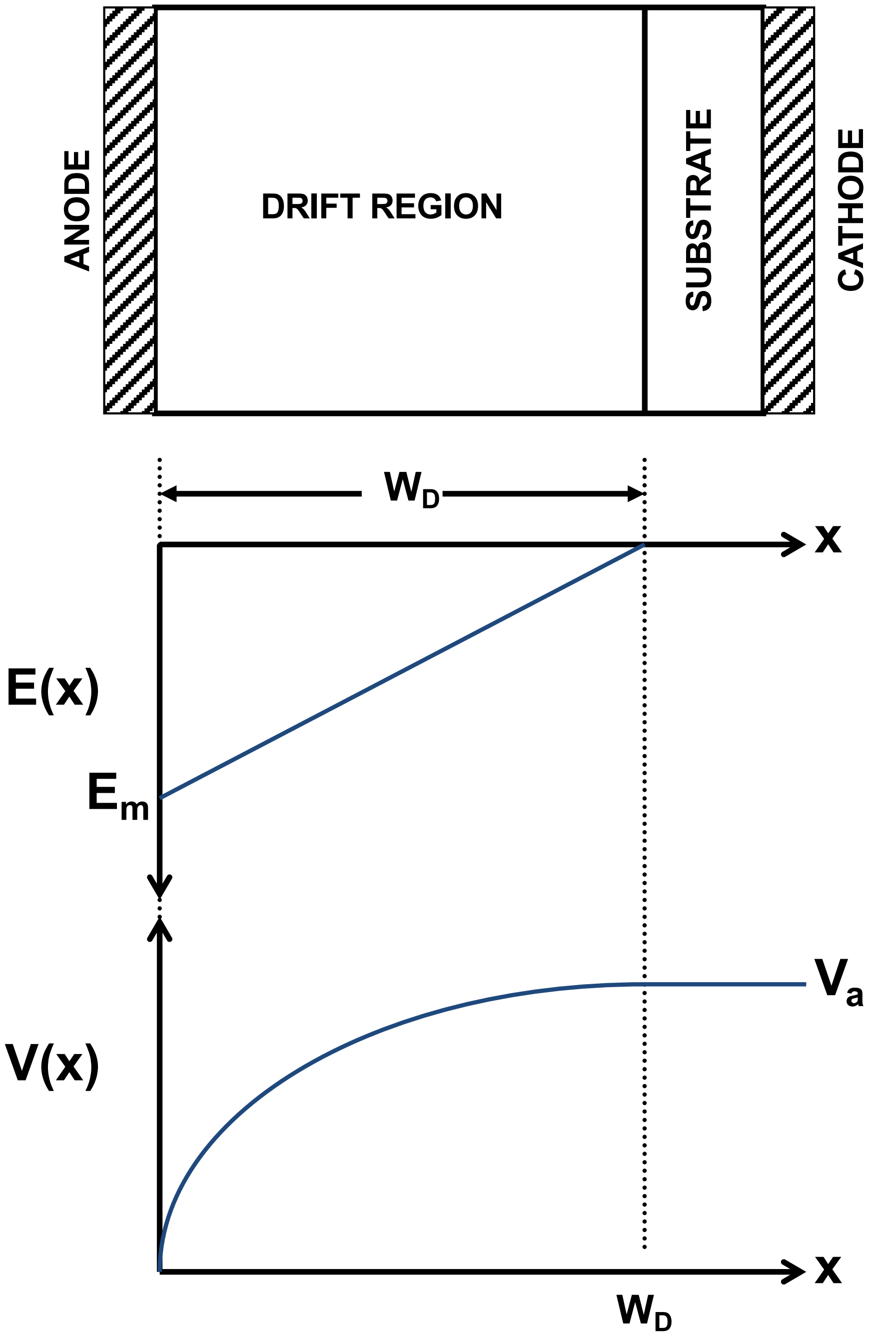


Figure of merit: how to compare different semiconductors



Specific on-resistance (Ωcm²)

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

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

Poisson's Equation:

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

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

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

$$V_a = \frac{qN_D W_D^2}{2\varepsilon_S} \qquad \boxed{N_D = \frac{\varepsilon_S E_C^2}{2qBV}}$$

