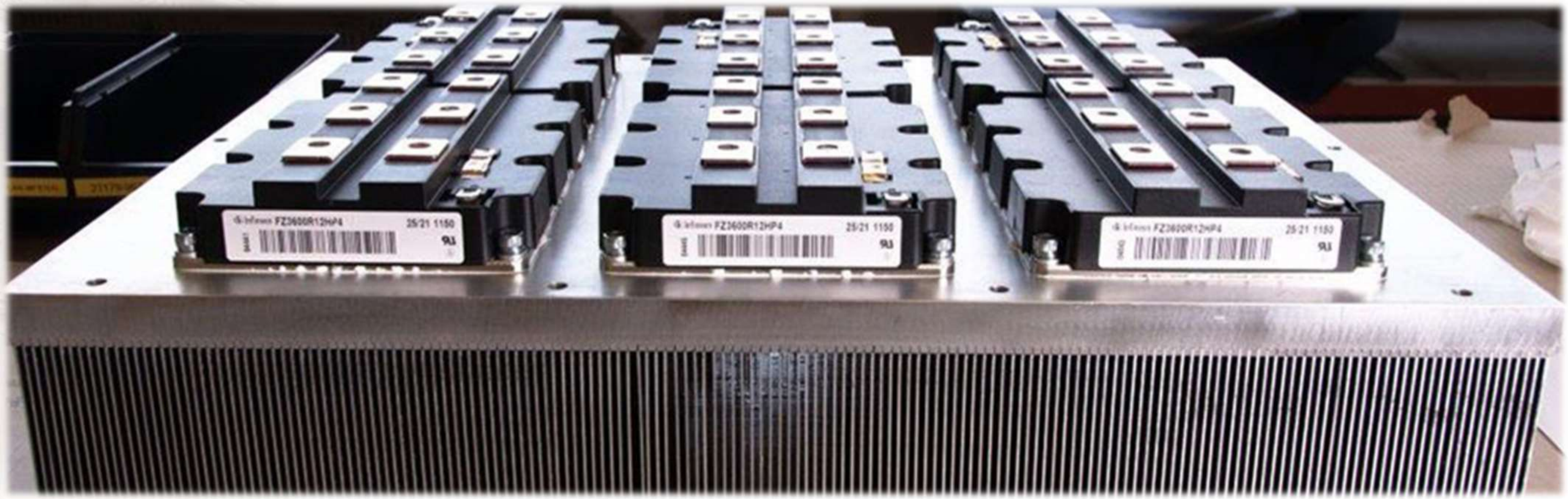
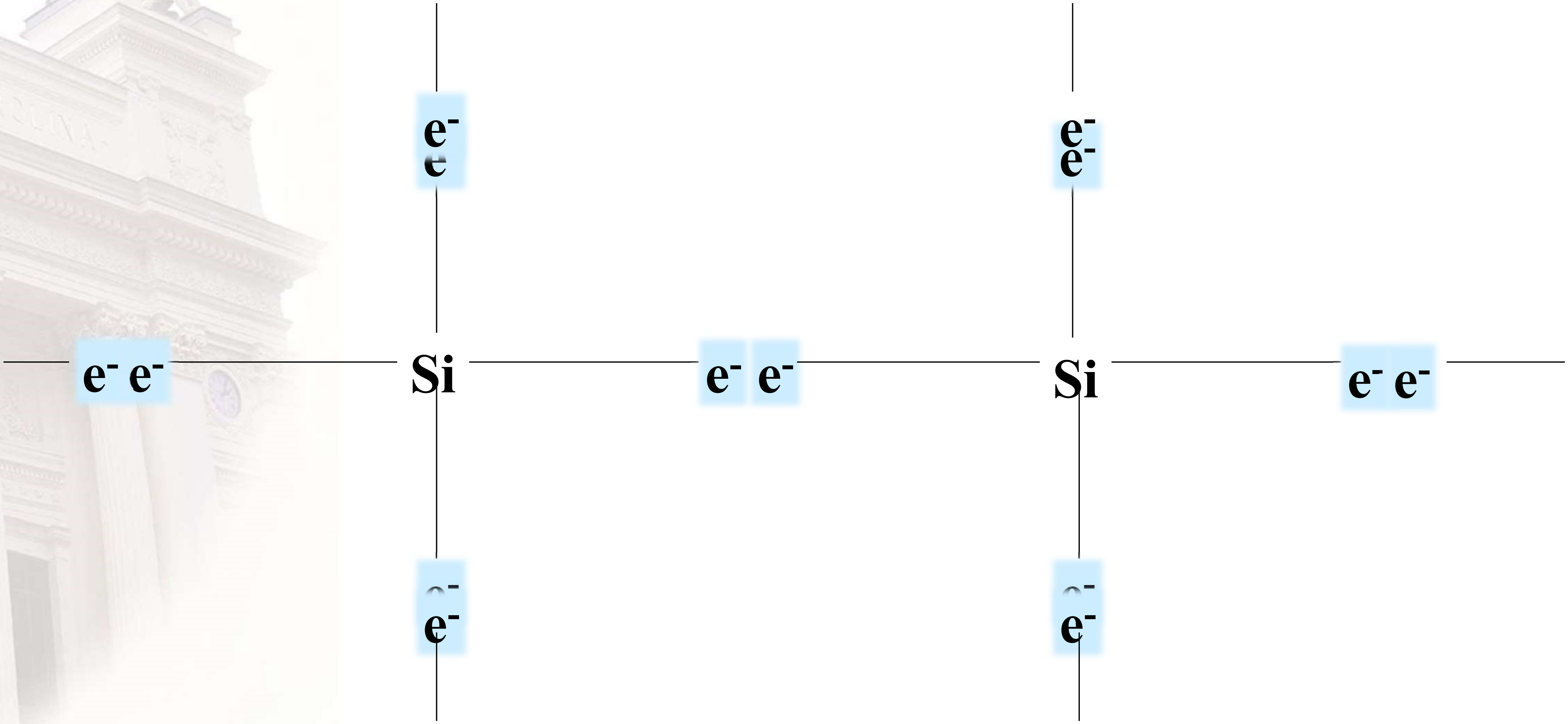
Power Semiconductors



