Budapest University of Technology and Economics
Department of Electron Devices

Microelectronics, BSc course

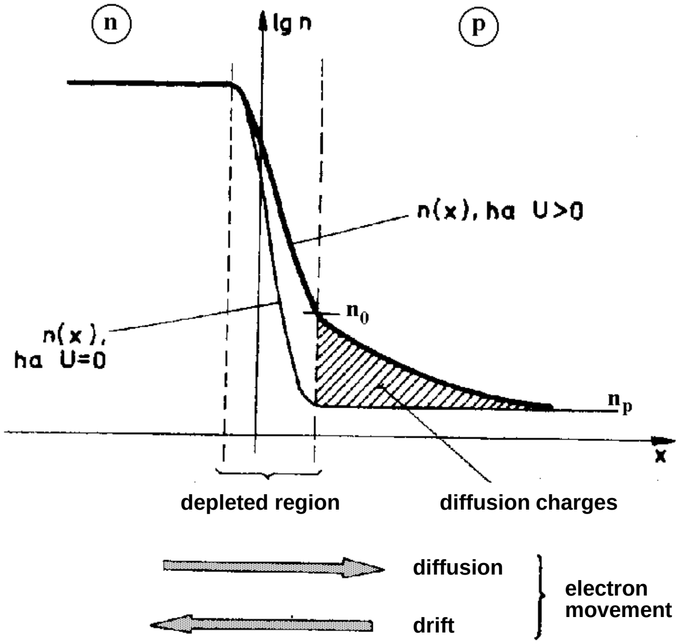
Operation of PN junctions: Characteristics

Diode characteristics

- Forward and reverse mode operation
- Ideal characteristic
- Secondary effects

Forward operation of the diode

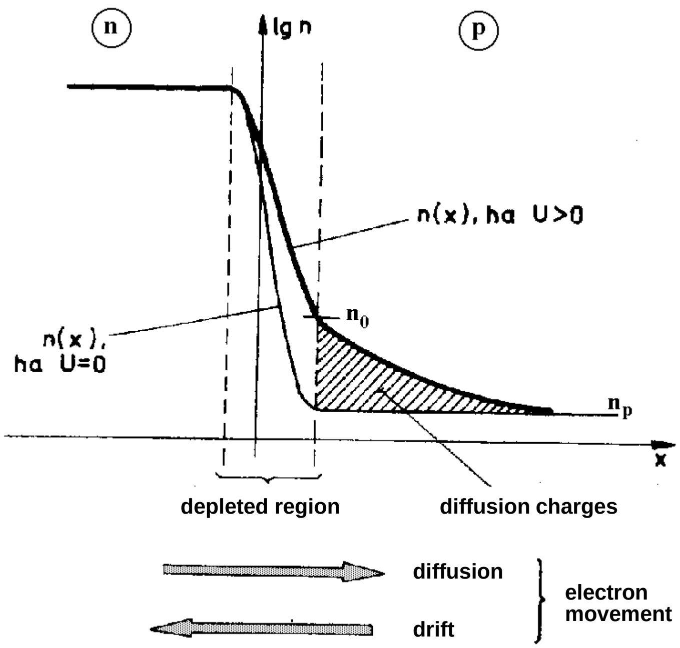
- Effect of forward (positive) U
  - Potential step decreases so as the electric field in the space charge region
  - Current balance disrupted: diffusion current became dominant, e^- diffusion from the n to the p region
- Majority carriers injected to the other side by diffusion



- e^- accumultion in the p region near the junction
- Diffusion carrier appear within the L_D distance (10um)

Forward operation of the diode

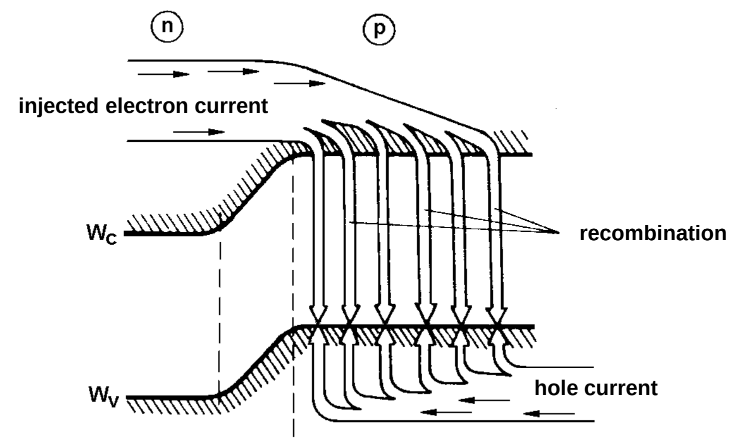
- Diffusion carrier accumulation:
  - grad(n) decreases along the depleted region → **e⁻ current decreaeses in the depleted region**
  - grad(n) in the p region → e⁻ that got though the junction moves further away **(diff. current) from the junction towards the contact**

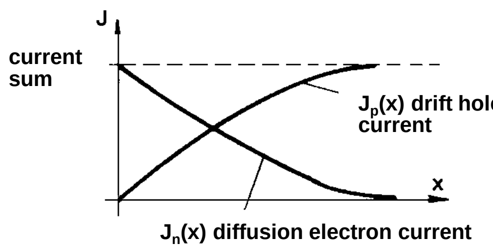


  - Diffusion carriers increase still the two current become equal
- This balanced current determines the current of the PN junciton!

Forward operation of the diode

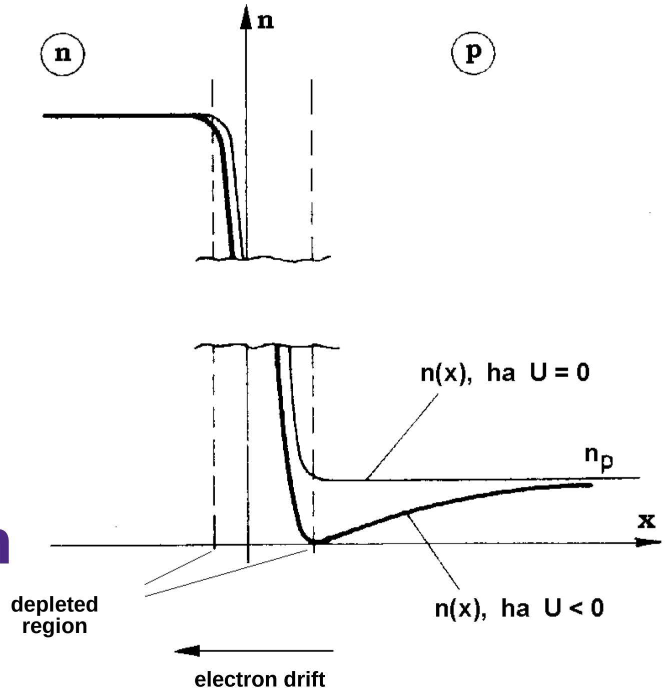
- The role of the e^- current is taken over by the holes in the p region!
- **Wide base structure**
  - Every e^- that got through the junction and recombinates in the p region
- **Narrow base structure**
  - The thickness of p region is smaller than the diffusion lenght $\rightarrow$ only a part of the e^--s recombination
- No difference in the (current) conduction!
- Electric field moves the holes from the contact to the PN junction
  - *Small part of the foward voltage is dropped here*





Reverse operation of the diode

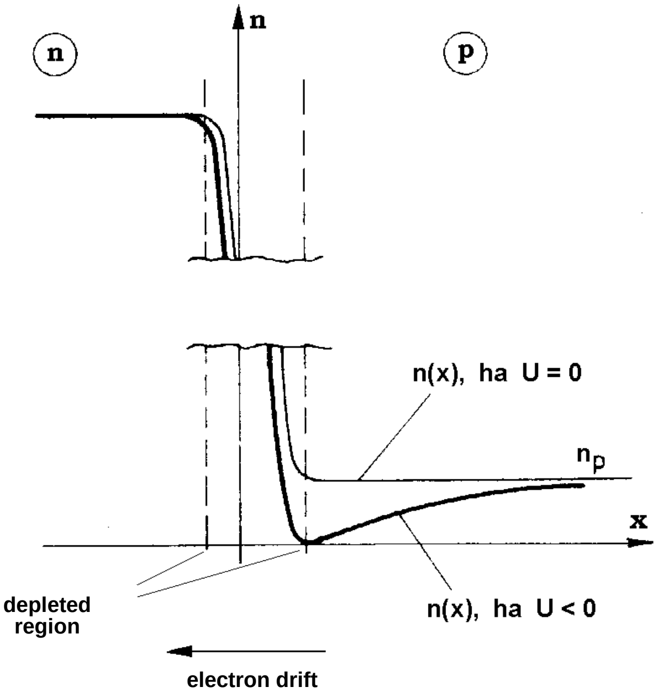
- Effect of reverse (negative) U
  - Potential step increases so as the electric field in the space charge region
  - Current balance disrupted: drift current became dominant, e^- drift from the p to the n region
- **Drift of the minority carriers on both sides towards the other region!**



- e^- concentration decreases in the p region near the junction
- PN junction behaves as a sink for the minority carriers!

Reverse operation of the diode

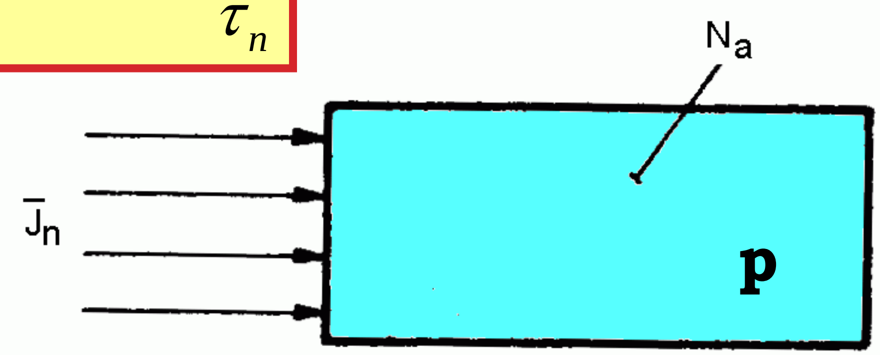
- **Reverse current is determined by the carrier generation rate**
  - e^- „supply” in the p region is determined by the generation rate.
  - ~10^{10}…10^{12} carrier/s/cm^3 in Si SLOW
  - In the range of nA!



- I_R- is not affected by the U_R!
- Generation is not affected by the E in the junction!
- + Generation is a secondary effect!

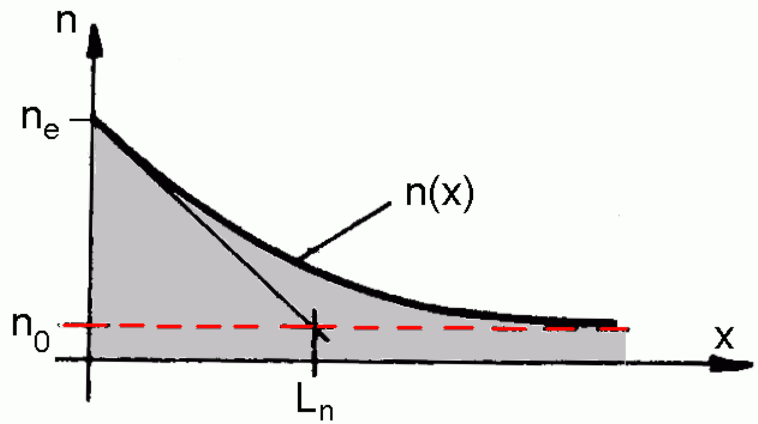
Reminder – Diffusion eq.