Figure of merit: how to compare different semiconductors

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

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

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

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

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

Baliga's figure of merit

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

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

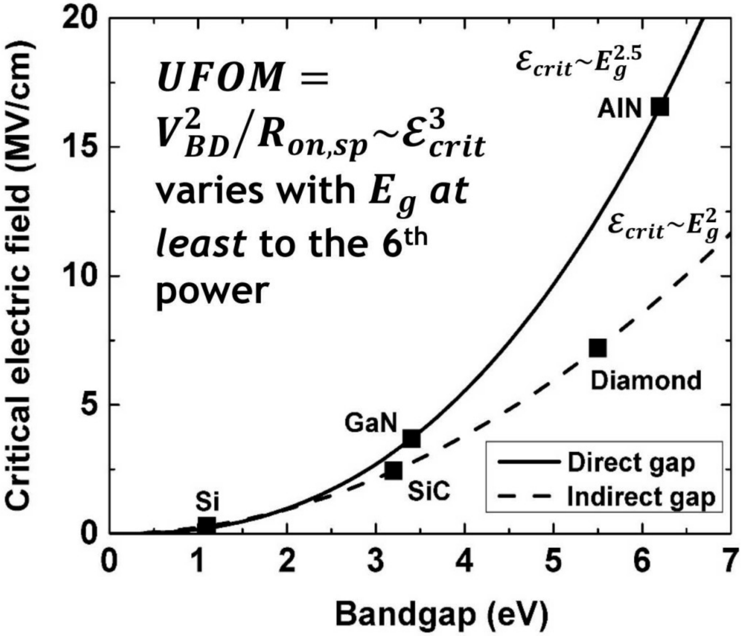
$$R_{ON,SP} = \frac{4BV^2}{\varepsilon_S \mu_n E_C^3}$$

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

Baliga's figure of merit

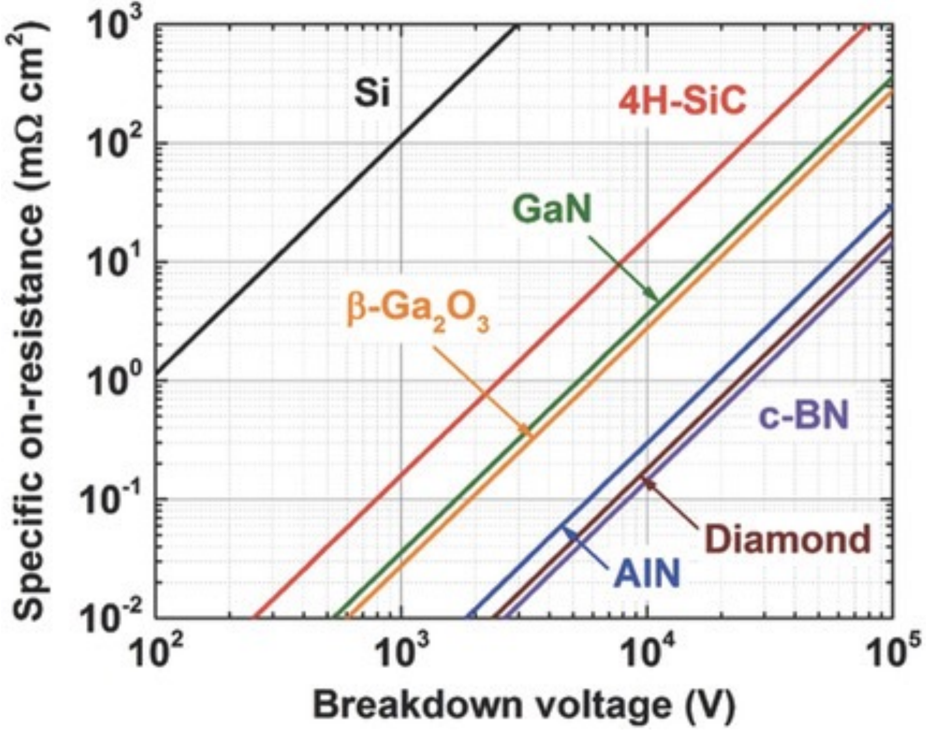
$$BFOM = \varepsilon_S \mu_n E_C^3 = \frac{4BV^2}{R_{ON,SP}}$$