Pure silicon, 4 valence electrons



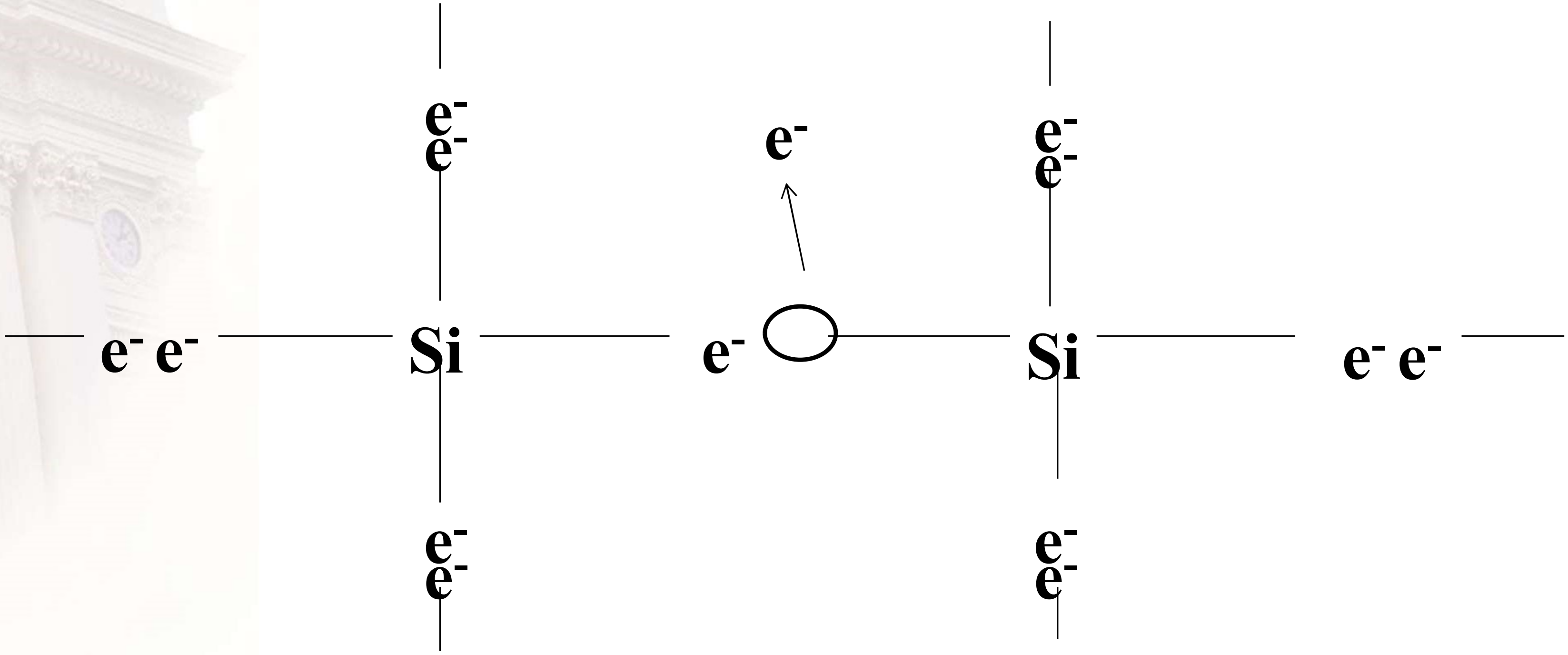
e^- e^- e^- e^-

e^- e^- Si e^- e^- Si e^- e^-

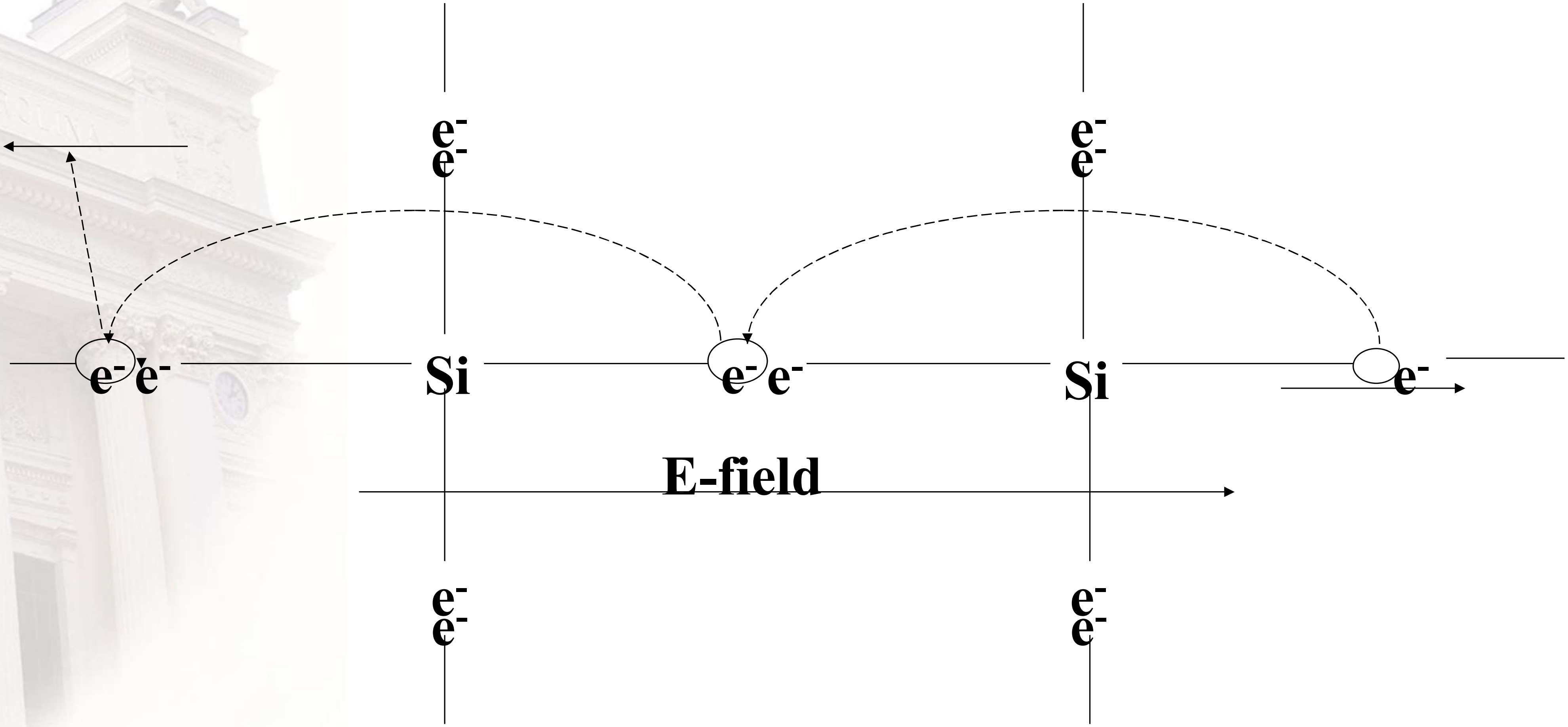
e^- e^- e^- e^-

Thermal ionisation

Free electrons and holes and naturally generated due to thermal ionization, the higher the temperature, the more carriers are generated

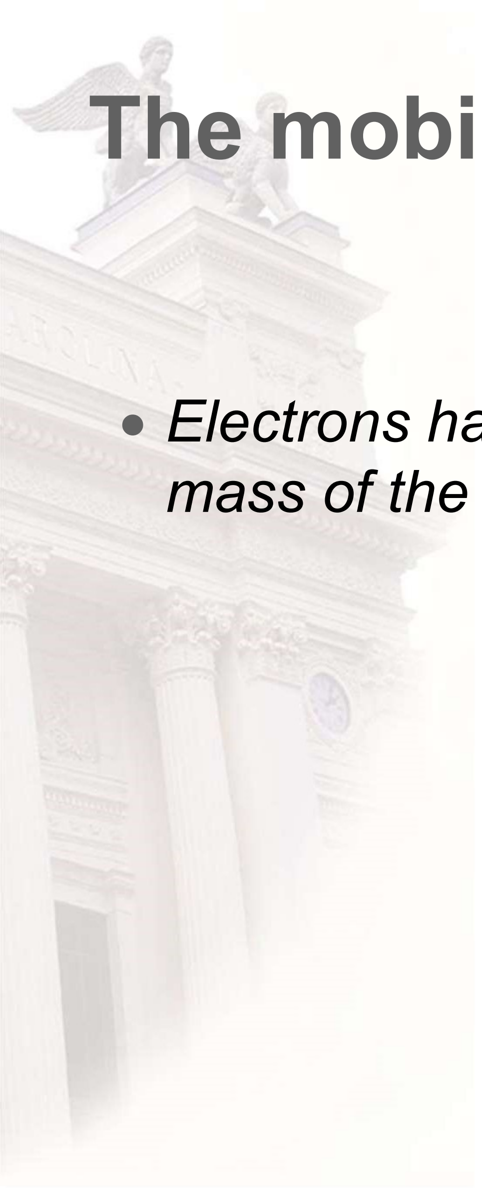


Electron/hole conduction



Mobility = the proportionality between the carrier velocity and the electric field

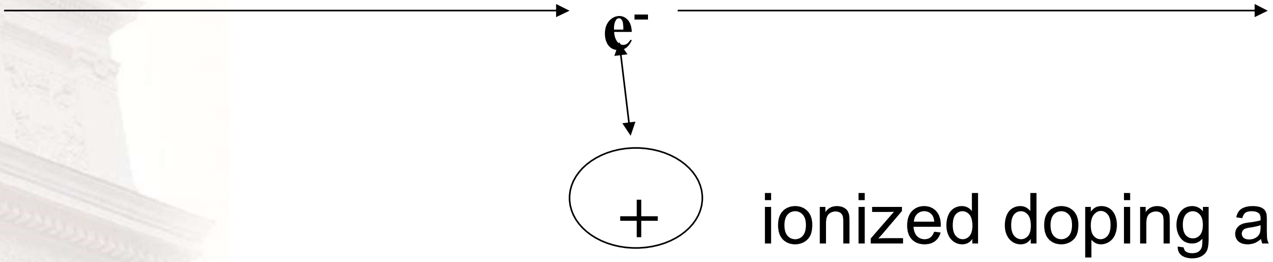
- ***The resistivity of a semiconductor is inversely proportional to the mobility of the carriers.***
- ***A high mobility gives a low resistance, and thus reduced power loss***



The mobility of the electrons and the holes

- *Electrons have higher mobility than the holes, since the effective mass of the electron is only one third of the hole effective mass*

Termed impurity scattering = the mobility is increased with increased temperature

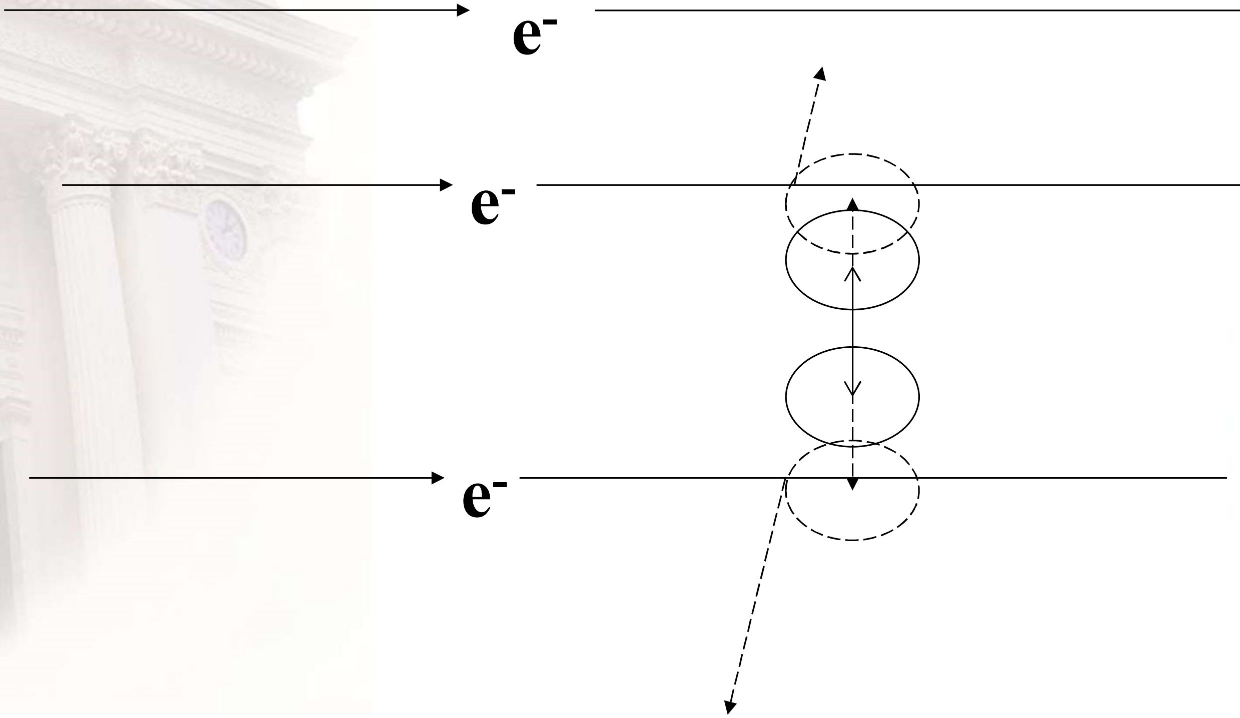


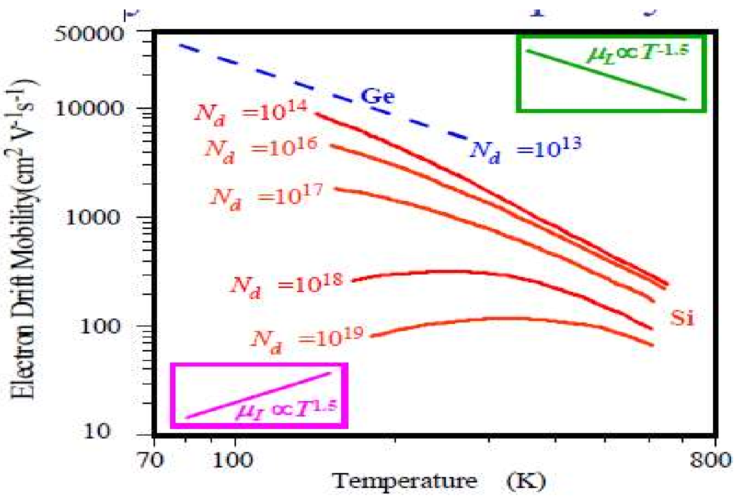
ionized doping atom

- *At low temperature the mobility is low because the carriers are affected by a ionized doping atoms. This interaction takes a long time since the passing time is long as the thermal velocity of the carrier is low*
- *At higher temperature the thermal velocity increases and thus the affection time is reduced and the mobility increases*