$$\boxed{\frac{dn}{dt} = \mu_n \operatorname{div}\left(n\overline{E}\right) + D_n \operatorname{div}\operatorname{grad} n + g_n - \frac{n}{\tau_n}}$$



$$0 = D_n \frac{d^2 n}{dx^2} + \frac{n_0}{\tau_n} - \frac{n}{\tau_n}$$

$$\boxed{n(x) = n_0 + (n_e - n_0)\exp(-x/\sqrt{D_n \tau_n})}$$



$$\boxed{L_n = \sqrt{D_n \tau_n}}$$

The ideal diode characteristic

$$n(x) = n_p + (n_0 - n_p)\exp(-x/L_n)$$

$$n_0 = n_p \exp\left(\frac{U}{U_T}\right)$$

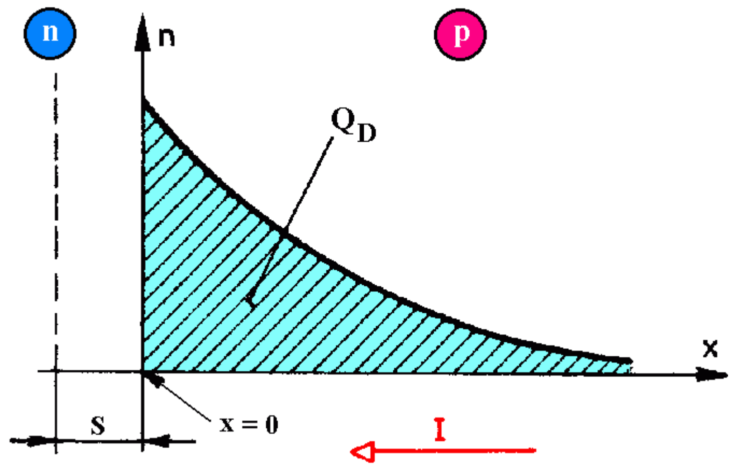
$$J_n(x) = -qD_n\frac{dn}{dx} = -qD_n(n_0 - n_p)\exp(-x/L_n)\left(\frac{-1}{L_n}\right)$$

$$J_n\big|_{x=0} = \frac{qD_n}{L_n}(n_0 - n_p) = \frac{qD_n n_p}{L_n}(\exp(U/U_T) - 1)$$

$$n_0 = n_p \exp\left(\frac{q \cdot U}{k \cdot T}\right) = n_p \exp\left(\frac{U}{U_T}\right)$$

$$J_p = \frac{qD_p p_n}{L_p}(\exp(U/U_T) - 1)$$

$$I = A(J_n + J_p)$$



The ideal diode characteristic

$$J_n\Big|_{x=0} = \frac{qD_n n_p}{L_n}(\exp(U/U_T)-1)$$

$$\boxed{I = I_0\left(\exp\left(U/U_T\right)-1\right)}$$

$$J_p = \frac{qD_p p_n}{L_p}(\exp(U/U_T)-1)$$

I_0 is proportional with the minority carrier concentrations

$$I = A(J_n + J_p)$$

$$I = \overbrace{Aq\left(\frac{D_n n_p}{L_n} + \frac{D_p p_n}{L_p}\right)}^{I_0}(\exp(U/U_T)-1)$$

The ideal diode characteristic

$$\boxed{I = I_0\left(\exp(U/U_T) - 1\right)}$$

$$\boxed{U = U_T \ln(I/I_0 + 1)}$$

Problem

Saturation current of Si diode: $I_0=10^{-13}$ A.

What is U_F, if I_F is 10 mA?

$$U \cong 0.026 \cdot \ln(10^{-2}/10^{-13}) = 0.658\ V$$

Problem

How much should we increase the forward voltage if we want to increase the current 10x ?

$$\Delta U = U_2 - U_1 \cong U_T\left(\ln(I_2/I_0) - \ln(I_1/I_0)\right) = U_T \ln(I_2/I_1)$$

$$\Delta U = 0.026 \cdot \ln 10 \cong 0.06\,V = 60\,mV$$

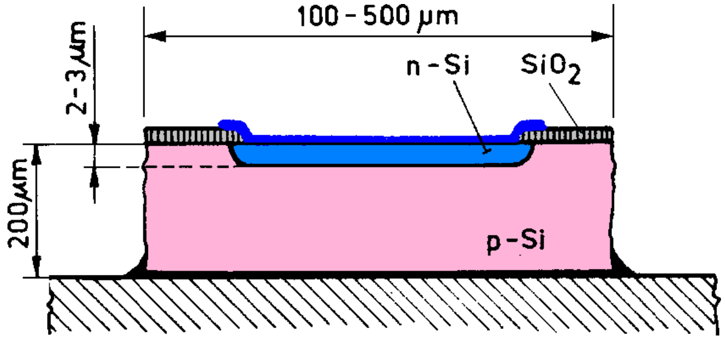
Secondary effects

- Series resistance
- Generation current
- Breakdown phenomena (a bit later)
- Recombination current (just mention)

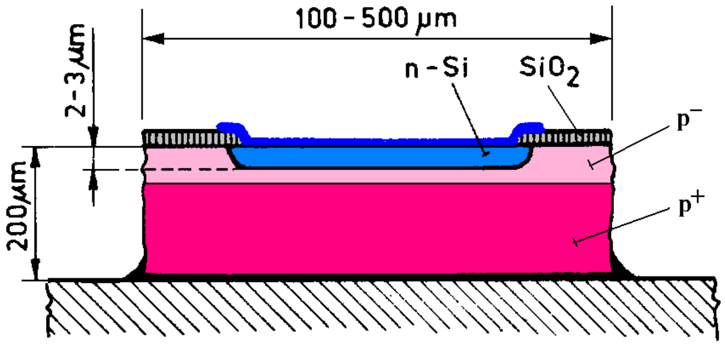
Secondary effects

The series resistance

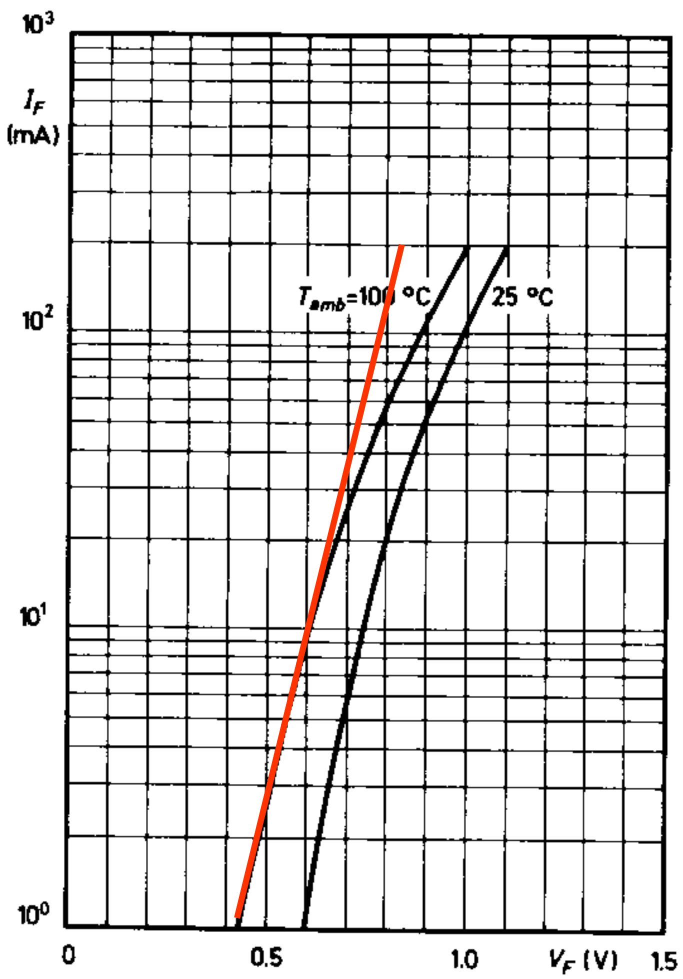
Appears at high current levels. Reason:



Solution: epitaxial structure



Forward characteristics $I_F = f(V_F)$



Secondary effects

Problem

The series resistance

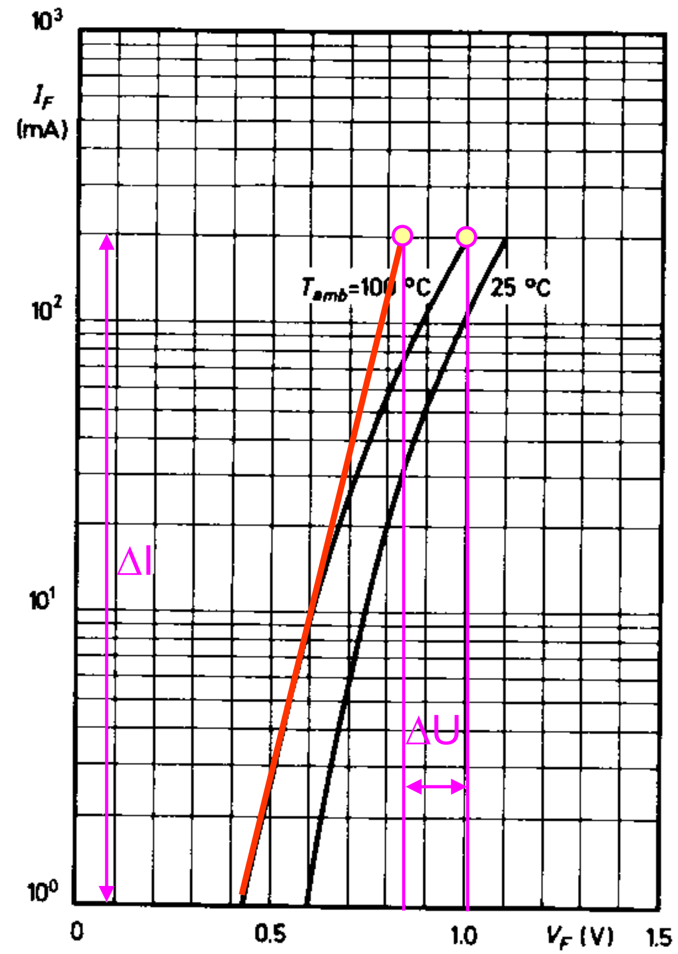
Calculate the series resistance according to the 100ºC characteristic!

$$\Delta U = 160\ mV$$

$$I = 200\ mA$$

$$r_s = 160 / 200 = 0,8\,\Omega$$

Forward characteristics $I_F = f(V_F)$



Secondary effects

The generation current

In reverse region, in theory:

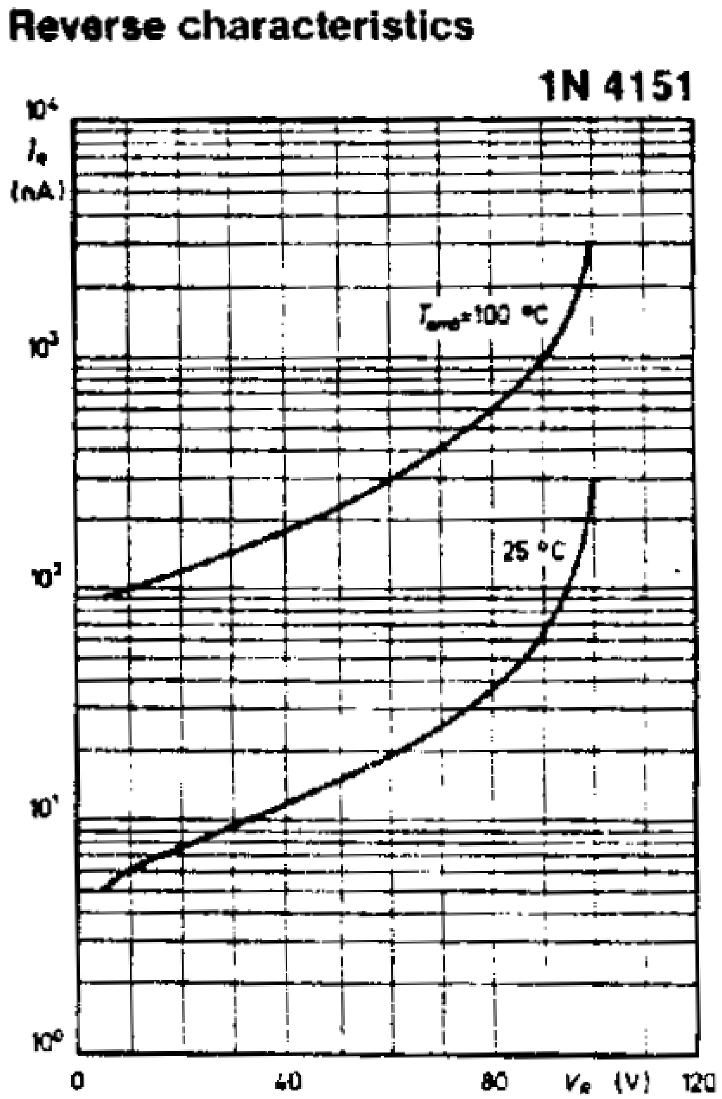
$$\boxed{I = I_0\left(\exp\left(U/U_T\right)-1\right) \Rightarrow -I_0}$$

that would result in pA only

The experince is:

$$g = \frac{n_i}{2\tau}$$

$$\boxed{I_R = const \cdot n_i \sqrt{-U_R}}$$



Secondary effects

The recombination current

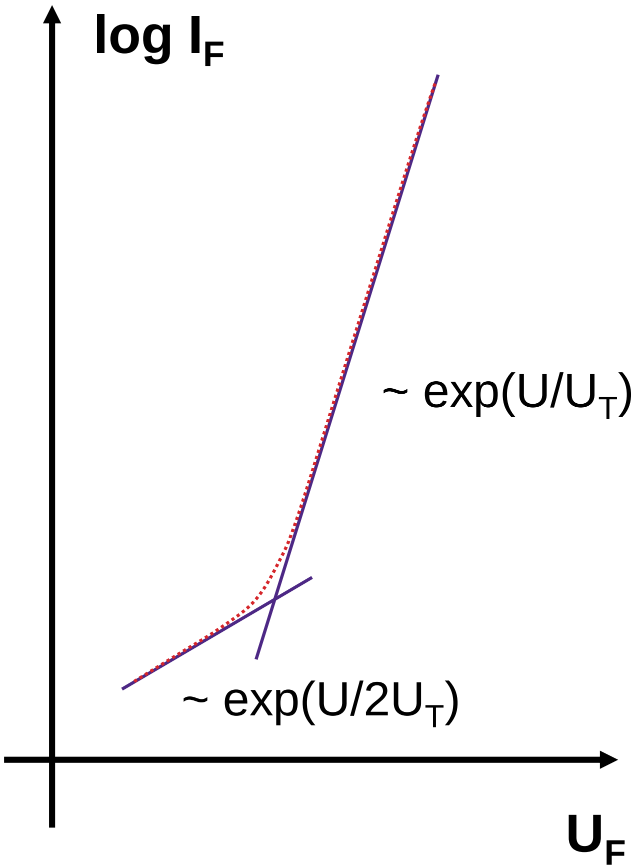
Phenomenon appearing in the forward region

$$I_{Rec} \approx const \cdot n_i \cdot \exp(U / 2U_T)$$

Can be well described by the Shockley-Read-Hall model for semiconductors with indirect band

$$I = I_0 \left(\exp(U / mU_T) - 1\right) = -I_0$$

m: non-ideality factor, between 1..2



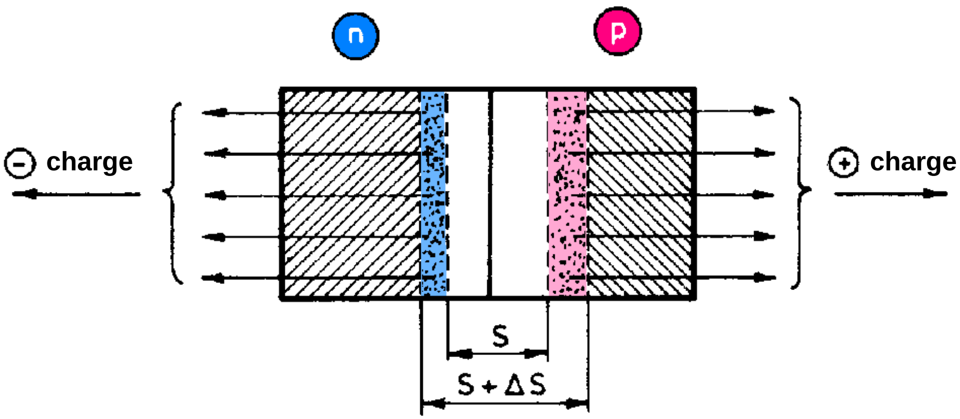
Capacitances of a diode

- Space charge capacitance
- Diffusion capacitance

Capacitances of the diode

Space charge capacitance

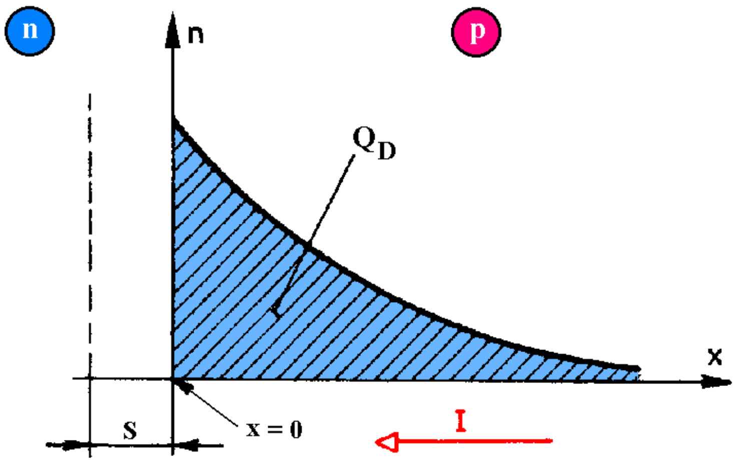
dominates in the reverse region



Interpretation as a differential at a given forward voltage/current

Diffusion capacitance

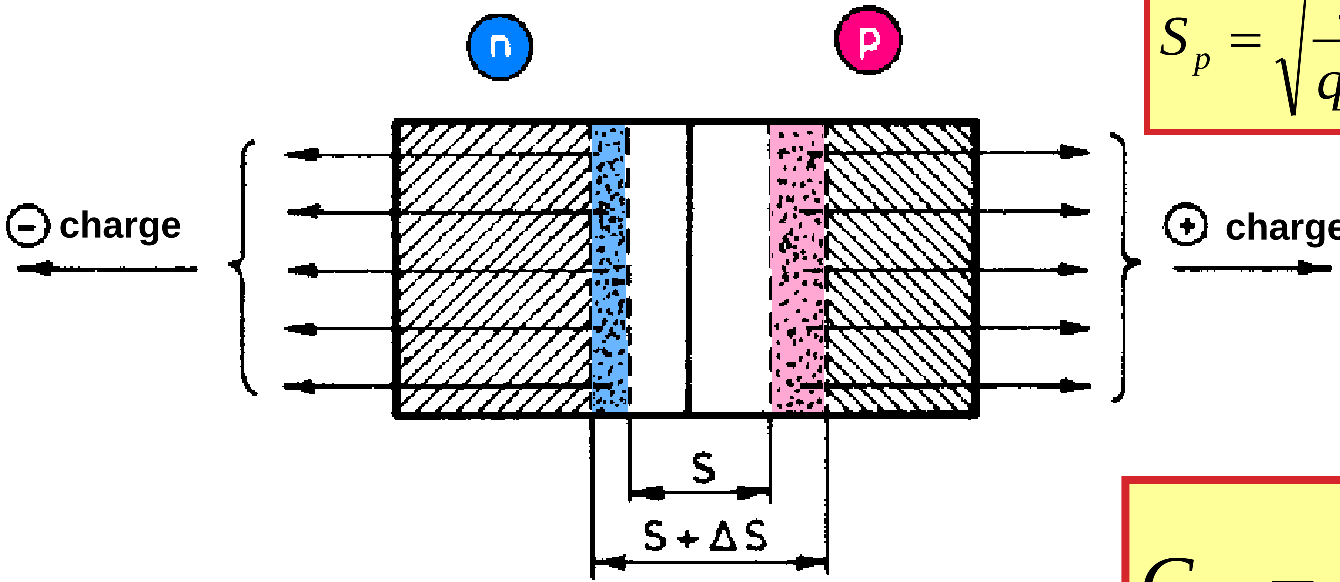
in forward region only



$$C = \frac{dQ}{dU}$$

Capacitances of the diode

The space charge capacitance



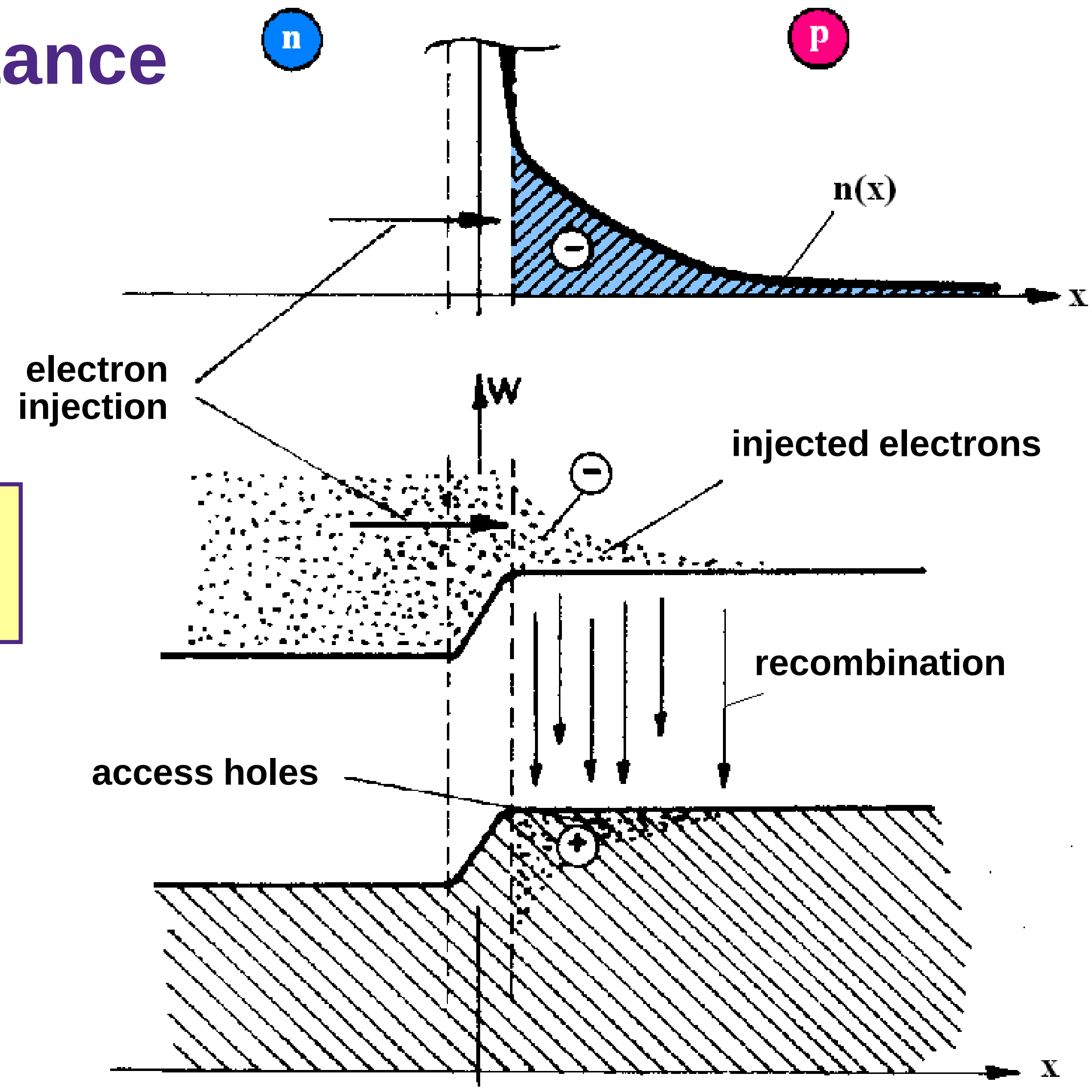
$$S_p = \sqrt{\frac{2\varepsilon}{qN_a}}\sqrt{U_D - U}$$

$$C_{Sp} = \frac{const}{\sqrt{U_D - U}}$$

$$C_{Sp} = \varepsilon\frac{A}{S} = \varepsilon A\sqrt{\frac{qN_a}{2\varepsilon}}\frac{1}{\sqrt{U_D - U}} = A\sqrt{\frac{q\varepsilon N_a}{2}}\frac{1}{\sqrt{U_D - U}}$$

Capacitances of the diode

The diffusion capacitance

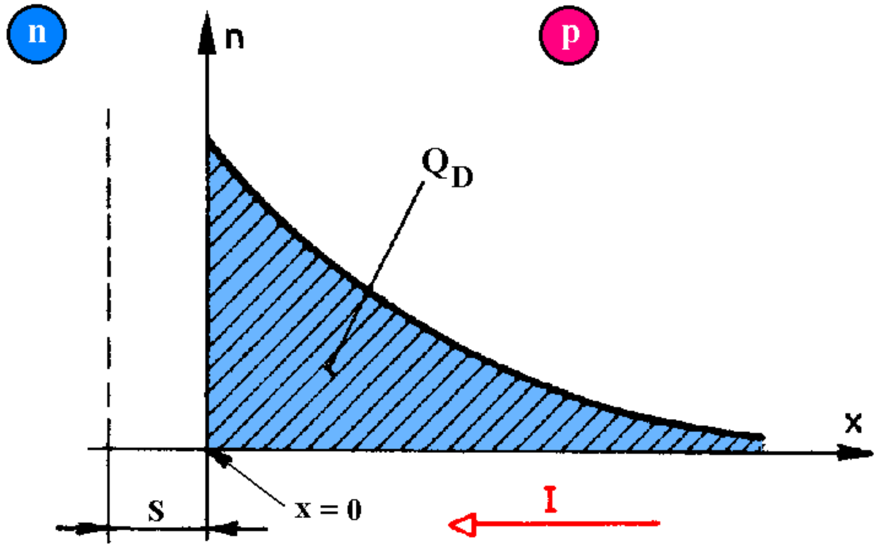


Where are the opposite charges?