Relationship between Ec and Eg

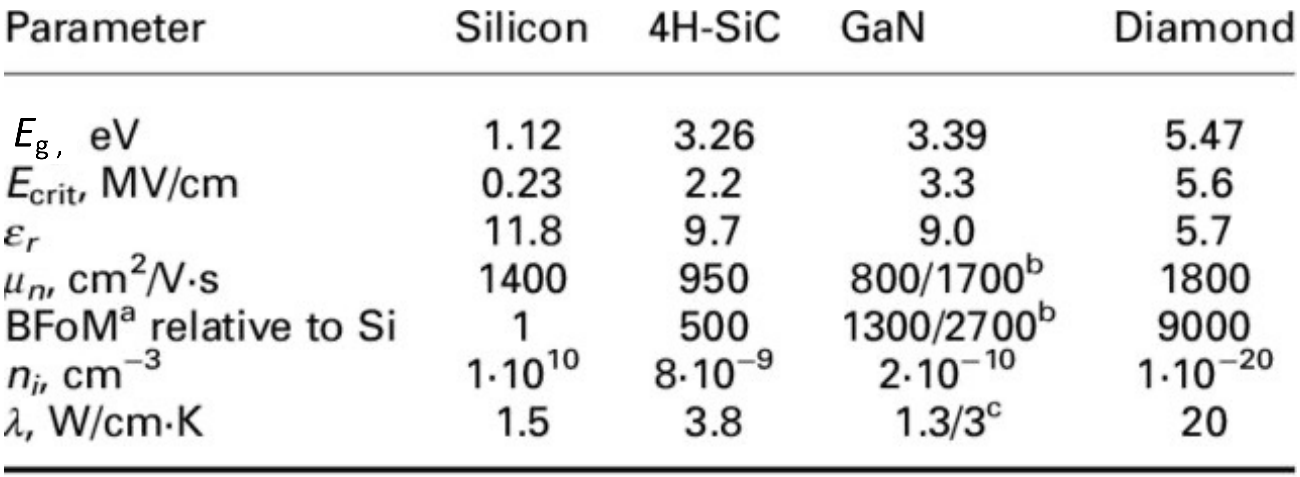


Hudgins et al., IEEE Trans. on Pow. Elec. 18, 3 (2003),
Tsao et al., Advanced Elec. Mat. 4, 1600501 (2018)

BFOM for different materials



Influence of material properties



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, $cm^2/V{\cdot}s$	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

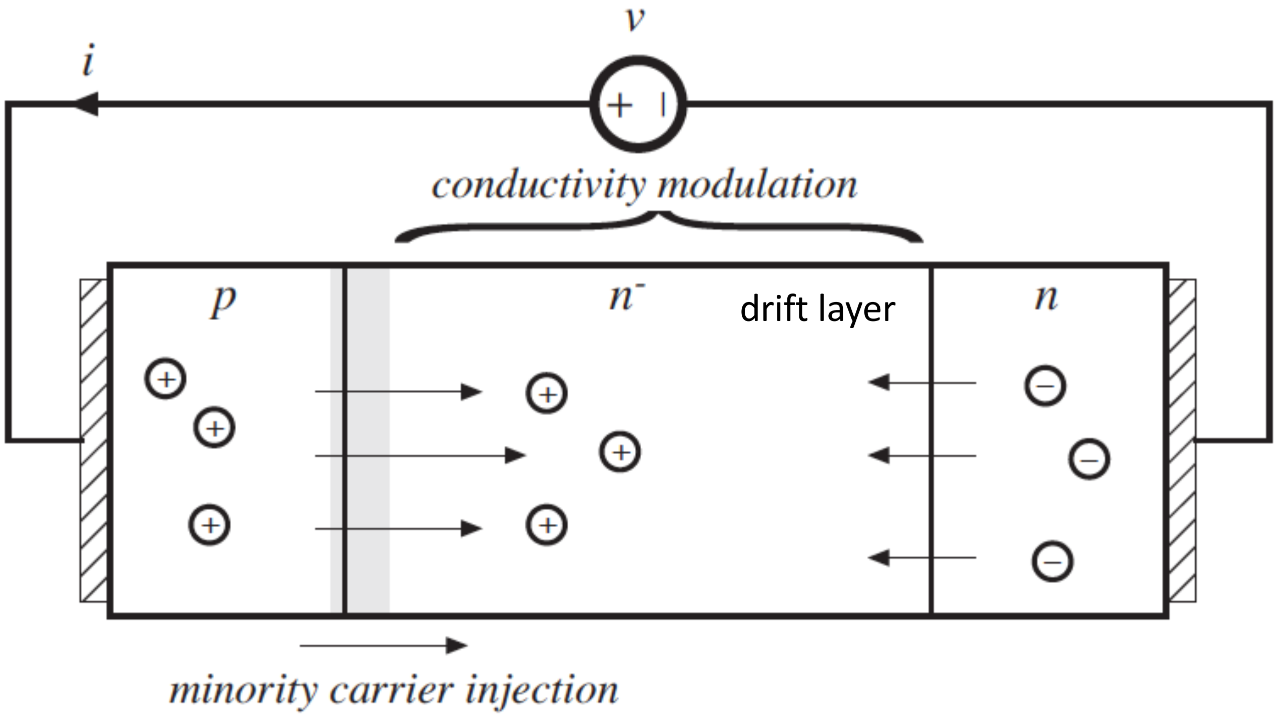
Desired properties, found in some of these wide band-gap materials:

- 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)