Lattice scattering = the carrier mobility is decreased with increased temperature

- *At higher temperature the atom vibration increases and the and the risk for collision is increased and the mobility is reduced*

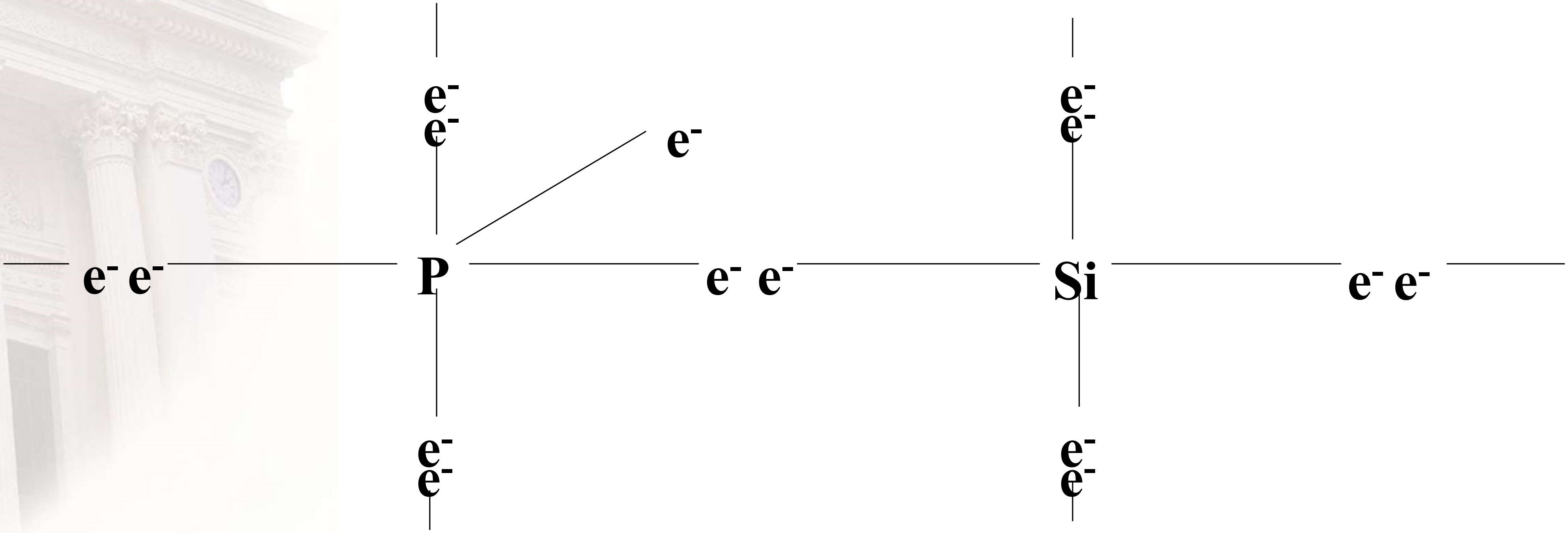




Doping

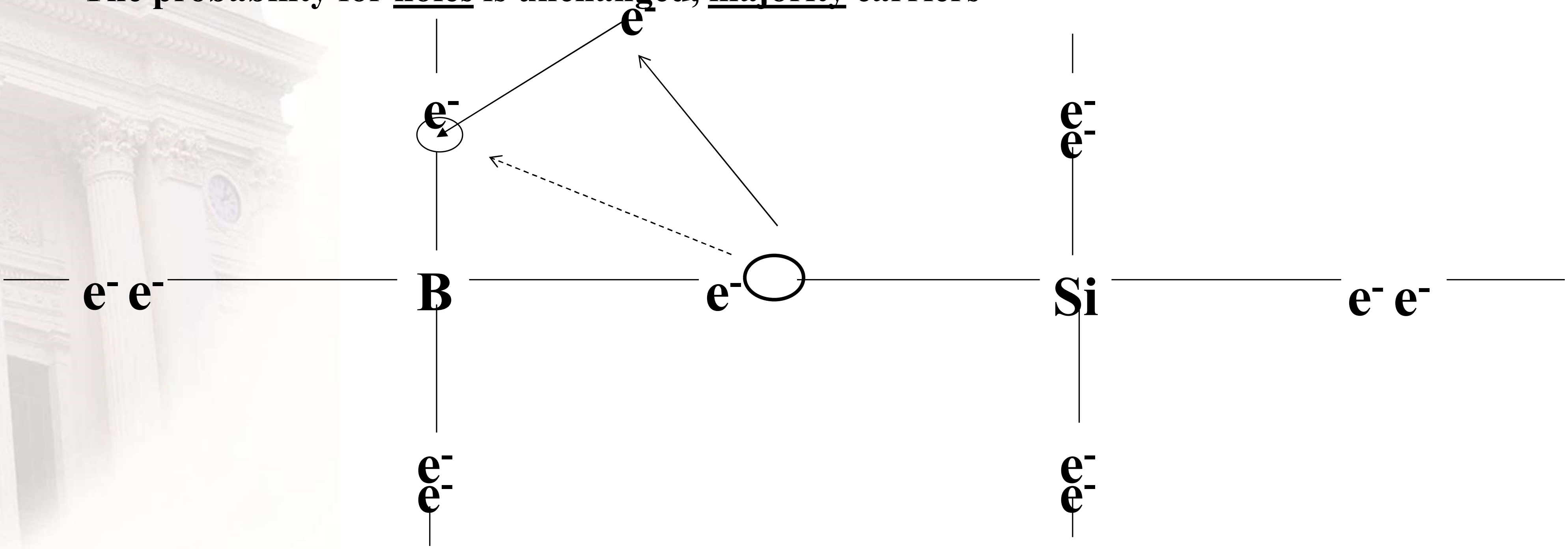
N-doping

- *By adding a material with 5 valence electrons, the fifth electron is an extra free electron.*
- *The probability of free __electrons__ is increased, __majority__ carriers.*
- *The probability for __holes__ is unchanged, __minority__ carriers.*



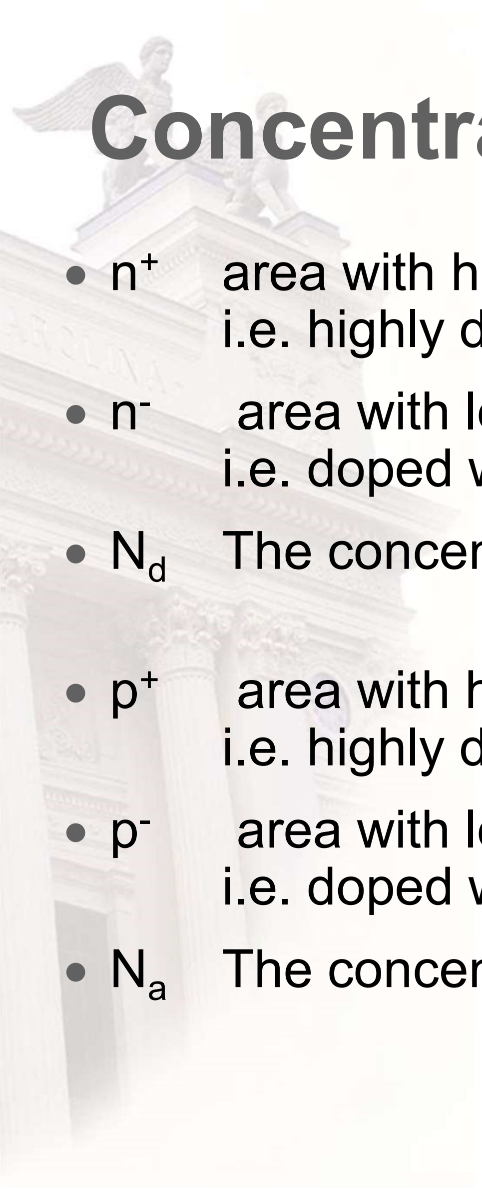
P-doping

- **By adding a material with 3 valence electrons, free electrons are easily captured in covalent bondings.**
- **The probability of free <u>electrons</u> is reduced, <u>minority</u> carriers**
- **The probability for <u>holes</u> is unchanged, <u>majority</u> carriers**



P and N doping materials

- In P doped silicon, the holes are majority carriers and electrons are minority carriers. The material is an electron acceptor
- In N doped silicon, the electrons are majority carriers, and holes are minority carriers. The material is an electron donor



Concentration notation

- n^+ area with high concentration of free electrons, i.e. highly doped with donor atoms
- n^- area with low concentration of free electrons, i.e. doped with a low amount of donor atoms
- N_d The concentration of donor atoms

- p^+ area with high concentration of holes, i.e. highly doped with acceptor atoms
- p^- area with low concentration of holes, i.e. doped with a low amount of acceptor atoms
- N_a The concentration of acceptor atoms

Minority carrier life time

- *The minority carrier life-time is the time-constant with which the excess carriers decrease*
- *At thermal equilibrium, the density of free carriers is constant. The free electron-hole pairs are created with the same rate as they disappear*
- *Carriers are disappearing*
  - *via recombination, i.e. the covalent bonding is re-established*
  - *carriers are captured by impurity atoms*
  - *carriers are captured by crystal imperfections*