Capacitances of the diode

The diffusion capacitance

$$\boxed{Q_D = I\tau_{n(p)}}$$



$$C_D = \frac{dQ_D}{dU} = \frac{dQ_D}{dI}\frac{dI}{dU}$$

$$C_D = \tau_{n(p)}\frac{1}{r_d} = \tau_{n(p)}\frac{I}{U_T} = const \cdot I$$

$$\boxed{C_D = const \cdot I}$$

Harmful! Slows down the operation.

Reduction: decrease τ, narrow base diode

Capacitances of the diode

Problem

Let us calculate the space charge capacitance of a Si diode if the width of the depletion layer is 0.33 μm and the cross-sectional area is 0.02 mm²!

$$C_{Sp} = \varepsilon \frac{A}{S} = 11.8 \cdot 8.86 \cdot 10^{-12} \frac{2 \cdot 10^{-8}}{0.33 \cdot 10^{-6}} = 6.34 \cdot 10^{-12} F = 6.34\ pF$$

Let us calculate the diffusion capacitance in the operating point of I=1 mA if τ=100 ns!

$$C_D = \tau \frac{I}{U_T} = 10^{-7} \frac{10^{-3}}{0.026} = 3.85 \cdot 10^{-9} F = 3.85\, nF$$

Capacitances of the diode

Orders of magnitude:

C_{Sp} 1-10 pF

C_D nF-s

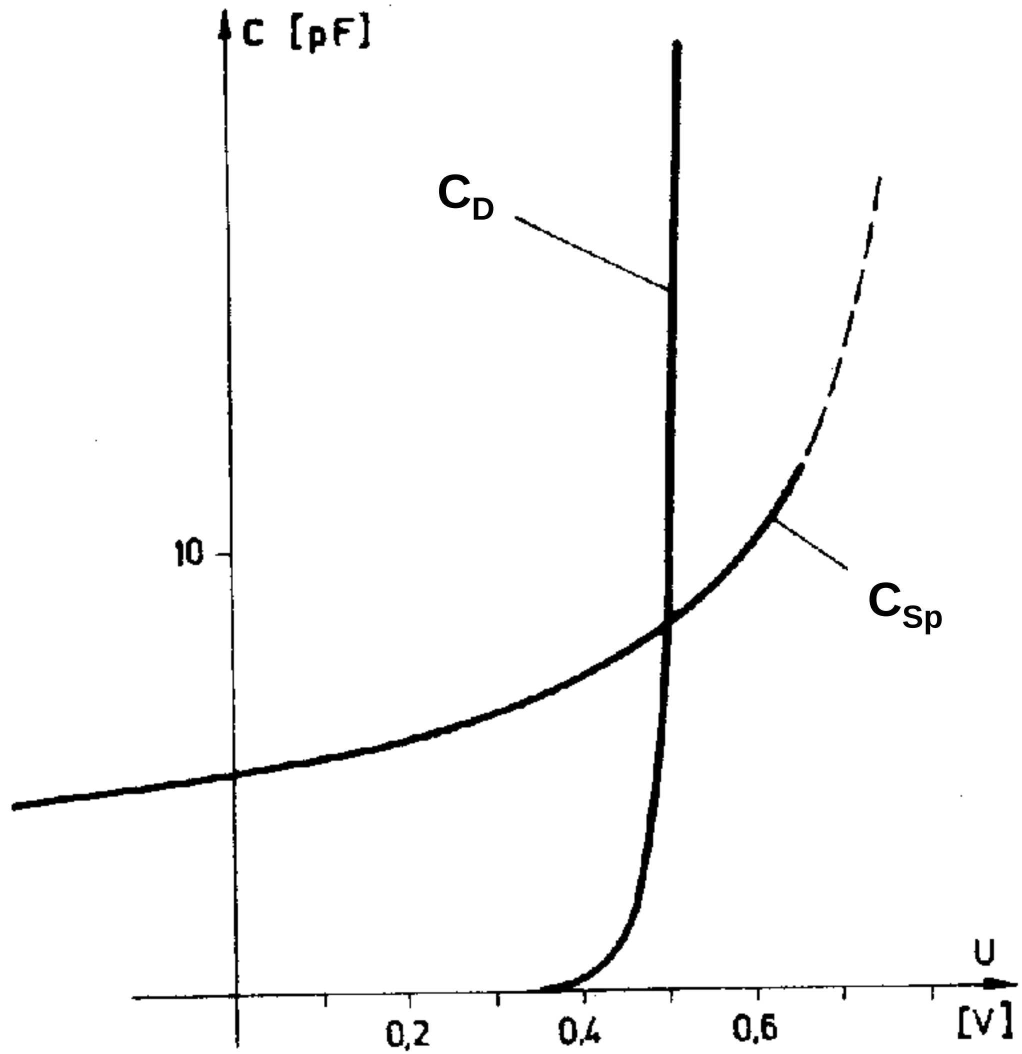
(for a small power diode)

Utilization

C_{Sp} tuning oscillators,

microwave amplification

C_D --



Operating point

- Finding the DC operating point
- Linearization in the operating point, small signal operation
- Differential resistance, capacitance
- Models

The operating point

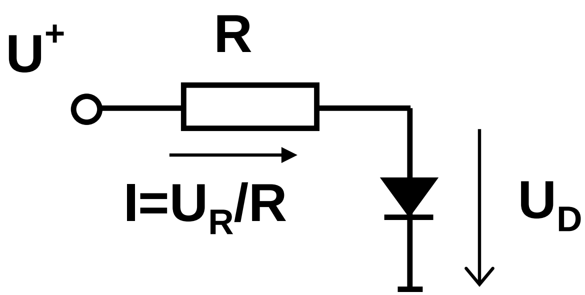
- ***Characteristics:*** defines the current-voltage pairs that may occur during the operation.

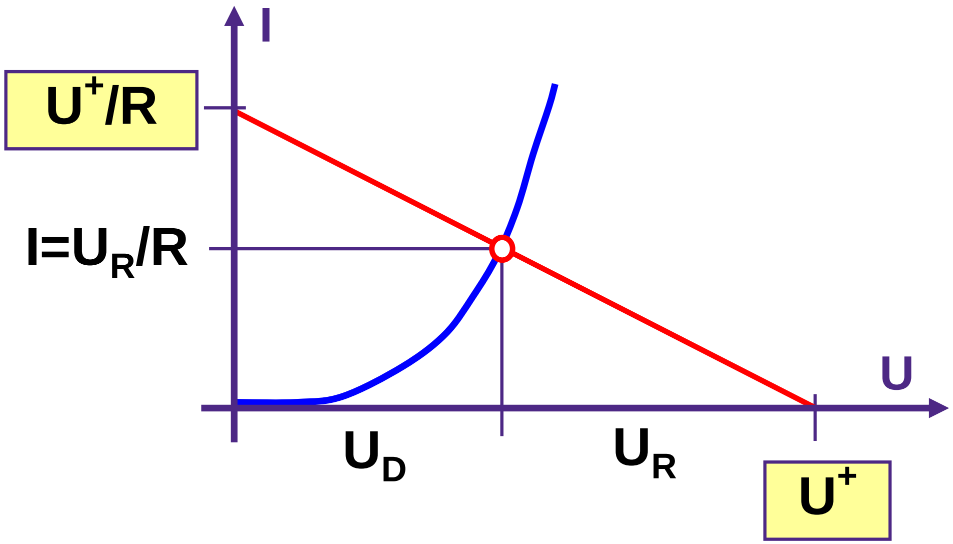
- During the real operation the diode or any nonlinear element works in one point of the characteristics, that is the ***operating point, or quiescent point***.

- This is determined also by the surrounding elements.

Finding the operating point

The problem: a linear element and a non-linear element connected in series:



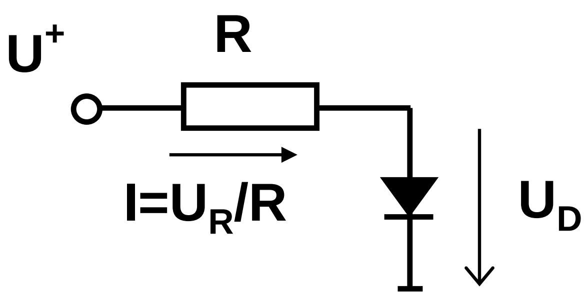


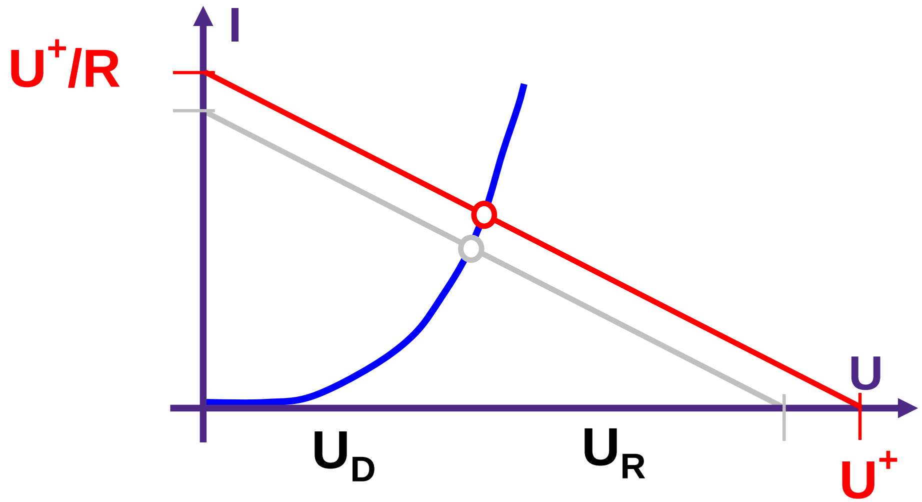
$$\left.\begin{aligned} I &= I(U_D) \\ I &= (U^+ - U_D)/R \end{aligned}\right\}$$

Graphical solution

Finding the operating point

How does the operating point change if the U^+ supply voltage is increased?

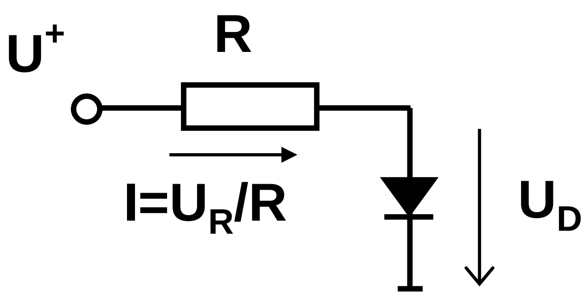


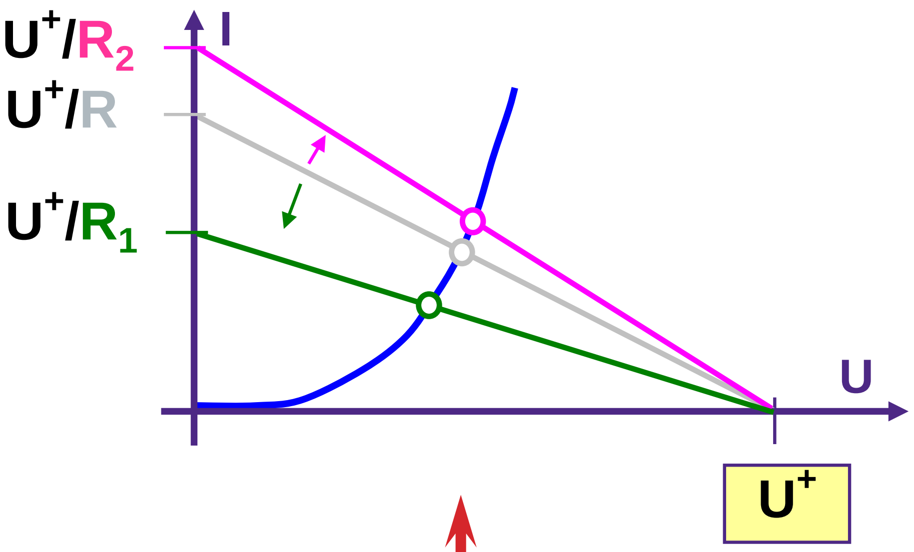


The operating line is shifted in parallel

Finding the operating point

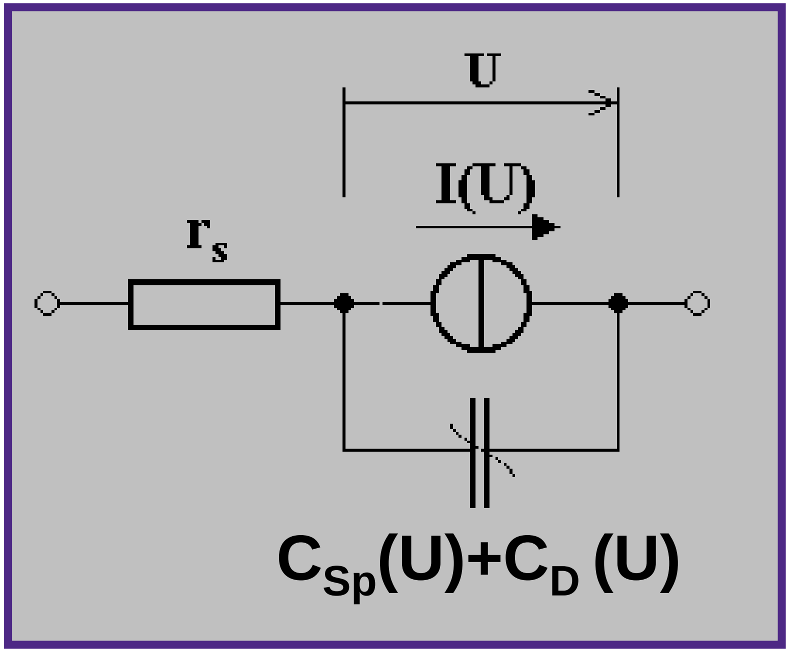
How does the operating line change if we change R?