Power diodes

diode PIN

Forward polarization

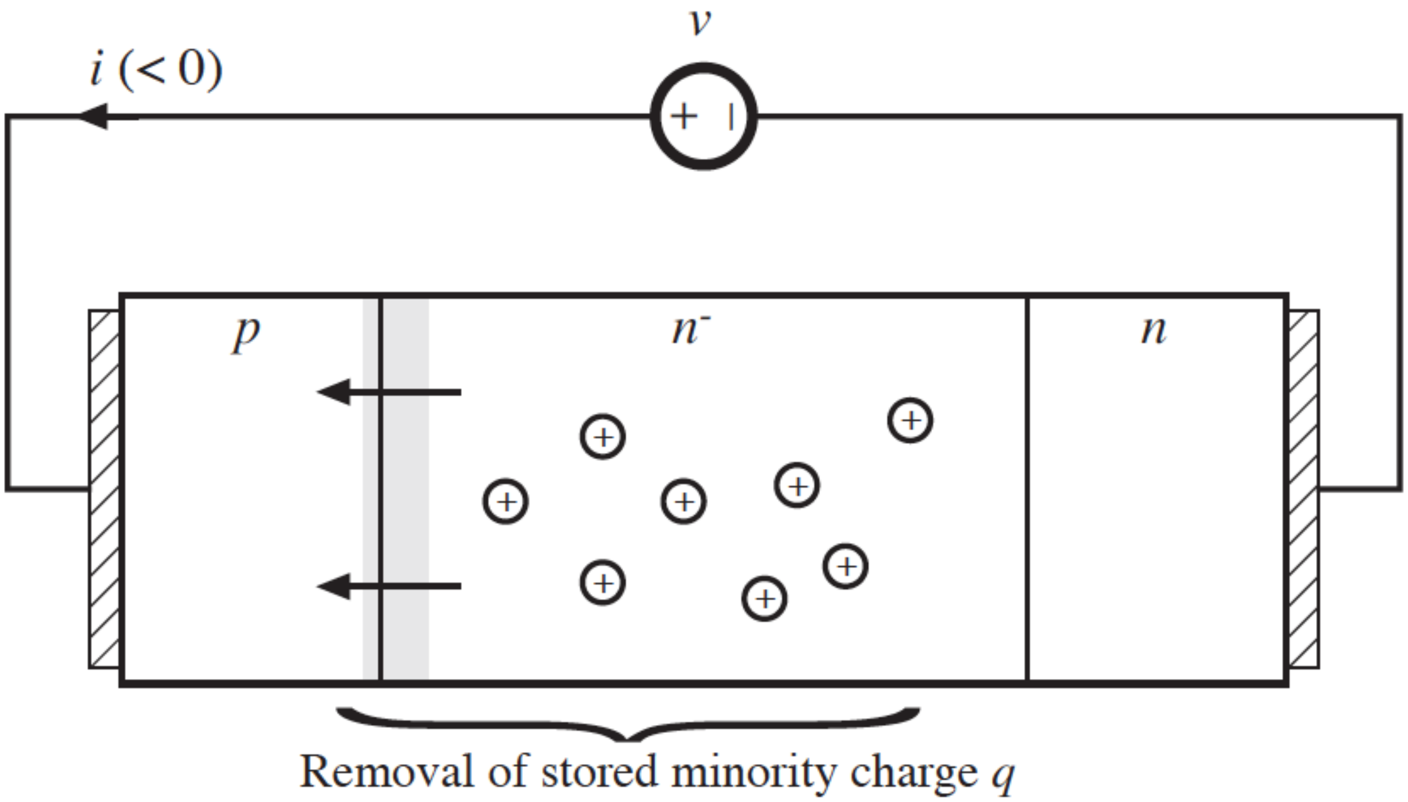


Forward polarization:

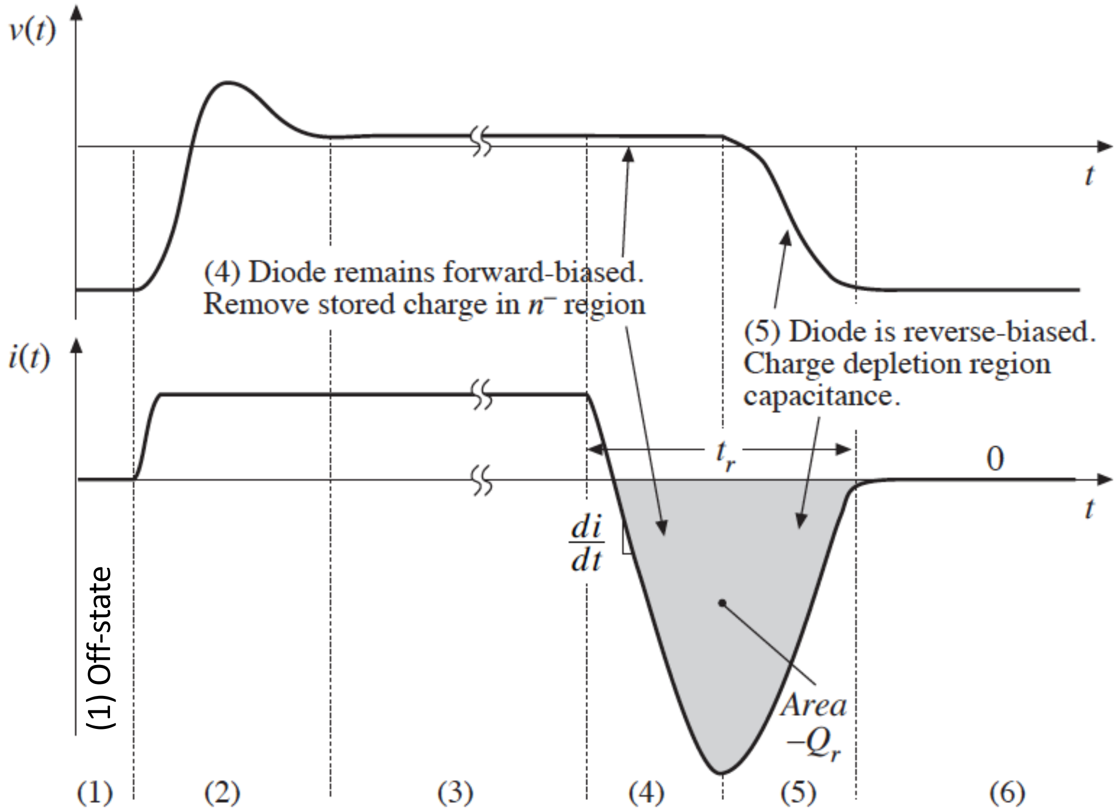
- Injection of minority carriers in the drift layer: conductivity modulation
- Charges are accumulated in the region «i»:
    - Resistance is reduced
    - But slows down the device
- Minority carrier device