Recombination

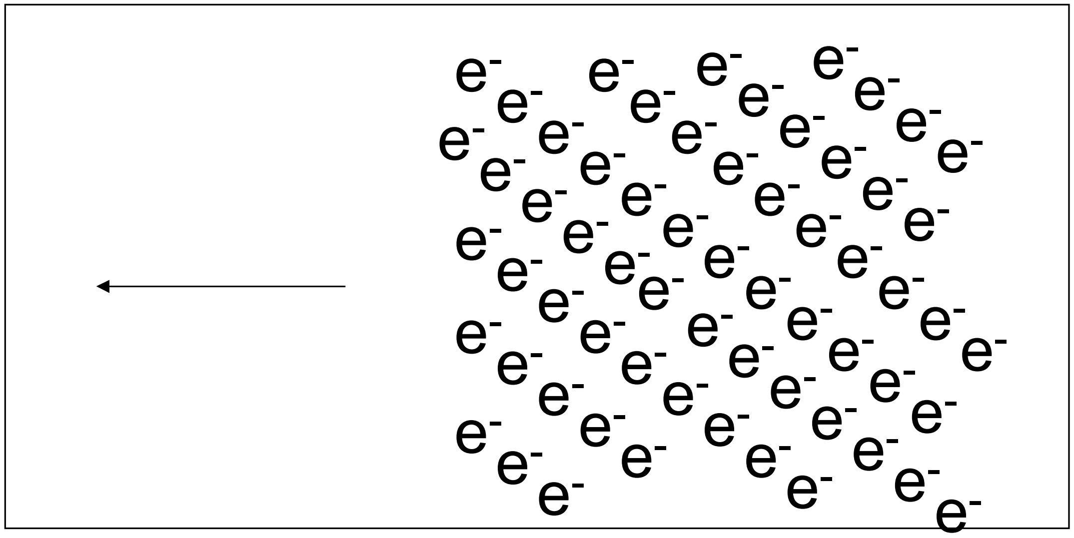
- Minority carrier life time increases with increasing temperature. At higher temperature the minority carrier has higher energy, higher speed. The probability that a free electron and hole come close enough to recombine decreases.
- The minority carrier time constant increases, and thus the turn-off time.

- Auger recombination. At higher carrier concentration, the probability that a free electron and hole come close enough to recombine increases.
- The minority carrier time constant decreases. With high carrier concentration, i.e. with high current, the carrier life time decreases, resulting in increased conduction losses.

Drift current

Diffusion current

From higher concentration to lower concentration, trying to equalize the concentration difference

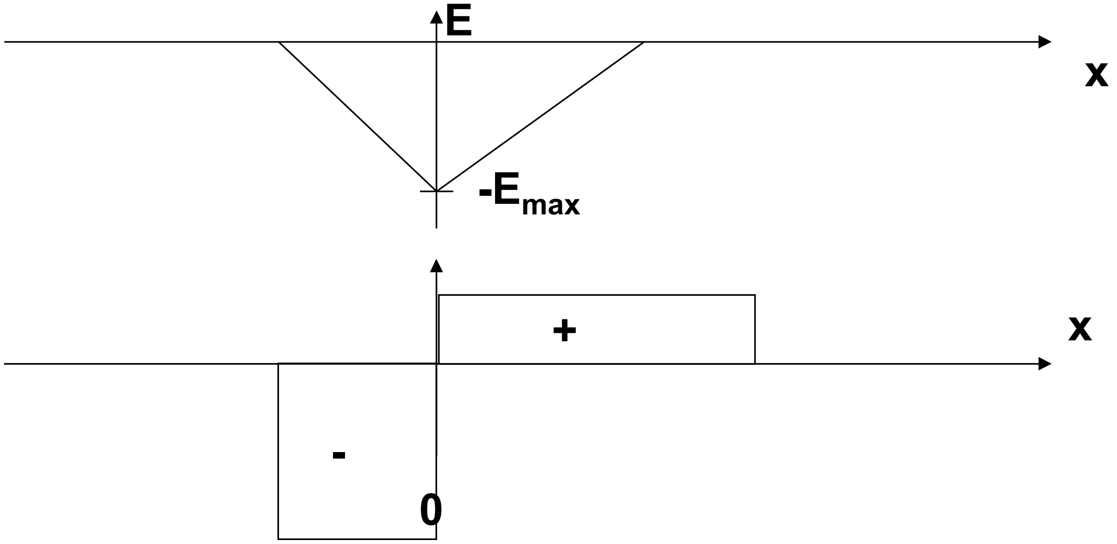


E-field in the depletion area

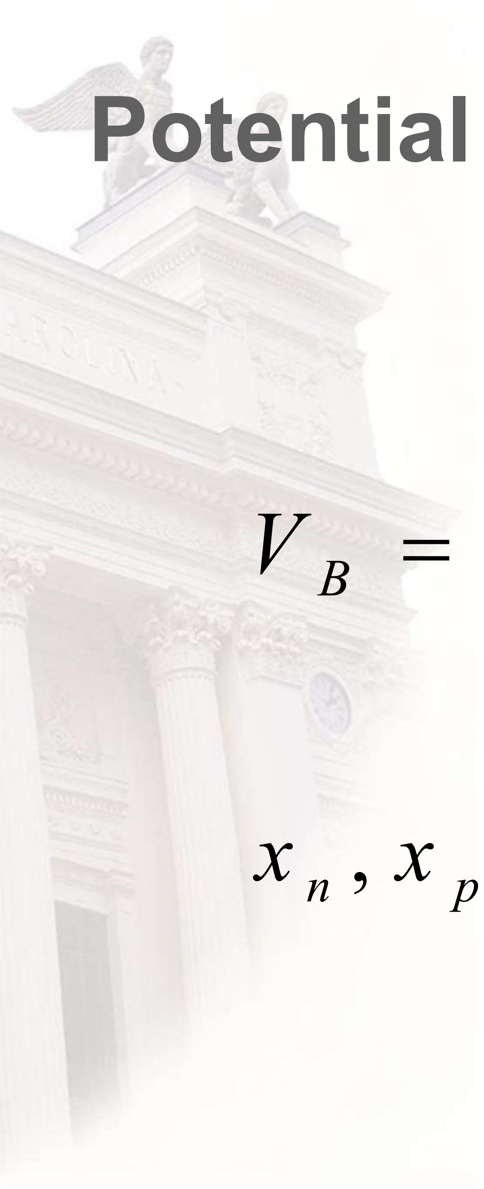
Poison’s equation

$$\nabla \cdot E = \frac{\partial E}{\partial x} = \frac{\rho}{\varepsilon}$$

$$E(x) = \begin{cases} -\dfrac{q_e \cdot N_a}{\varepsilon} \cdot (x + x_p) & -x_p < x < 0 \\ \dfrac{q_e \cdot N_d}{\varepsilon} \cdot (x - x_n) & 0 < x < x_n \end{cases}$$



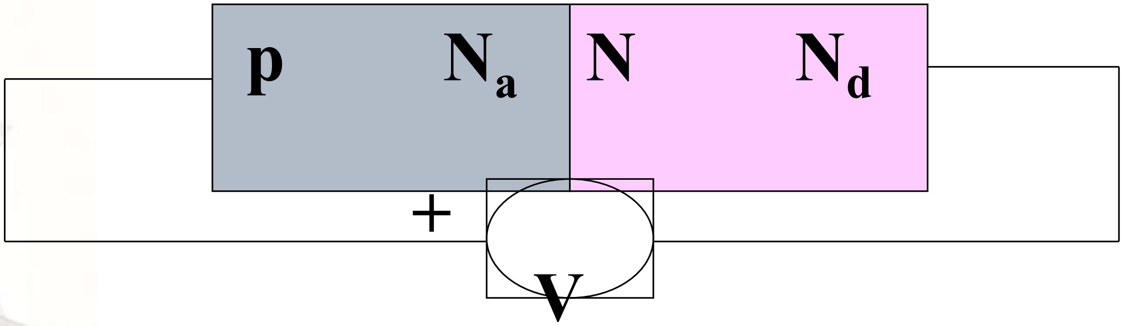
Potential barrier in a pn-junction



$$V_B = \frac{q_e}{2 \cdot \varepsilon} \cdot \left(N_a \cdot x_p^2 + N_d \cdot x_n^2 \right)$$

$$x_n, x_p \propto \sqrt{1 - \left(\frac{V}{V_B} \right)}$$

Bias



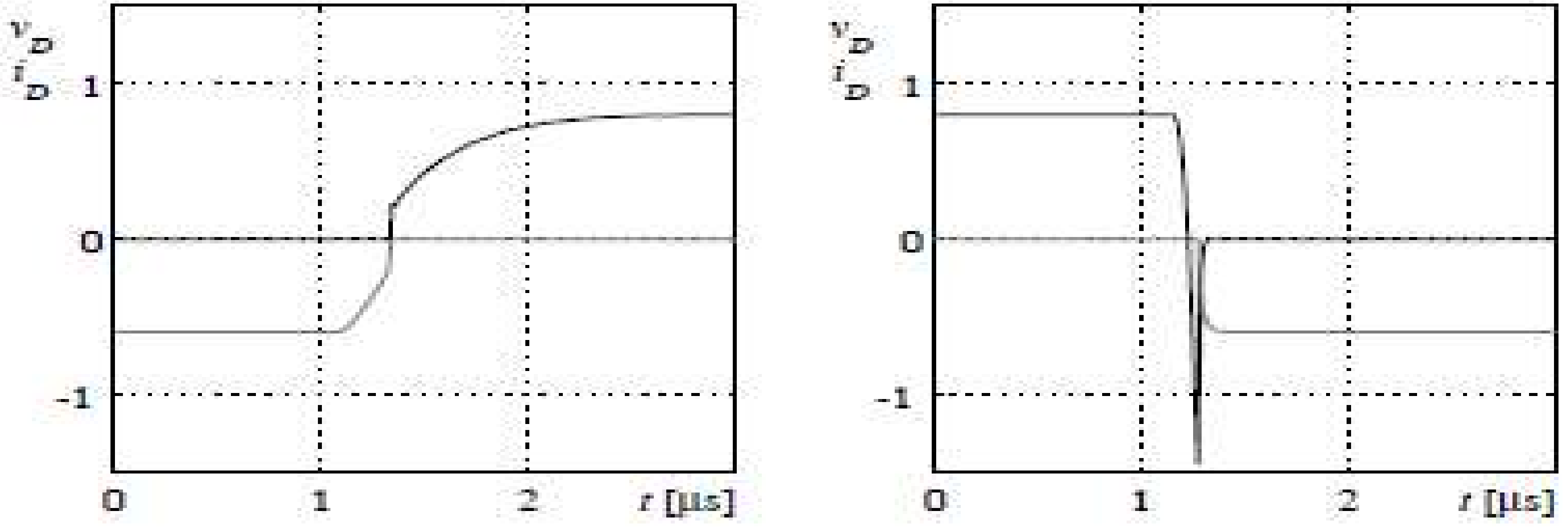
- ***Field strength***

$$\left|E_{\max}\right| = \sqrt{\frac{V_B \cdot q_e}{2 \cdot \varepsilon} \cdot \left(\frac{N_a \cdot N_d}{N_a + N_d}\right) \cdot \left(1 - \frac{V}{V_B}\right)}$$

- ***Forward bias no e-field when $V>V_B$v-> fully conducting***

- ***Reverse bias e-field increases with increased voltage***

Diode



(a) (b)

Figure 4.6: The freewheeling diode current i_D (black) and forward voltage v_D (grey) during (a) turn-on, and (b) turn-off. Note that the corresponding transistor, an IGBT in this case, is non-ideal, i.e. it affects the diode switching waveforms.