It turns around point U^+ - its slope will change

Large signal model of the diode



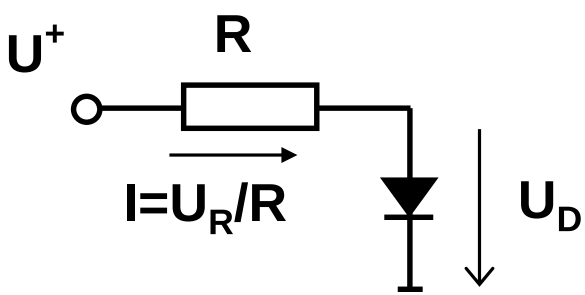
The computer simulation model also looks like this.

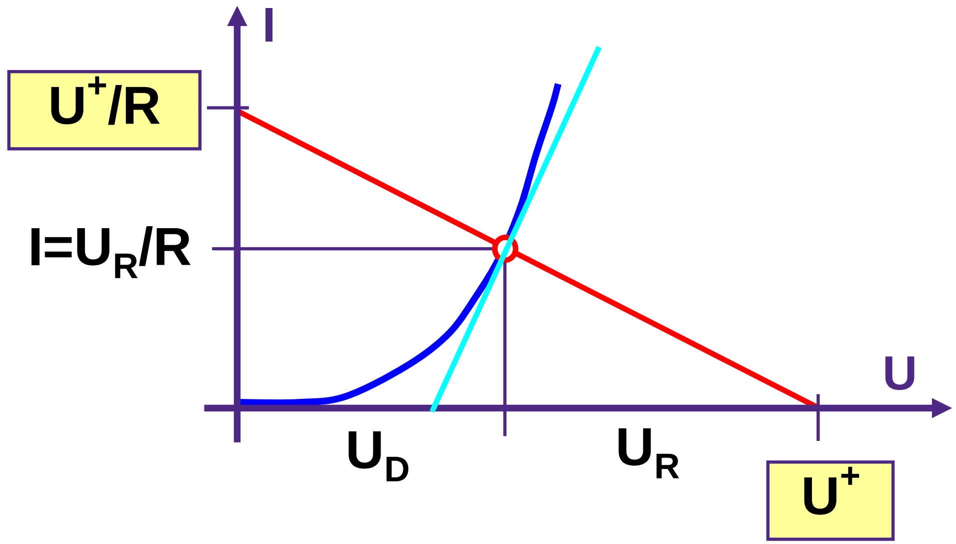
Also needed:

model equations (e.g. $I=I_0(\exp(U/U_T)-1)$

model parameters (e.g.. I_0, r_s, etc.)

Linearization in the operating point

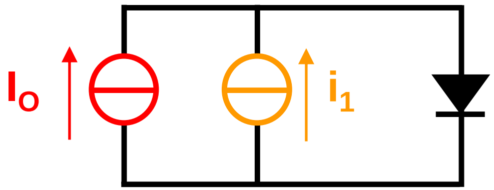


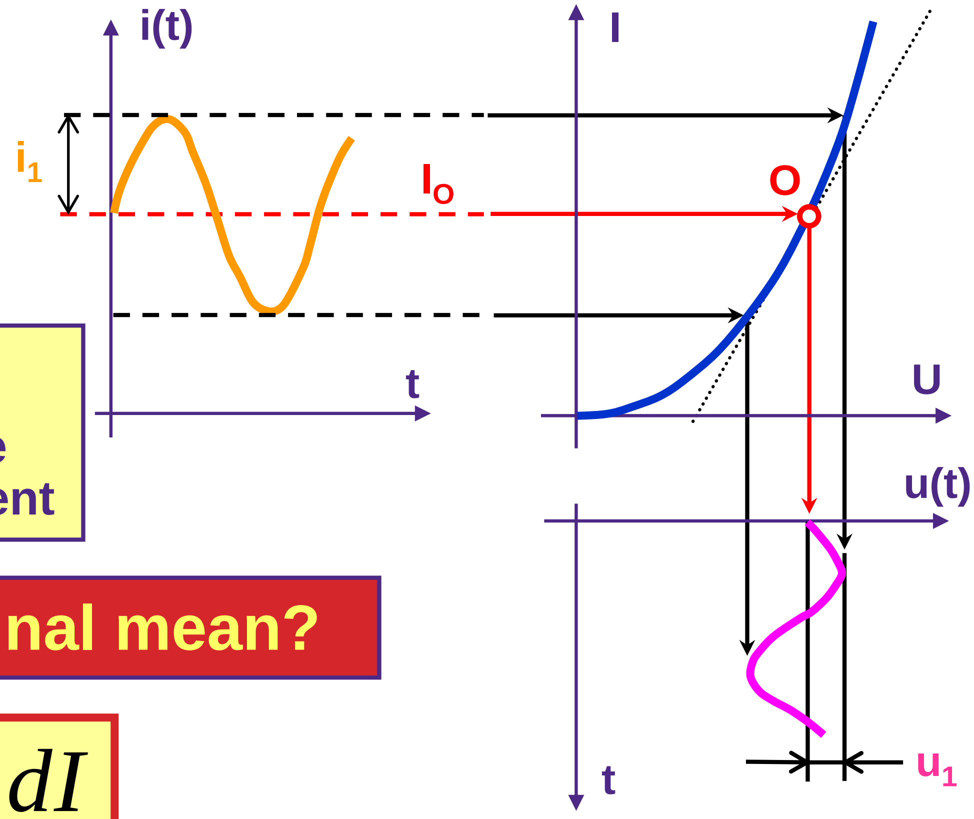


For small changes we can ***linearize*** the characteristics

Small signal operation of diodes

The operating point





Small signal:

***linearized analysis*, for the alternating current component**

What does small signal mean?

$$r_{diff} = u_1 / i_1 = dU / dI$$

r_{diff} **operating point dependent**

Differential resistance of the diode

$$\boxed{U = U_T \ln(I / I_0 + 1)}$$

$$r_d = dU / dI = U_T \frac{1}{I / I_0 + 1} \frac{1}{I_0} = \frac{U_T}{I + I_0}$$

Forward region, $I \gg I_0$:

$$\boxed{r_d = \frac{U_T}{I}}$$

If we consider the series resistance as well:

$$\boxed{r_d = \frac{U_T}{I} + r_s}$$

Differential resistance of the diode

Problem

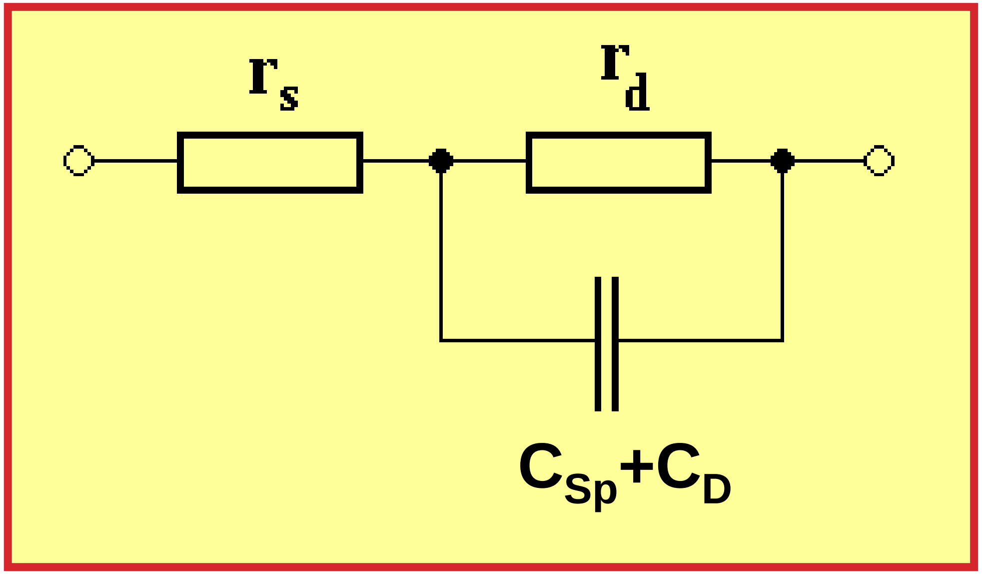
The series resistance of a diode is 2 Ω. Let us calculate its differential resistance in the I=1 mA, 10 mA, 100 mA operating points!

$$r_d\Big|_{1mA} = \frac{26}{1} + 2 = 28\ \Omega$$

$$r_d\Big|_{10mA} = \frac{26}{10} + 2 = 4.6\ \Omega$$

$$r_d\Big|_{100mA} = \frac{26}{100} + 2 = 2.26\ \Omega$$

Small signal model of the diode



Element values are operating point dependent!

Recall: $r_d = \frac{U_T}{I}$ $C_{Sp} = \frac{const}{\sqrt{U_D - U}}$ $C_D = const \cdot I$

Temperature dependence

Temperature dependence

- The characteristics shows *strong temperature dependence*
- Reason: temperature dependence of the minority carriers
  - ***Forward voltages:*** V_F at I_F ***decreases with about 2mV for 1℃ increase***
    - *linear temperature dependence in a large range → appropriate for temperature measurements*
  - ***Reverse voltages:*** I_R at U_R ***decreases with ≈ 7-10% for 1℃***

    (that means doubling at each 10 °C)

Temperature dependence

Reverese region:

For a Si diode: $I_R \sim n_i \rightarrow \sqrt{1{,}15} \cong 1{,}075 \rightarrow 7{,}5\ \%/^oC$

Forward region:

$$U = U_T \ln\frac{I}{I_0} = \frac{kT}{q}\ln\frac{I}{I_0(T)}$$

$$\frac{d\,n_i^2}{n_i^2} = \left(3 + \frac{W_g}{kT}\right)\frac{d\,T}{T} = \frac{dI_0}{I_0}$$

$$\frac{dU}{dT} = \frac{U}{T} + U_T\,\frac{I_0}{I}\left(\frac{-I}{I_0^2}\right)\frac{dI_0}{dT} = \frac{U}{T} - U_T\,\frac{1}{I_0}\,\frac{dI_0}{dT}$$

$$\boxed{\frac{dU}{dT} = \frac{U}{T} - U_T\left(3 + \frac{W_g}{kT}\right)\frac{1}{T} = \frac{U - 3U_T - W_g/q}{T}}$$

Temperature dependence

Forward region:

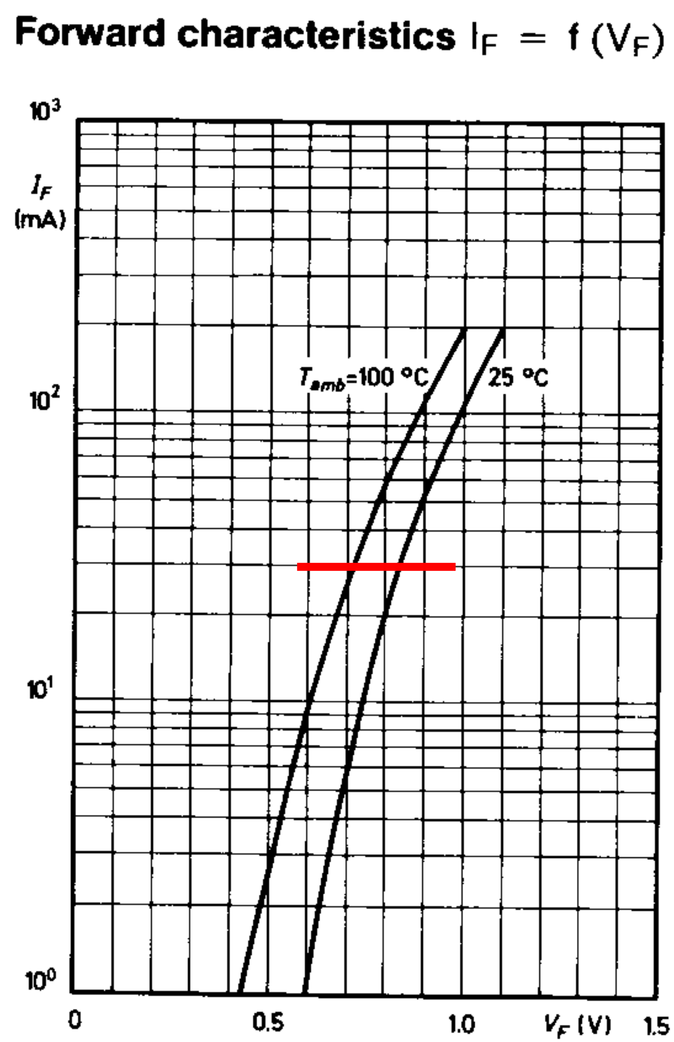
$$\frac{dU}{dT} = \frac{U - 3U_T - W_g / q}{T}$$