Power diodes

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.**

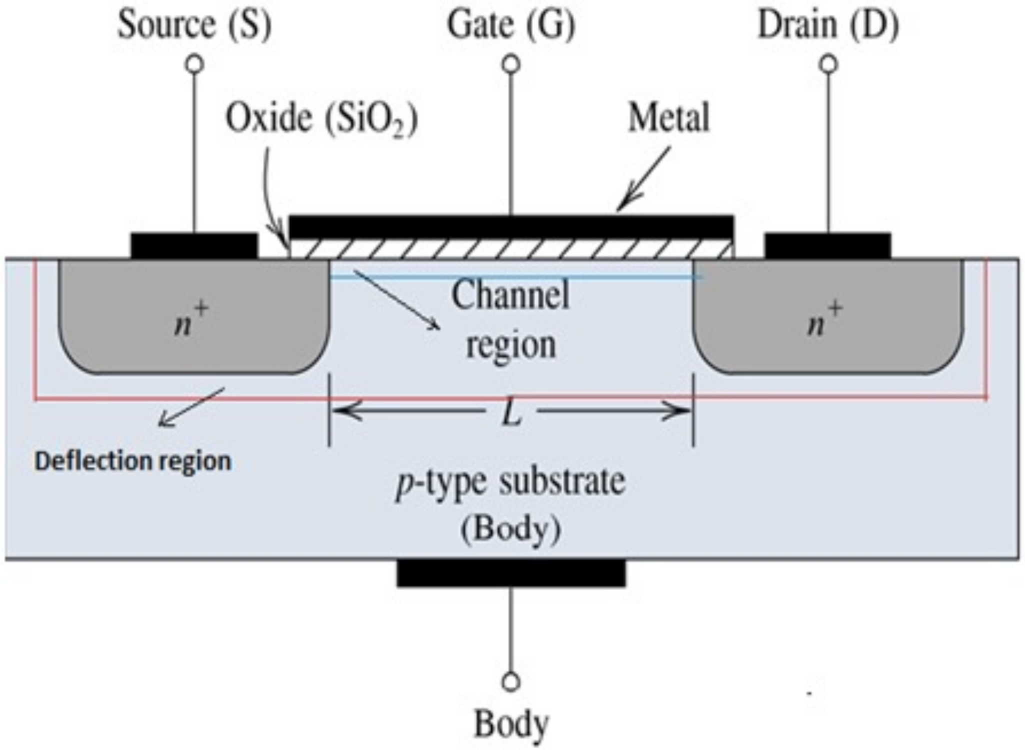
The depletion region **effective capacitance is then charged** during interval (5) to the negative off-state voltage.

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**.