Exercise

- ***Calculate the e-field at an un-biased PN-junction?***
  See equation (4.16). There is an error in the expression in the book!

$N_a >> N_d$

$N_d = 10^{15}\ cm^{-3} = 10^{21}\ m^{-3}$

$\varepsilon_r(for\ \ Si) = 11.7$

$V = 0\,V$

$Assume V_B = 0.7\,V$

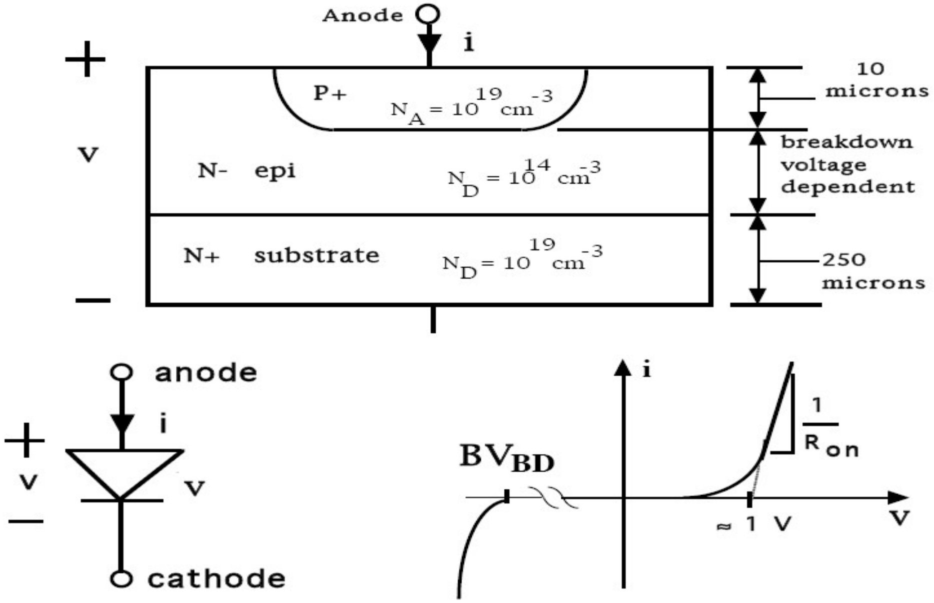
$$\left|E_{\max}\right| = \sqrt{\frac{V_B \cdot q_e}{2\cdot\varepsilon}\cdot\left(\frac{N_a\cdot N_d}{N_a + N_d}\right)\cdot\left(1-\frac{V}{V_B}\right)} = \sqrt{\frac{V_B\cdot q_e}{2\cdot\varepsilon_r\cdot\varepsilon_0}\cdot\frac{N_a}{N_a}\cdot\left(\frac{N_d}{1+\frac{N_d}{N_a}}\right)\cdot\left(1-\frac{V}{V_B}\right)} \approx$$

$$\approx \sqrt{\frac{V_B\cdot q_e}{2\cdot\varepsilon_r\cdot\varepsilon_0}\cdot N_d\cdot\left(1-\frac{V}{V_B}\right)} = \sqrt{\frac{0.7\cdot 1.6\cdot 10^{-19}}{2\cdot 11.7\cdot\frac{10^{-9}}{36\pi}}\cdot 10^{21}} \approx \sqrt{5.4\cdot 10^{21-19+9}} \approx 10^{6}\,\frac{V}{m}$$

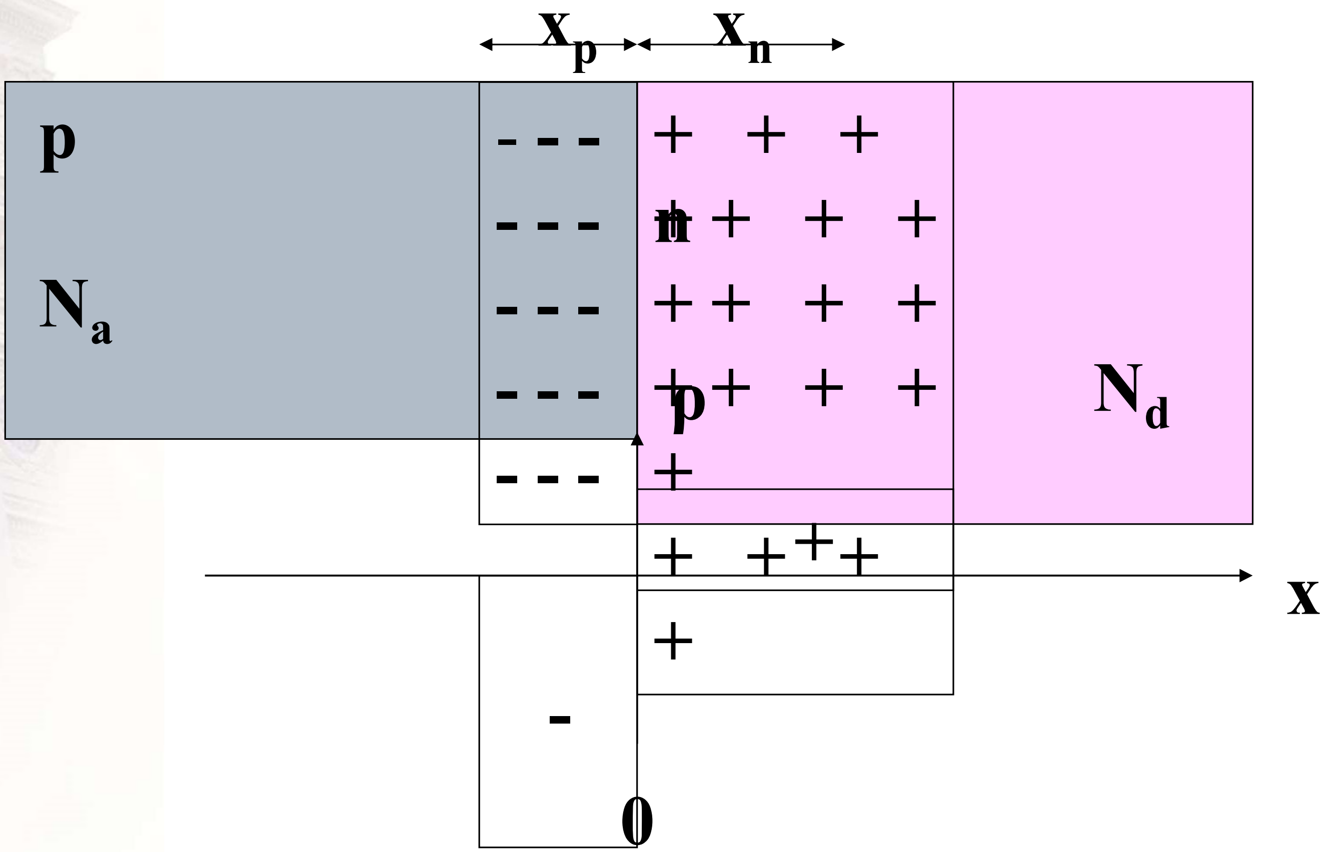
Diodes

Basic Structure

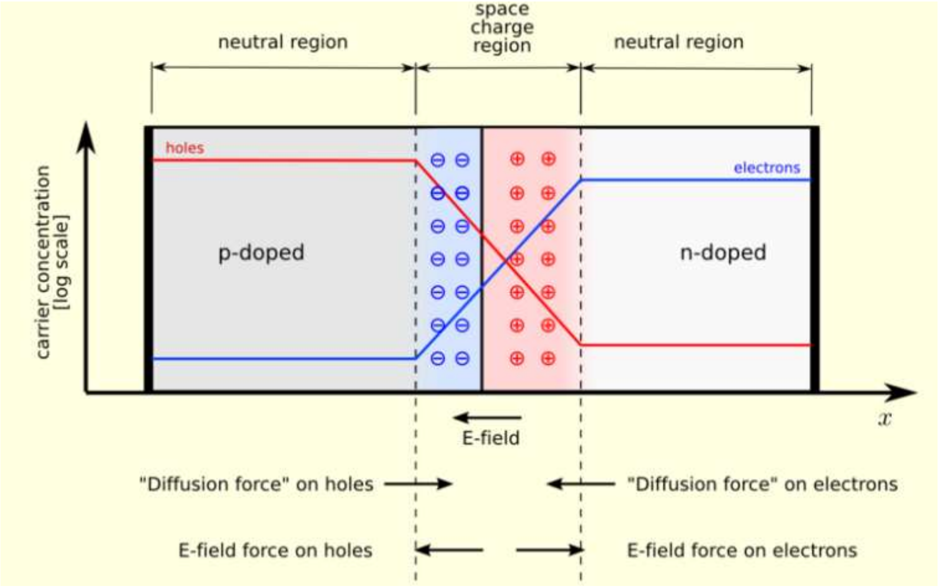
- A *pn* junction
- Conducts in one direction when ‘forward biased’.
- Blocks in the other direction (‘reverse baised’).
- Provides unidirectional current flow.