Problem

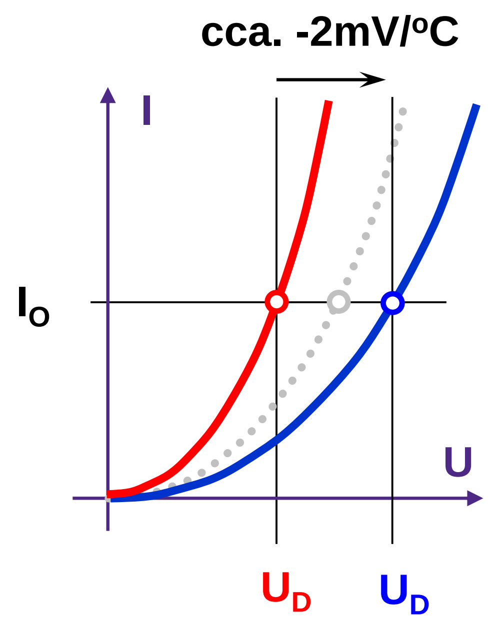
If U=700 mV, what is dU/dT for a Si diode?

$$\frac{dU}{dT} = \frac{700 - 3 \cdot 26 - 1120}{300} = -1.66\ mV /^o\ C$$

Compare with the characteristics!



Temperature dependence



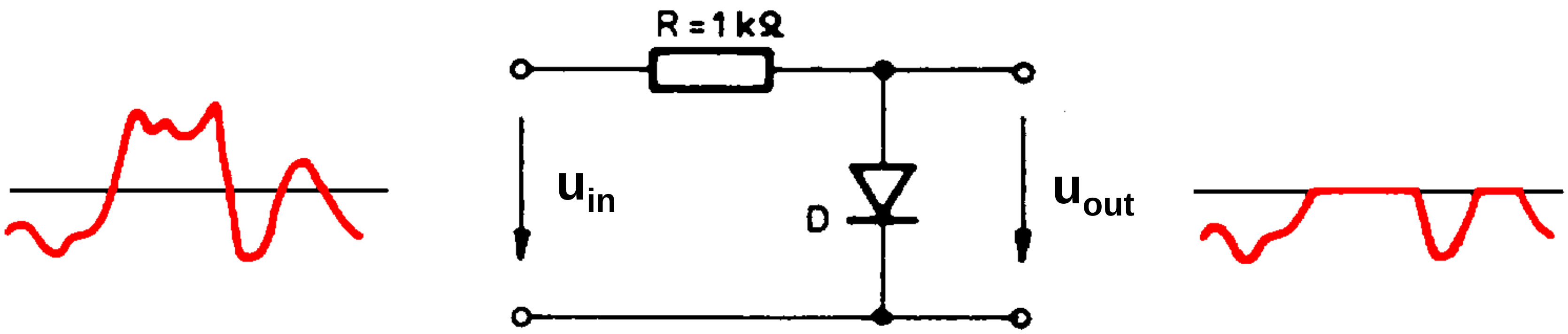
$$\frac{dU}{dT} = \frac{U - 3U_T - W_g / q}{T}$$

In case of a forced current the forward voltage of a pn junction is an excellent temperature sensor...

The sensitivity slightly depeneds on the I_O current

The diode in switching mode

Diodes as rectifiers

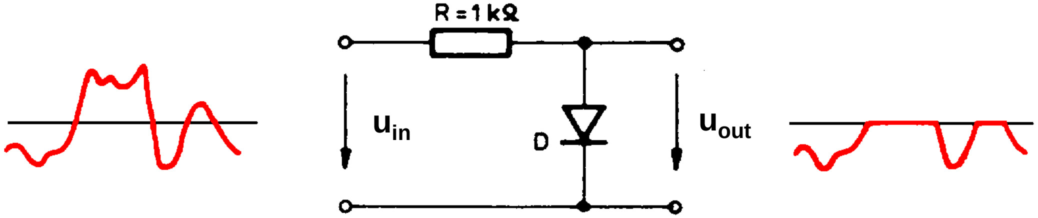


$$U_{out}(t) = \begin{cases} 0, & \text{if } U_{in}(t) \geq 0 \\ U_{in}(t), & \text{if } U_{in}(t) < 0 \end{cases}$$

The diode was considered to be ideal!

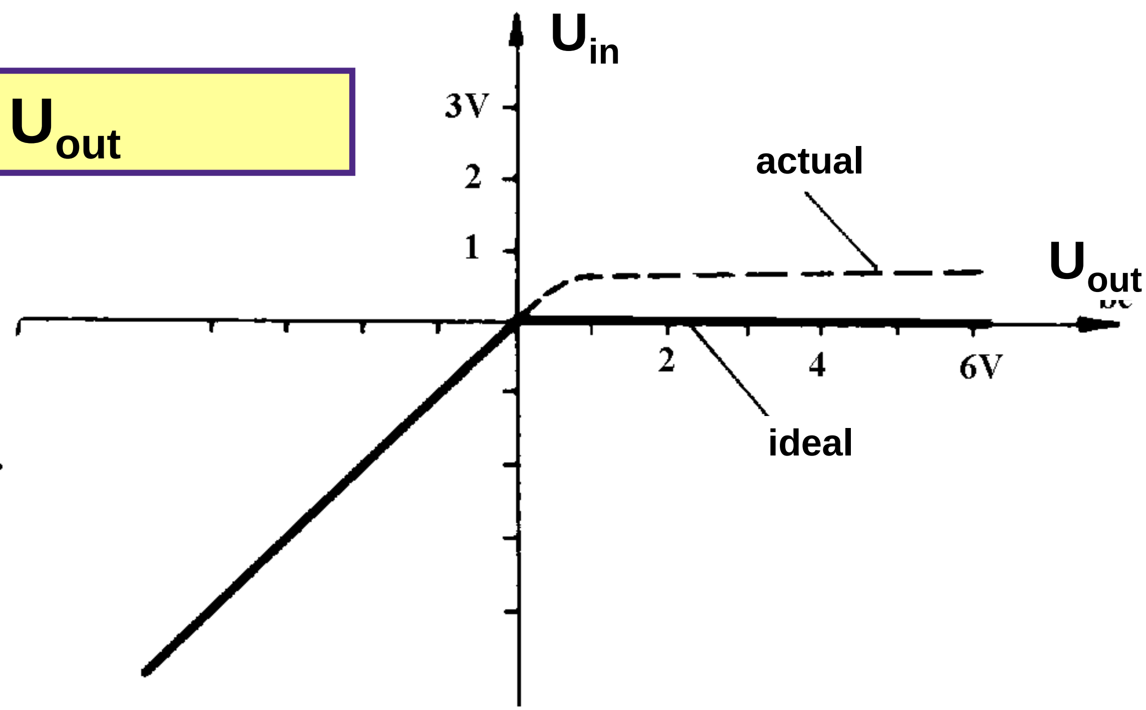
What if this is not the case?