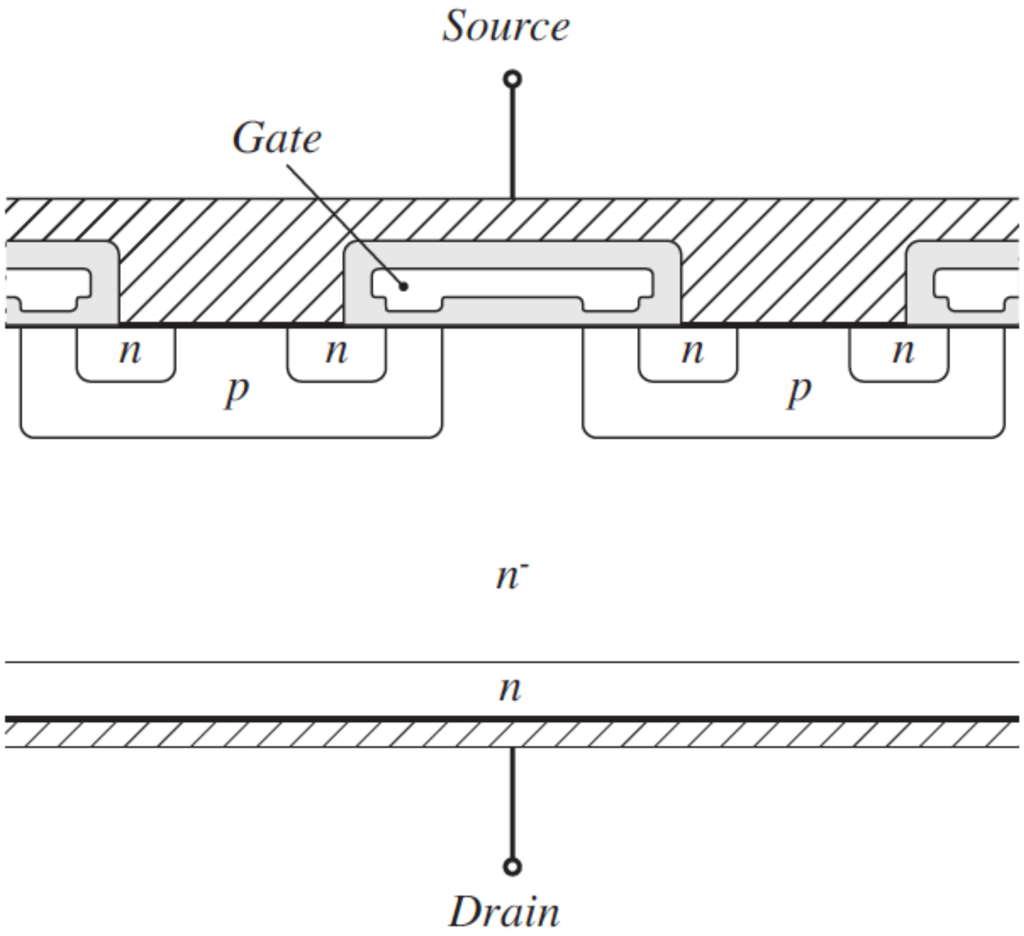
The length of intervals (4) and (5) is the **reverse recovery time t_r**

Q_r: reverse recovery charges: diode is very slow!



How to make a power MOSFET?