PN-junction and depletion area



Depletion Layer



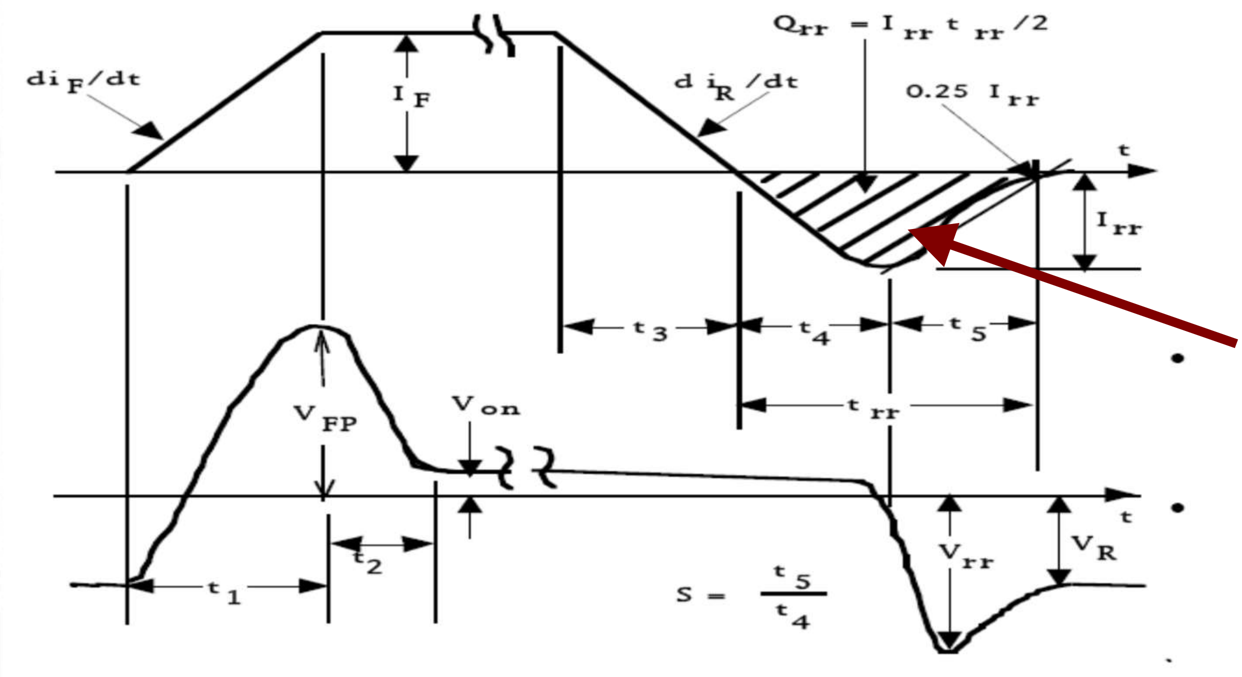
- *When reverse biased, all mobile carriers are swept away from the junction forming a depletion layer (a region that has no charge carriers therefore is non-conducting)*

PN junction

- Animated (from 2:37 min)

https://www.youtube.com/watch?v=JNi6WY7WKAI

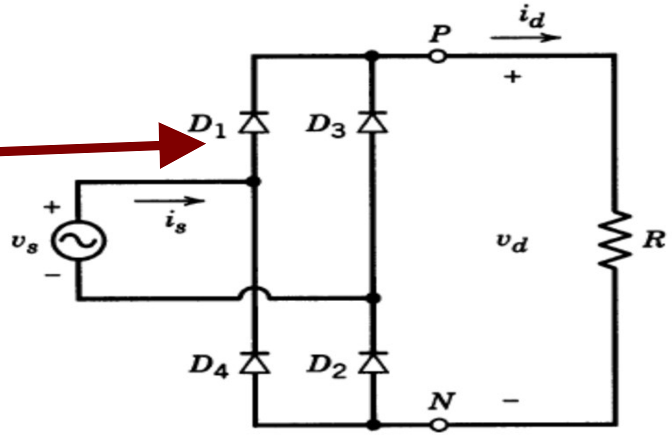
Turn-on and turn-off waveforms



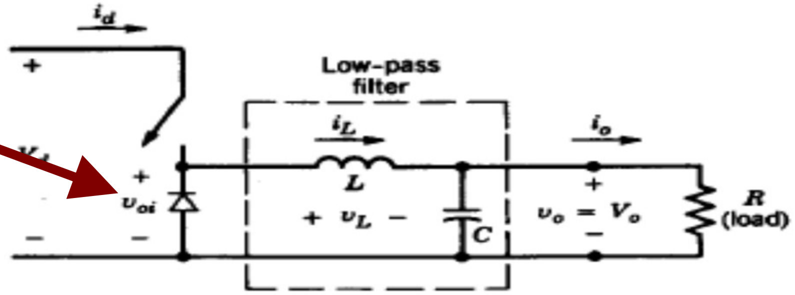
- Reverse recovery is the process by which the diode transits from being forward biased to reverse biased.
- In essence, the diode will conduct current in the reverse direction.
- The charge represented by the integral of reverse current with time is known as the recovery charge.
- Big problem in power electronics

Diode flavours

- Rectifier diodes for mains and low frequency applications.



- Fast and ultrafast recovery diodes for high-frequency switching circuits (e.g. switched-mode power supplies)
- Schottky diodes – excellent reverse recovery and low forward voltage drops, but restricted voltage and current ratings and high reverse leakage current



Diode losses

- Conduction losses
  - $P_c = v_f \times i_{F,rms}$
- Switching loss
  - $P_{sw} = f_{sw} \times E_{off} = f_{sw} \times \textit{reverse recovery energy}$
- Leakage loss (reverse only)
  - $P_r = v_r \times i_l$

NPN junction – basic transistor

- Animated (from 4:11 min)

https://www.youtube.com/watch?v=7ukDKVHnac4&list=WL&index=5&t=216s

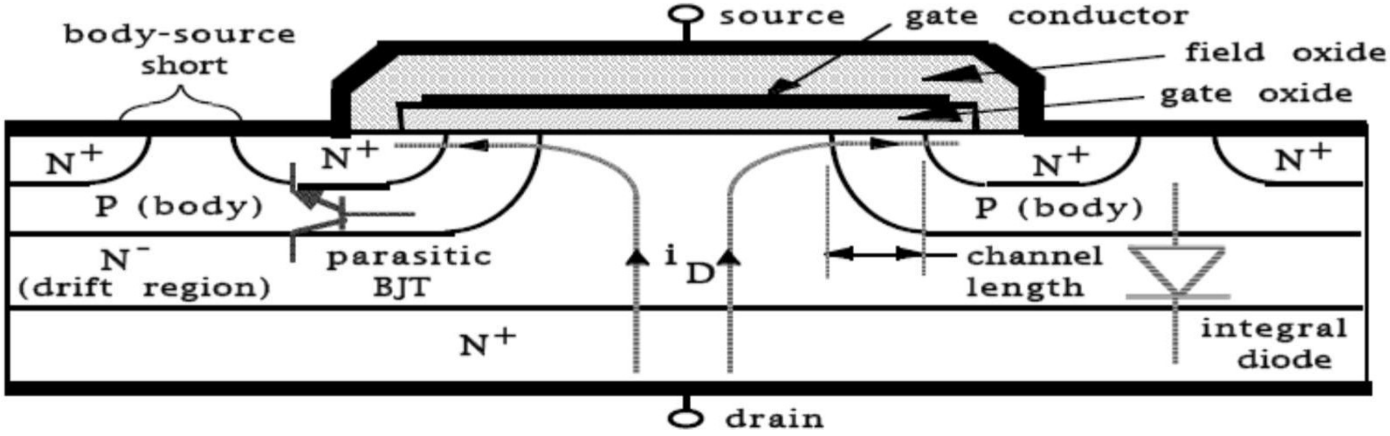
MOSFETs

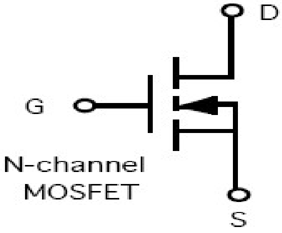
MOSFET

- Metal-Oxide-Semiconductor Field-Effect Transistor

- A voltage-controlled switch with three terminals – Gate, Drain and Source.
- Turn-on by applying a voltage (~15V) between Gate and Source. Turn-off by removing this voltage.