Diodes as rectifiers

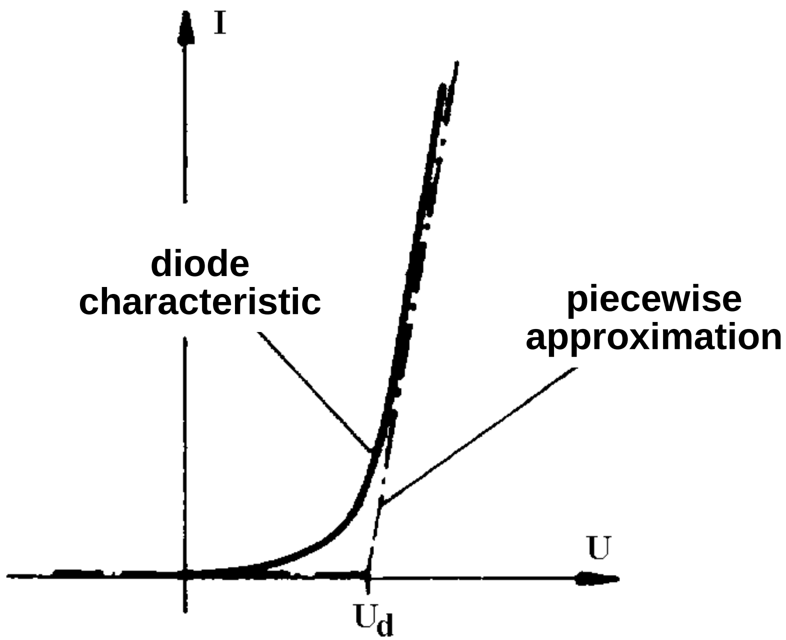


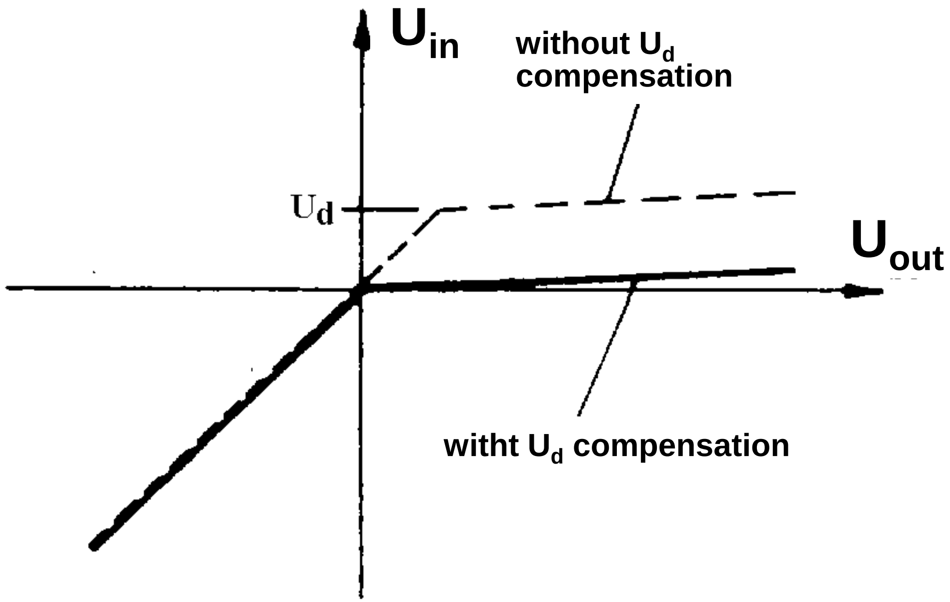
Relation of U_{in} and U_{out}

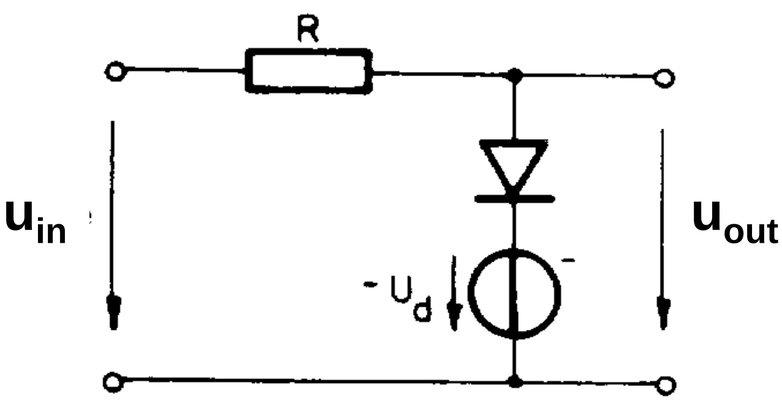
Transfer characteristic



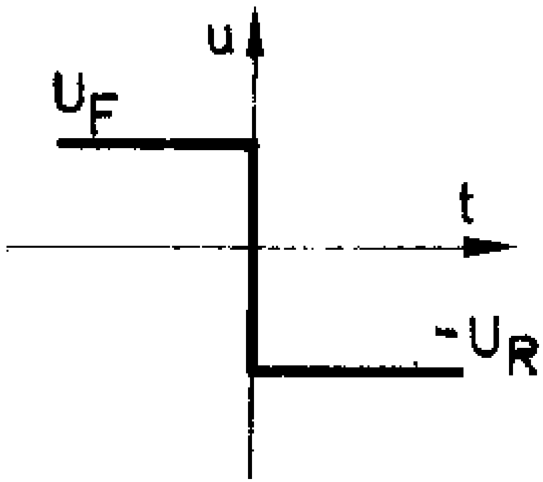
Diodes as rectifiers

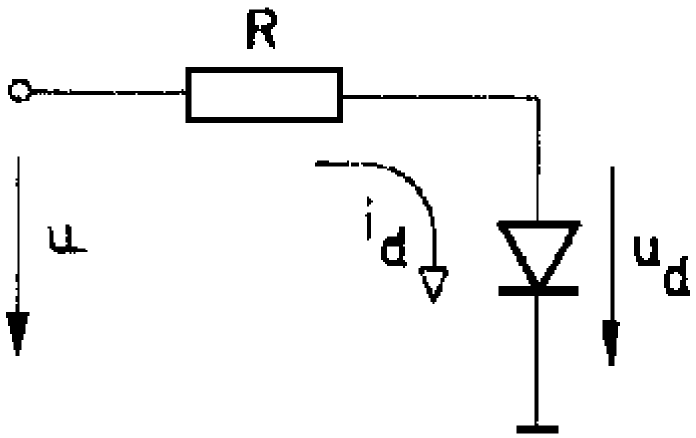






Transient phenomena



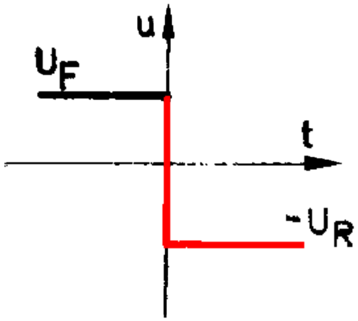


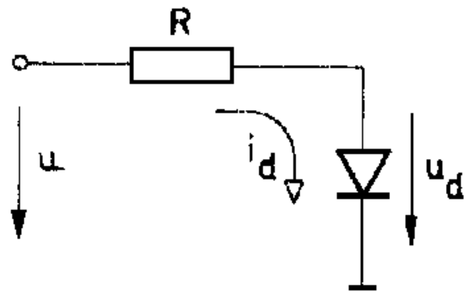
***<u>Abrupt switching from forward to reverse voltage</u>*: **

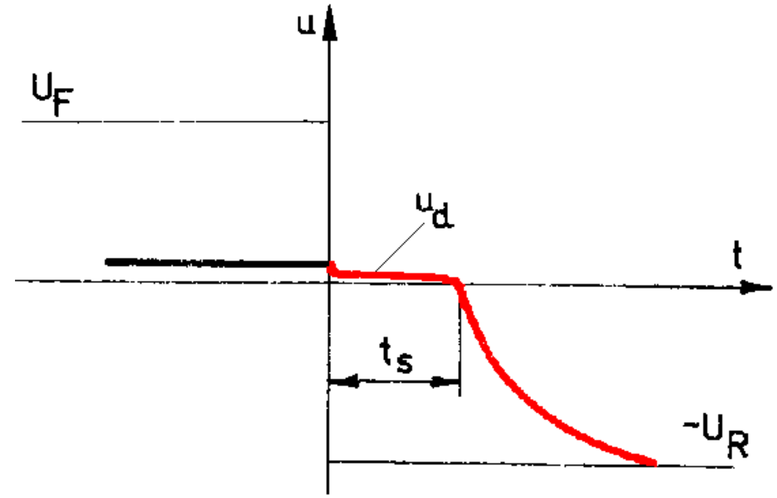
due to its capacitances, the diode is open for some time.

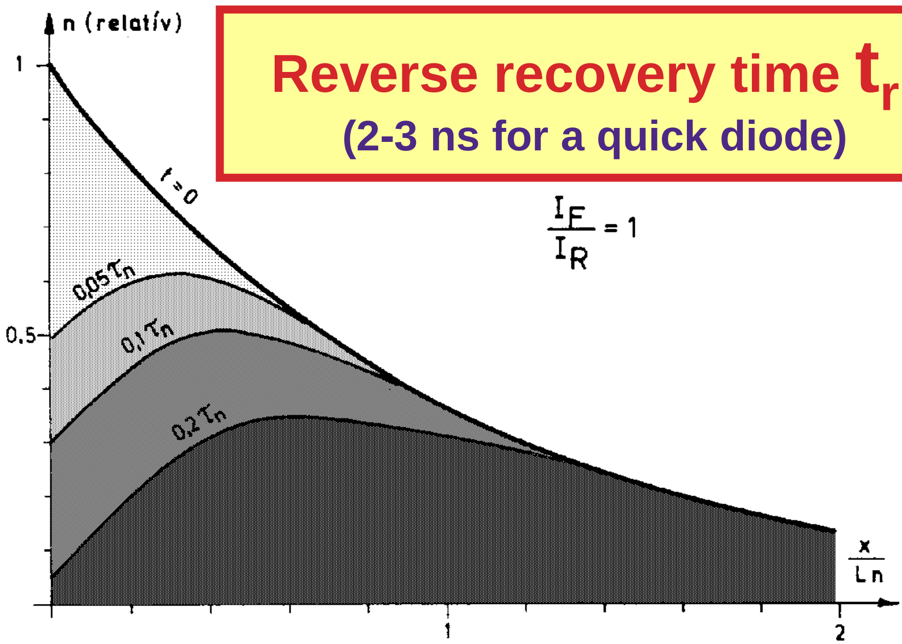
This is called reverse recovery.

Reverse recovery







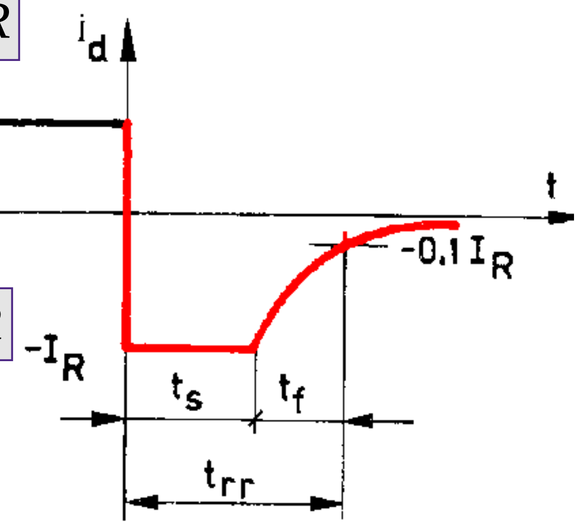


Reverse recovery time t_{rr}

(2-3 ns for a quick diode)

$$I_F = U_F / R$$

$$I_R = U_R / R$$

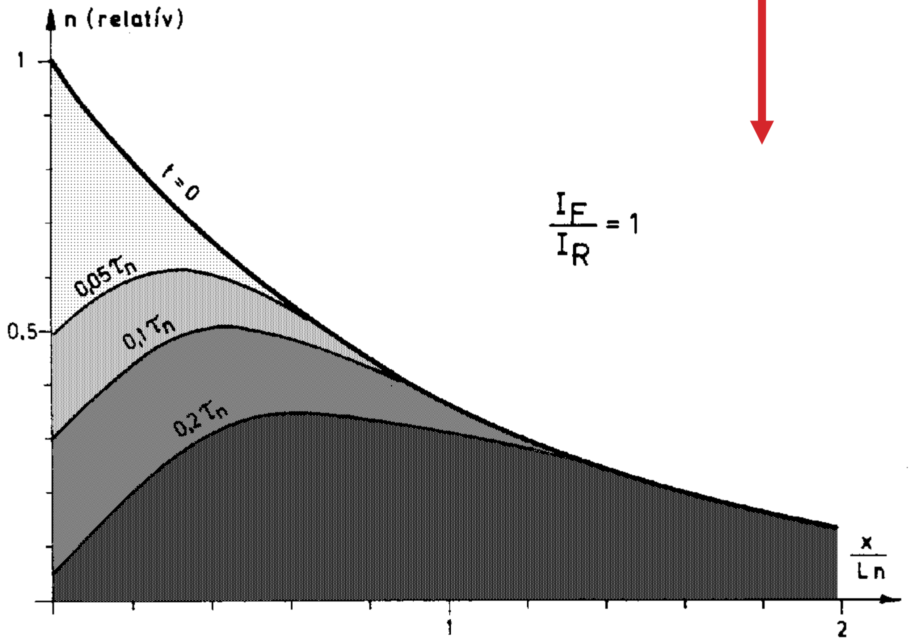


Transient behavior of the diode

The diffusion equation:

$$\frac{\partial n}{\partial t} = D_n \frac{\partial^2 n}{\partial x^2} - \frac{n - n_p}{\tau_n}$$

We calculate n(x,t) from this



Simplification:

instead of n(x,t)

we calculate with Q(t)