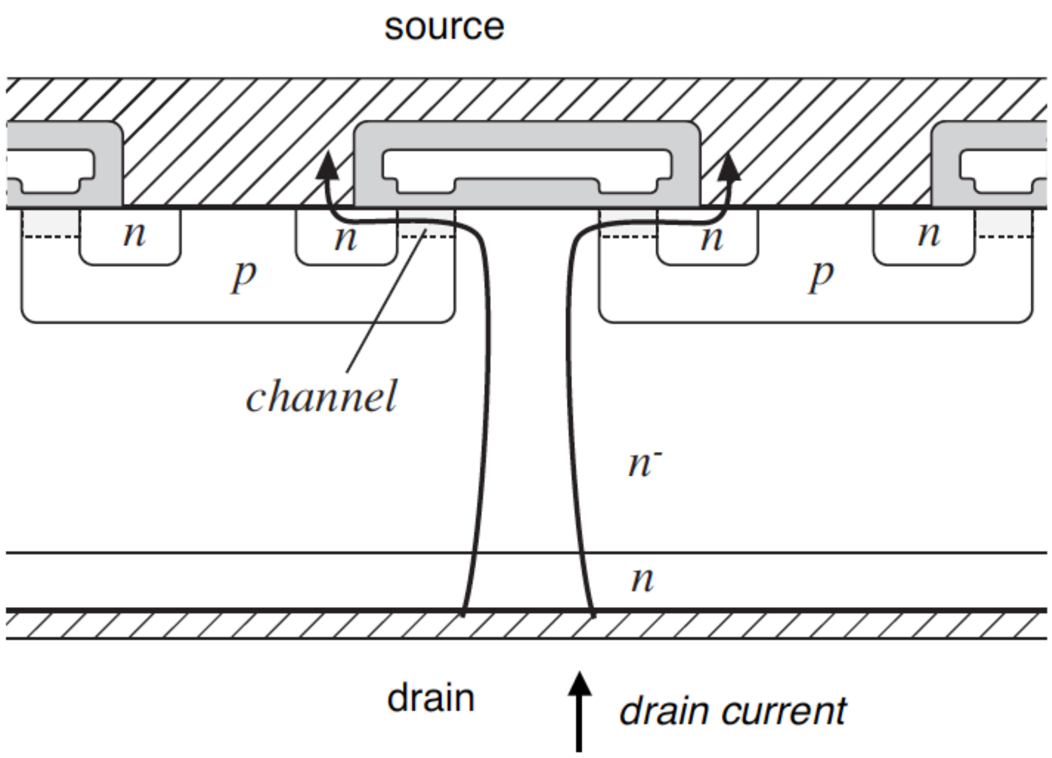
Power MOSFETs



- 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: $V_{gs} > 0$



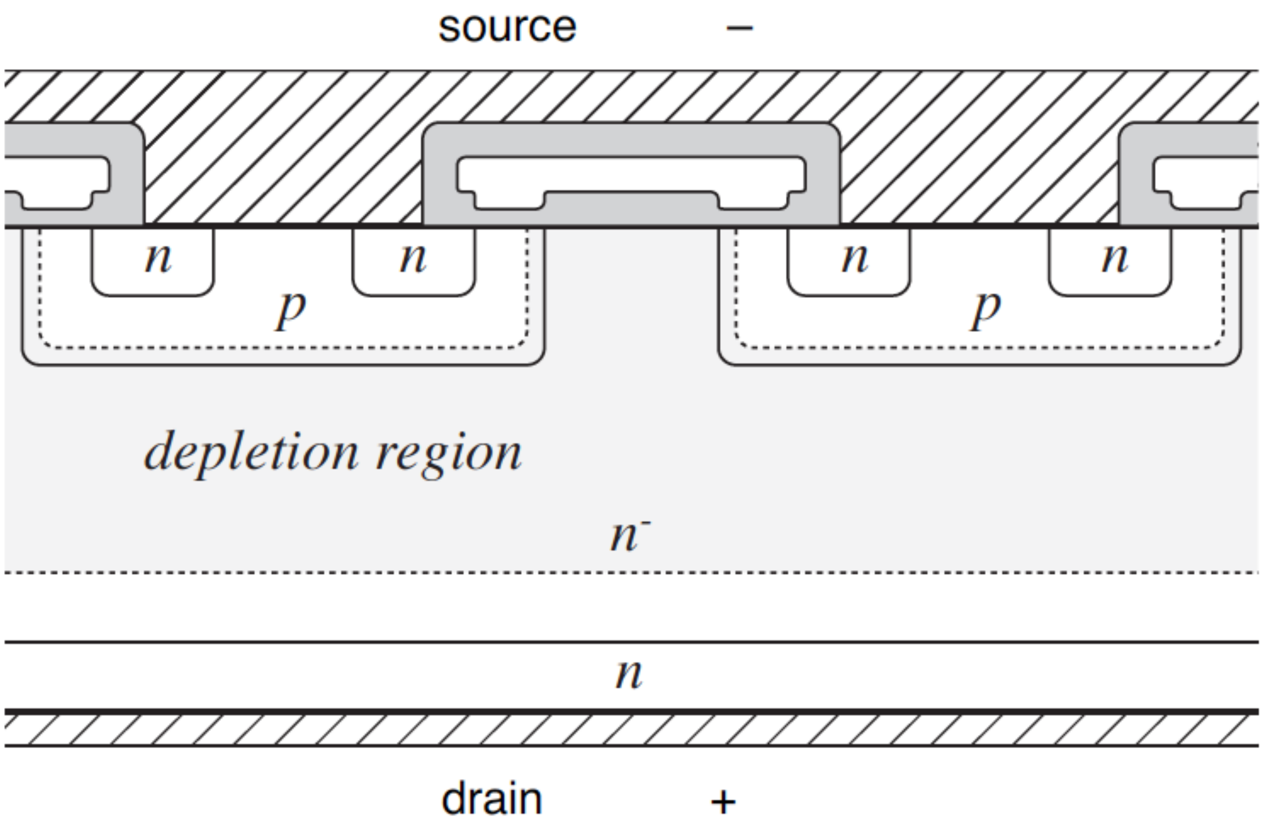
- p-n^- junction is slightly reverse-biased
- positive gate voltage induces conducting channel
- drain current flows through n^- region and conducting channel
- on resistance = total resistances of n^- region, conducting channel, source and drain contacts, etc.