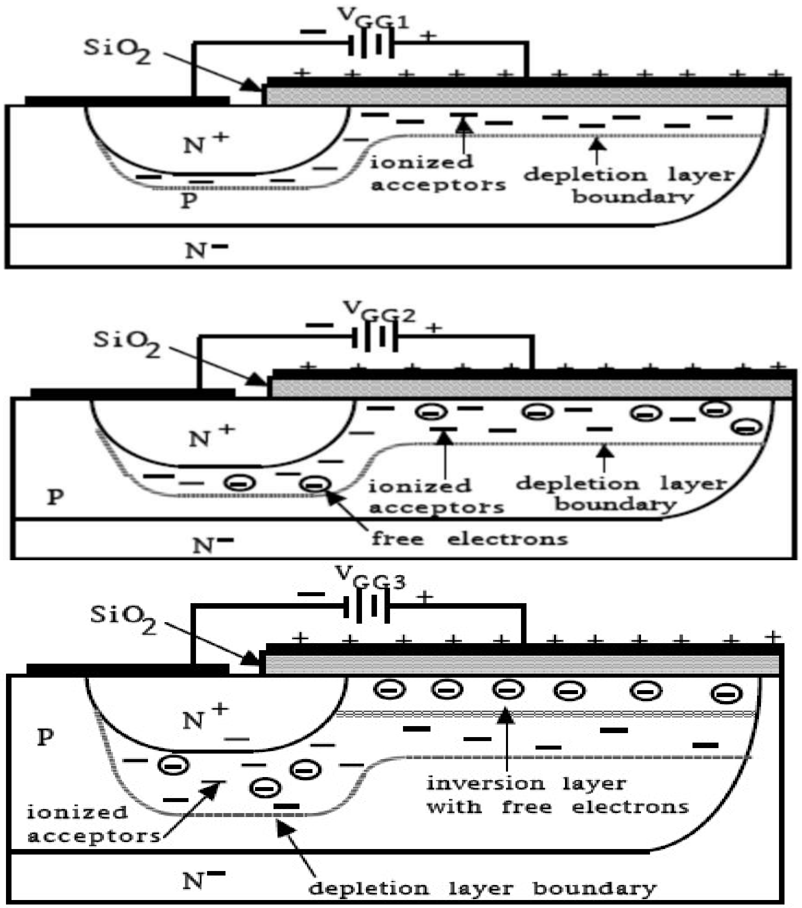
MOSFET Structure





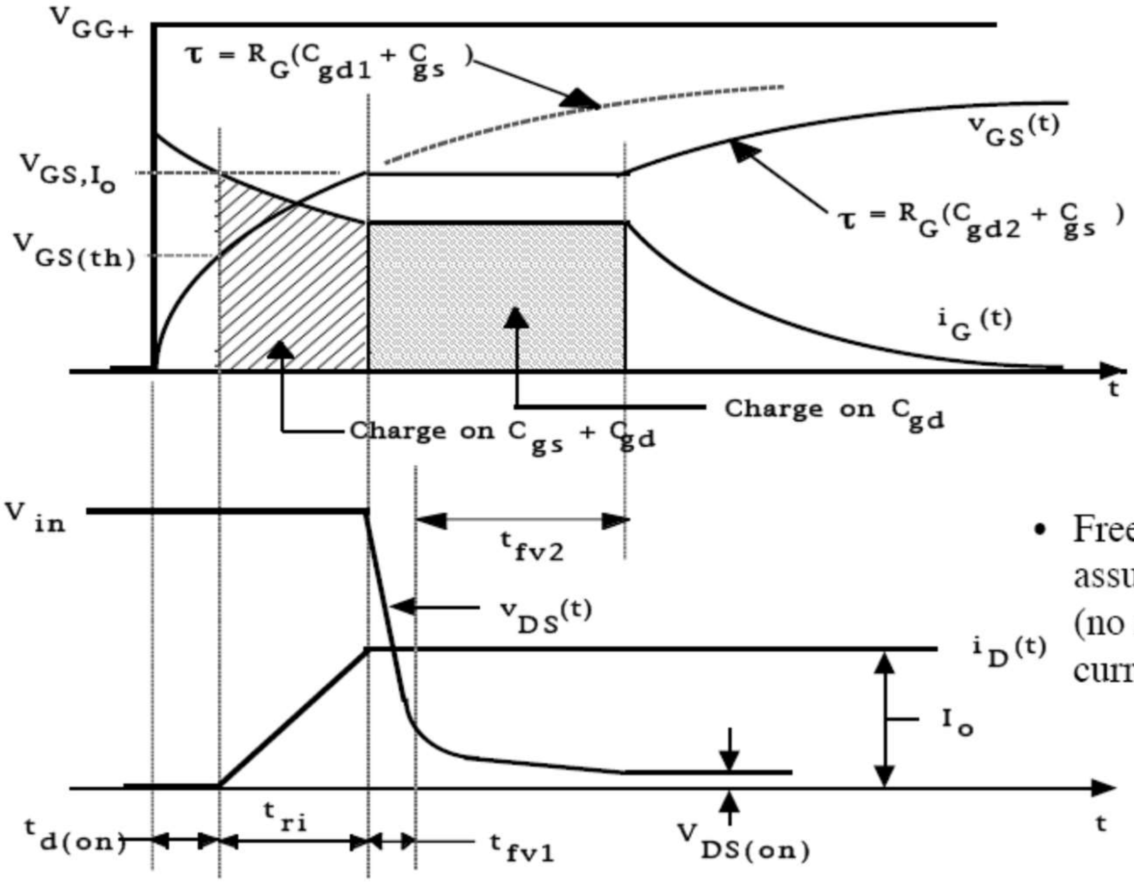
- Gate-source characteristics– high-input impedance, low power requirement.
- Body diode – reverse bias voltage will force diode to conduct. Sometimes used as a freewheel diode.

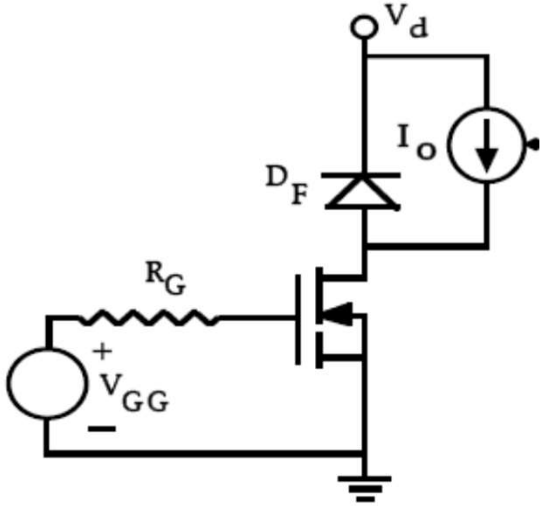
The Field Effect



- As V_{gs} is progressively increased the gate charge forms a depletion layer.
- As V_{gs} is increased further it attracts free electrons to the underside of the oxide.
- When enough free electrons have accumulated we have an inversion layer.
- The inversion layer is a conducting channel and allows current to flow from drain to source.

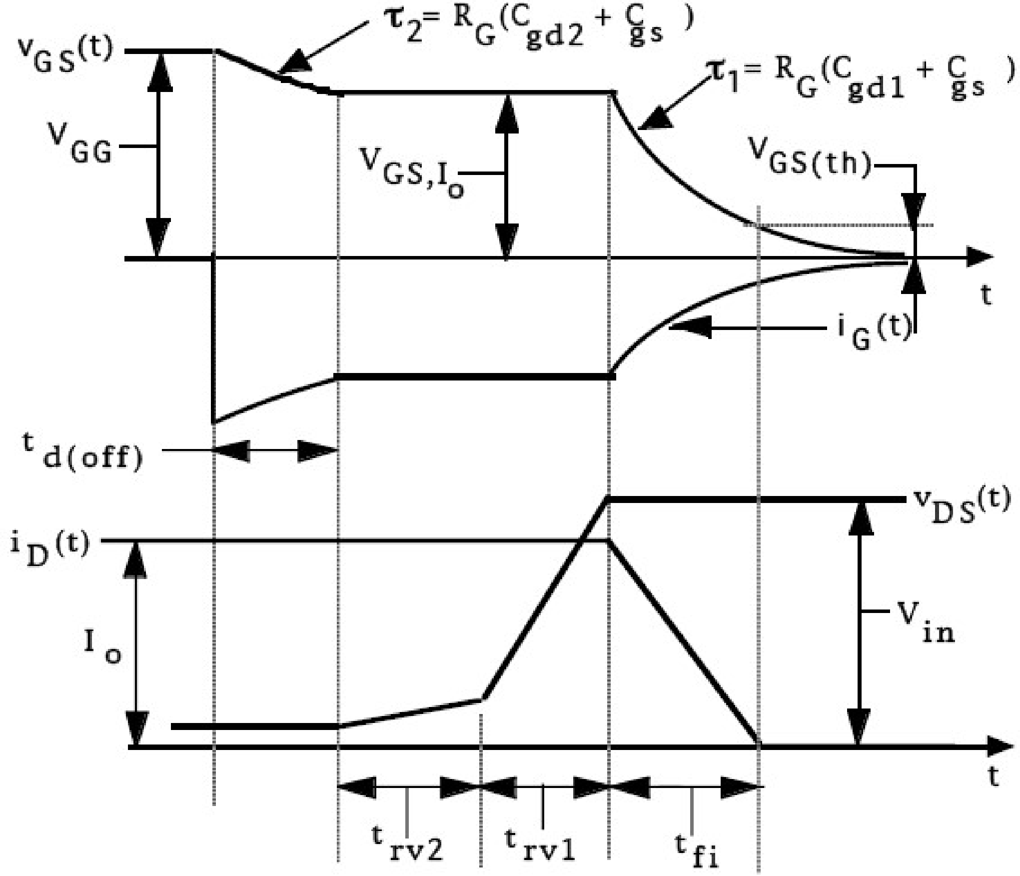
Turn-on waveforms

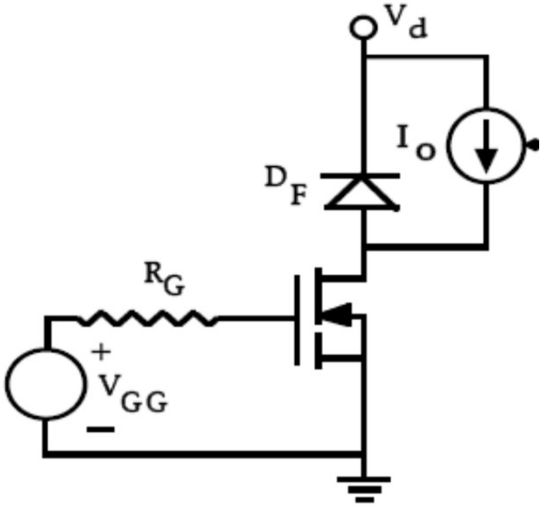




- Free-wheeling diode assumed to be ideal. (no reverse recovery current).

Turn-off waveforms





MOSFET

- MOSFETs are easy to drive, have fast switching times and low losses.

- Application Areas:
  - *Switched-mode power supplies*
  - *Low voltage motor drives (AC and DC) typically below a few hundred volts.*
  - *Synchronous rectification.*

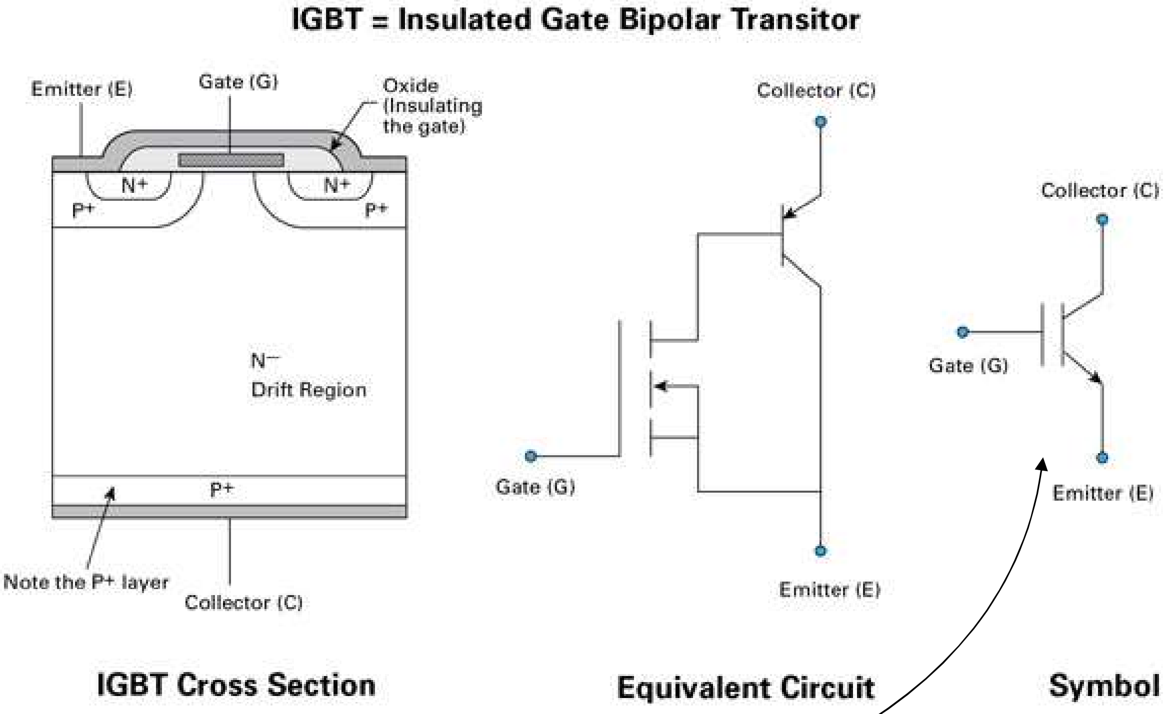
IGBTs

IGBT

- Insulated-Gate Bipolar Transistor

- Structure look similar to MOSFET but has some of the performance attributes of the BJT.

- Equivalent circuit sometimes drawn as



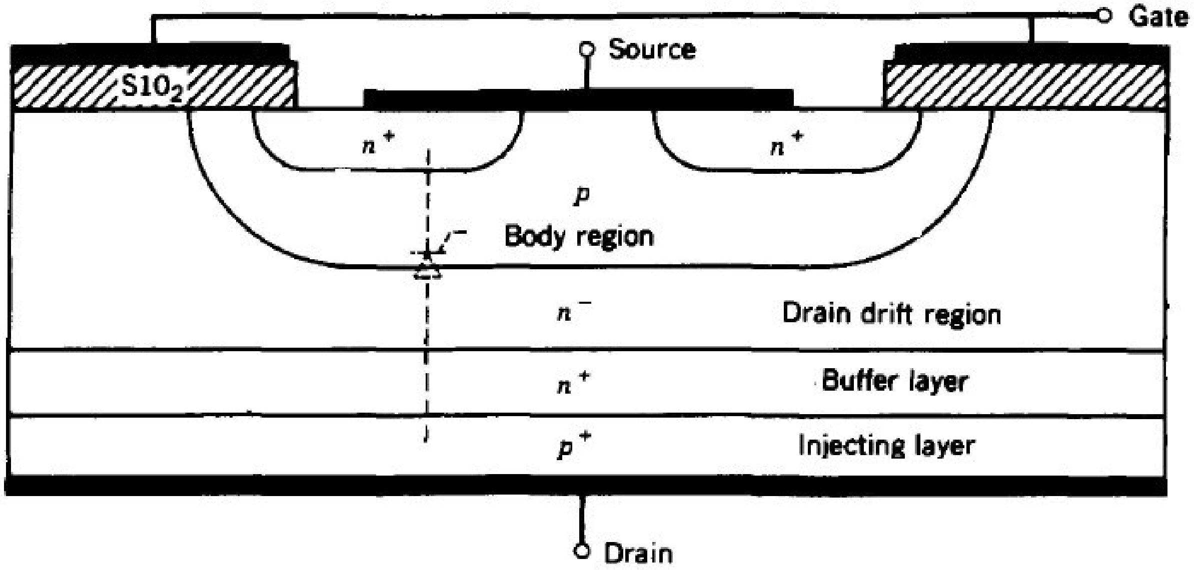
IGBT = Insulated Gate Bipolar Transitor

IGBT Cross Section

Equivalent Circuit

Symbol

IGBT Structure



- Gate-source characteristics similar to MOSFET – high-input impedance, low power requirement.
- No body diode – must avoid excessive reverse bias voltage as this will destroy the device.

Turn-on waveforms

- At turn-on, MOSFET characteristics dominate. MOSFET current turns on internal PNP BJT section and the two sections share the current.

- During initial transient, MOSFET section carries all current.

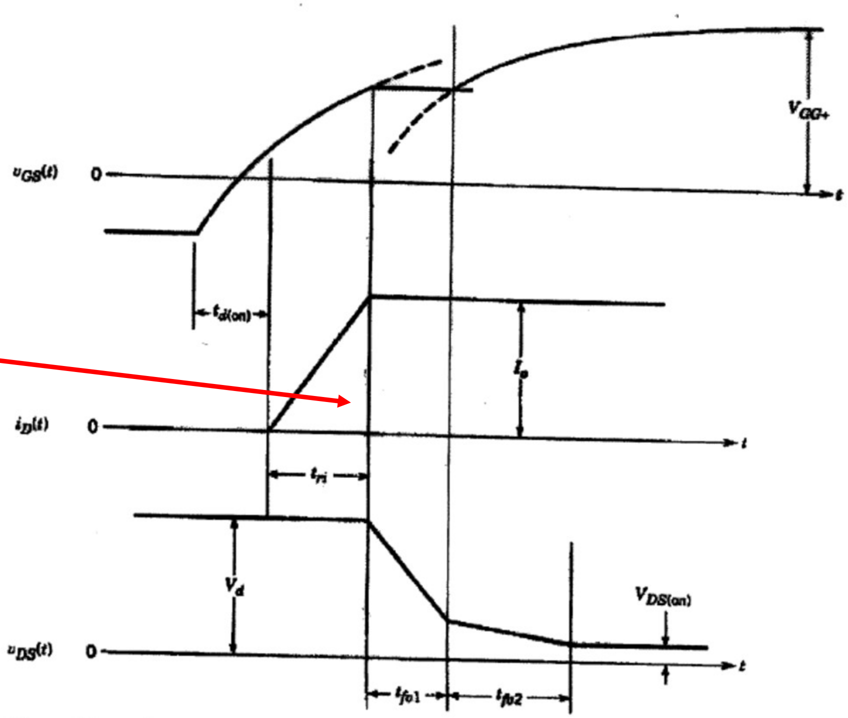


Figure 25-6 Turn-on voltage and current waveforms of an IGBT in a step-down converter circuit.

Turn-off waveforms

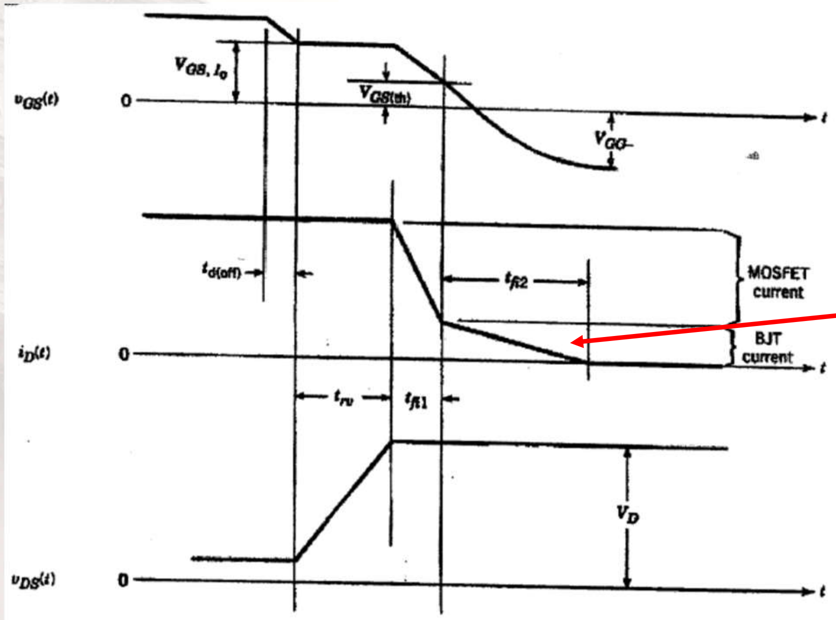


Figure 25-7 Turn-off voltage and current waveforms of an IGBT embedded in a step-down converter circuit.

- During turn-off, the MOSFET section turns-off quickly, but the BJT section turns off slower causing a current tail.
- The tail current contributes a significant lass as it conducts with off-state voltage across diode.

IGBT

- Advantages over MOSFETS
  - *Higher voltage ratings*
  - *Higher current ratings*

- Disadvantages
  - *Slow turn-off due to tail current*
  - *Higher turn-off losses*
  - *Lower switching frequencies*

- Application Areas
  - *Motor drive – traction drives (dc and ac), 400 – 3000V*
  - *Utility interfaces – AC-DC, UPS, VAr compensation*
  - *Unity power factor converters*

- Use
- Above 600 V use IGBT
- Below 200 V use MOSFET
- Between 200 and 600V consider both options.

Wide Band Gap Devices

Videos

- Mitsubishi (50 s – 6 min)

https://youtu.be/iz_QNdhFG

- ST Microelectronics (0 s – 1:34 min)

https://youtu.be/hV5mqmuozlA