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: $V_{gs} < 0$

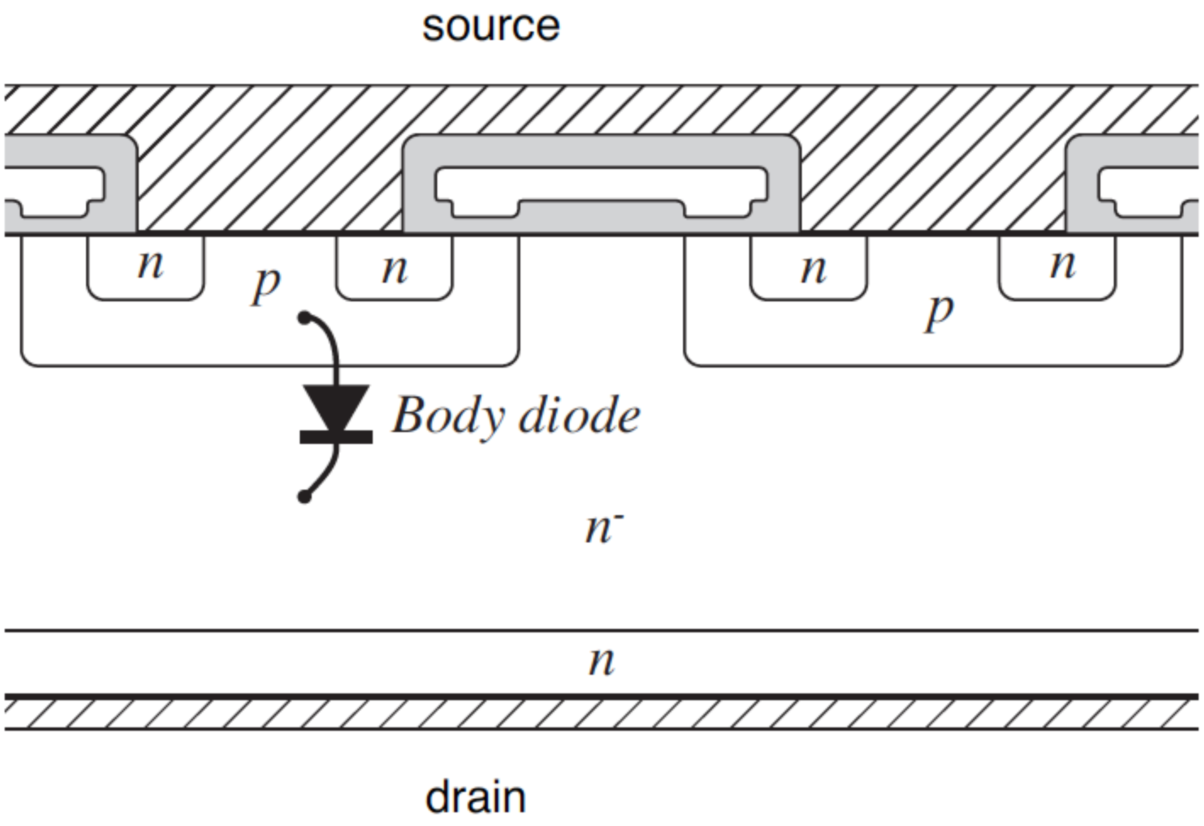


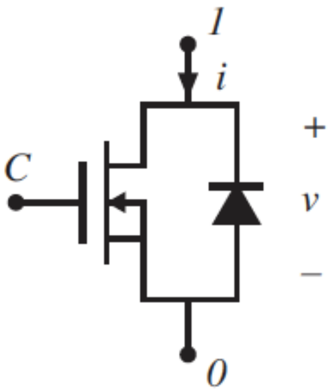
- p-n^- junction is reverse-biased
- off-state voltage appears across n^- region

Polarisation reverse:

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

MOSFET: body-diode

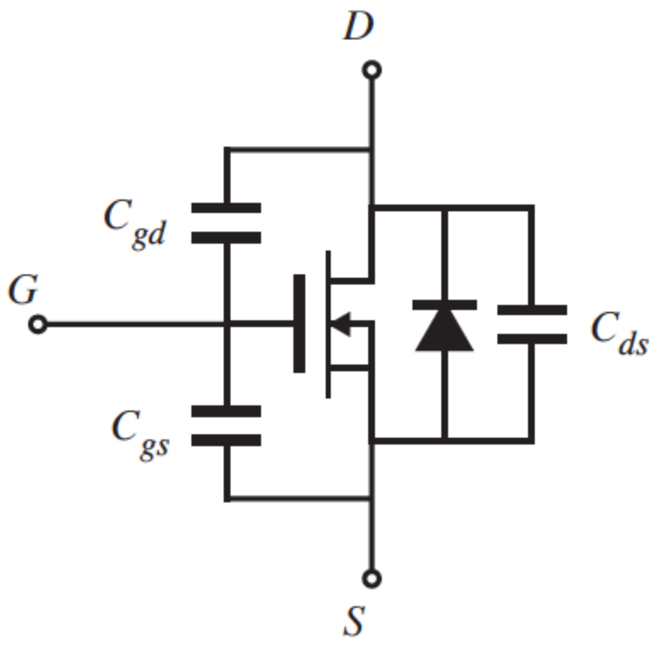




Power MOSFET, and its integral body diode

- 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}

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

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

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