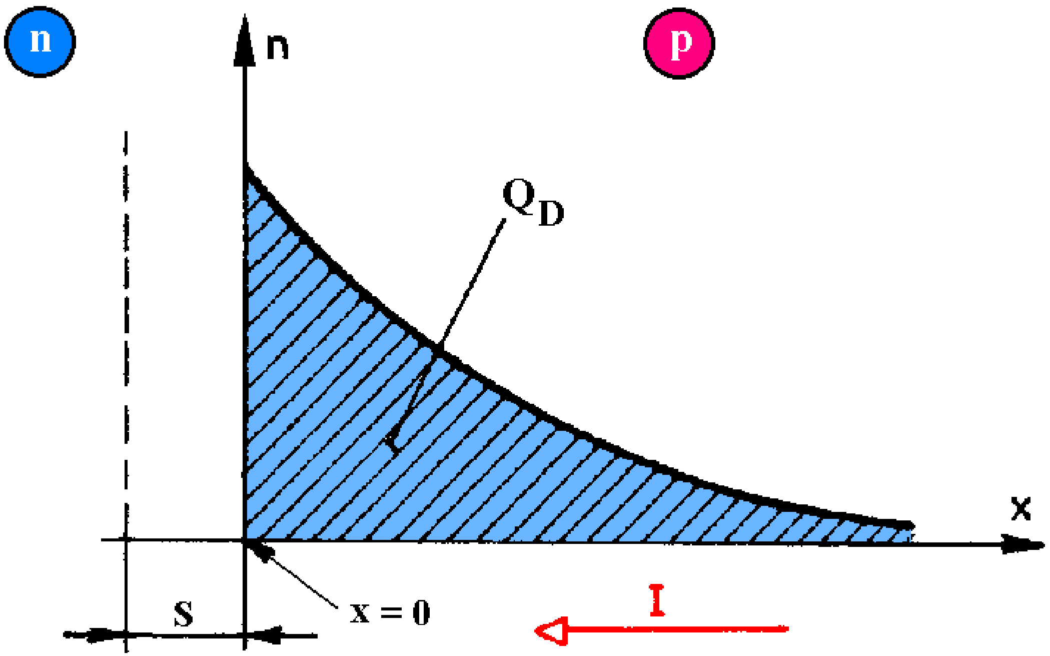
net charge

Transient behavior of the diode

The charge equation

$$\boxed{Q_D = f(t)}$$

$$\boxed{I = \frac{Q_D}{\tau_{n(p)}} + \frac{dQ_D}{dT}}$$



The current is spent on

maintaining recombination

depleting/supplying diffusion charge

Break-down phenomena

- Avalanche
- Zener

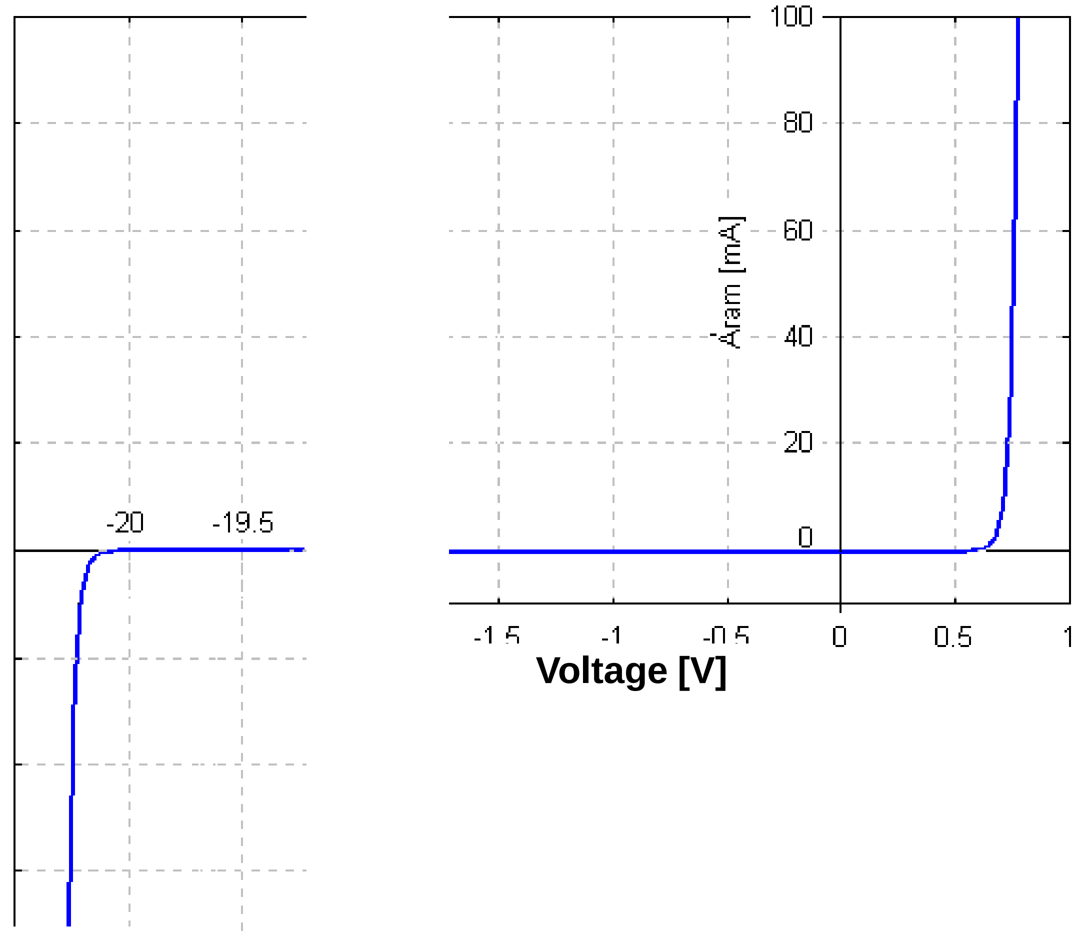
Break-down phenomena

Reason: either of

Avalanche mechanism

Zener tunneling

Punch-though



Avalanche break-down

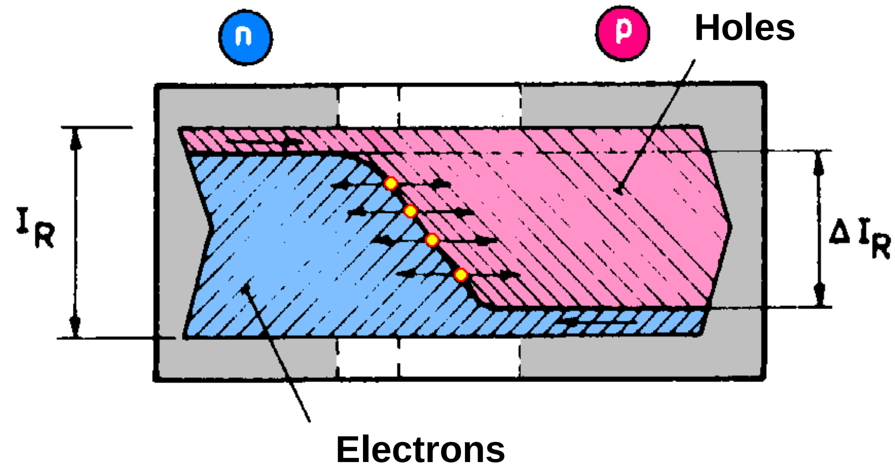
$$I_R = M(U_R)\cdot I_{R0}$$

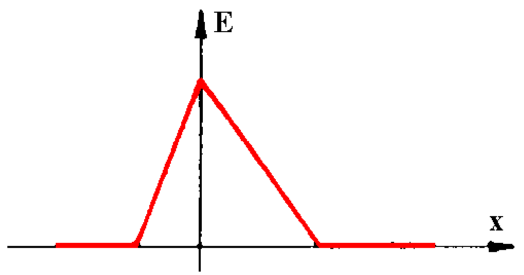
M – multiplication factor

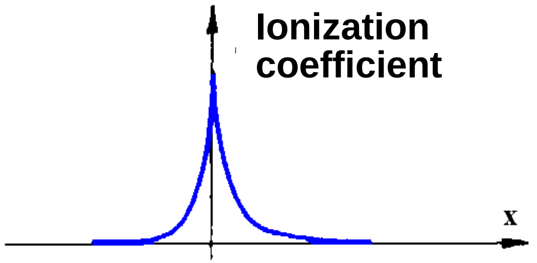
$$M = \frac{1}{1-\left(\frac{-U}{U_L}\right)^m}$$

U_L depends on the less doped side:

$$\boxed{U_L \sim N^{-0.7}}$$





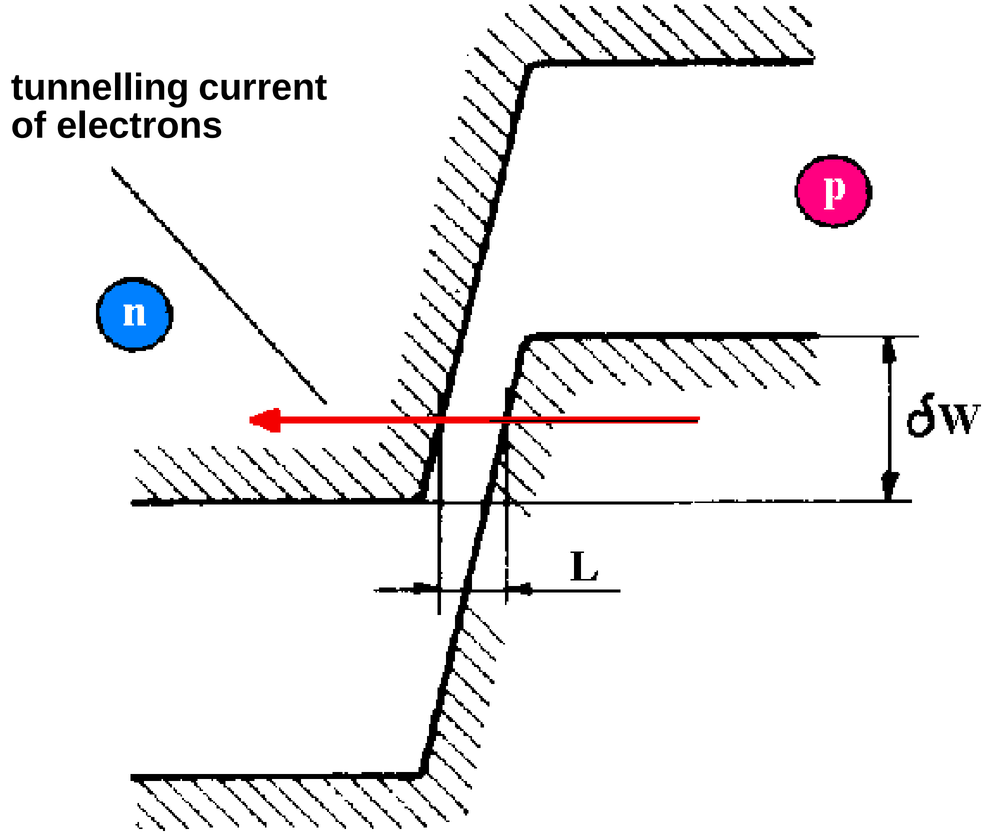


The Zener effect

Physical reason:

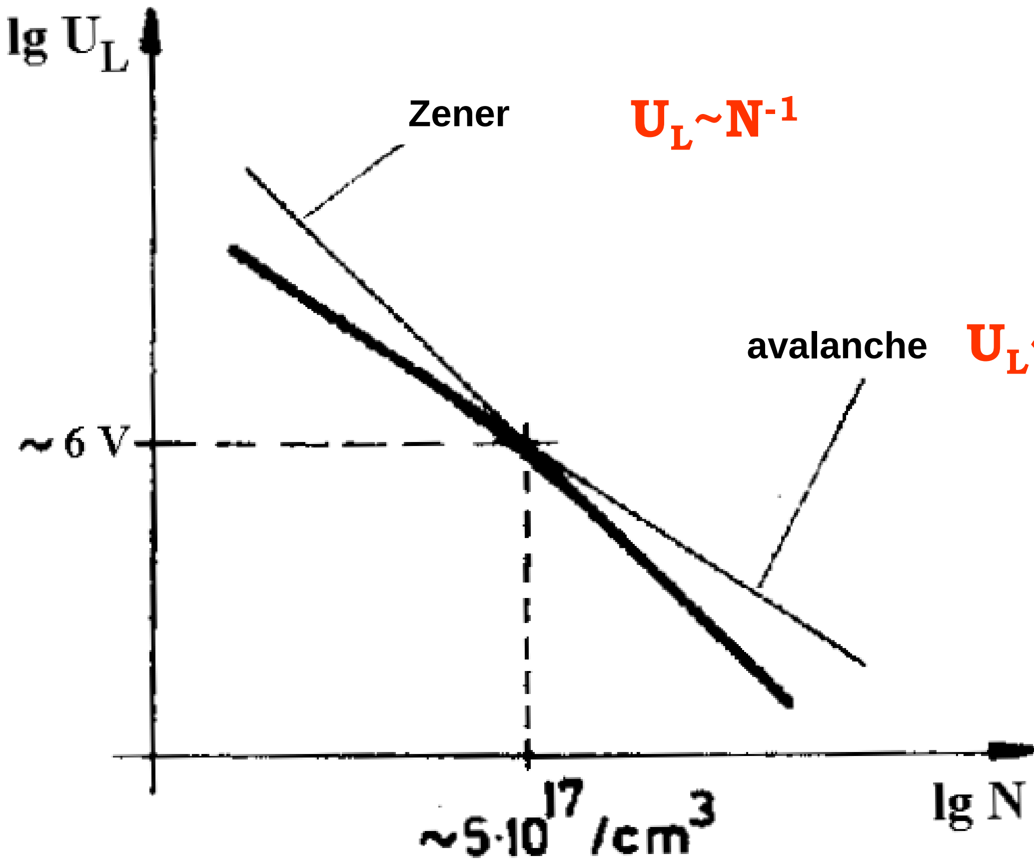
tunneling

$$\boxed{U_L \sim N^{-1}}$$



Break-down phenomena

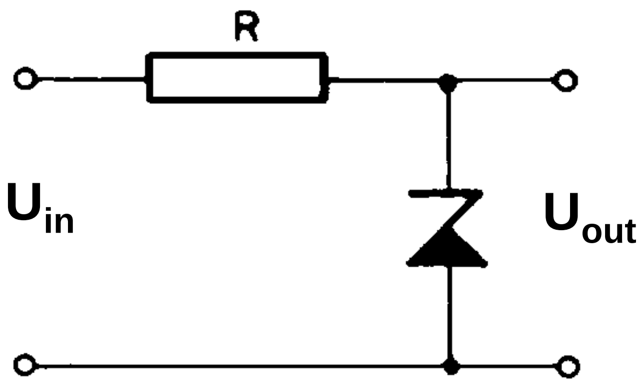
Comparison of the two phenomena

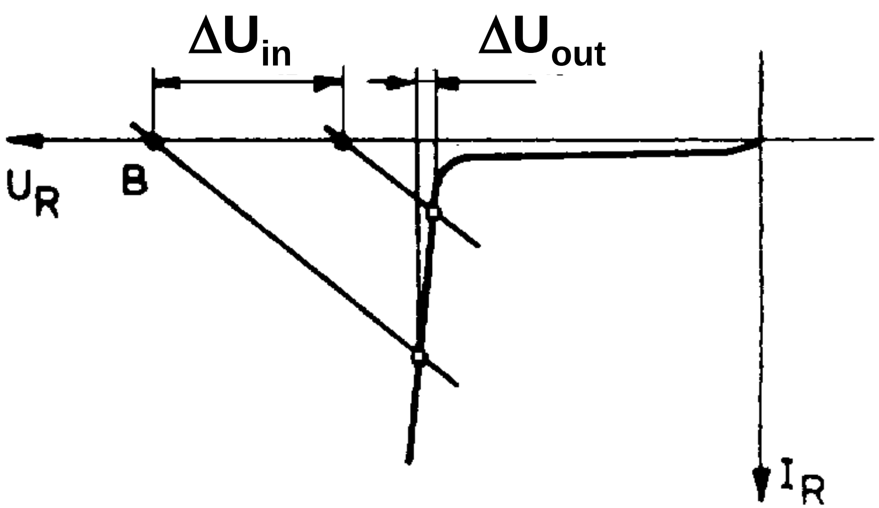


In case of Si: below 6V – Zener, above this – avalanche.

Break-down phenomena

Application: a Zener-diode





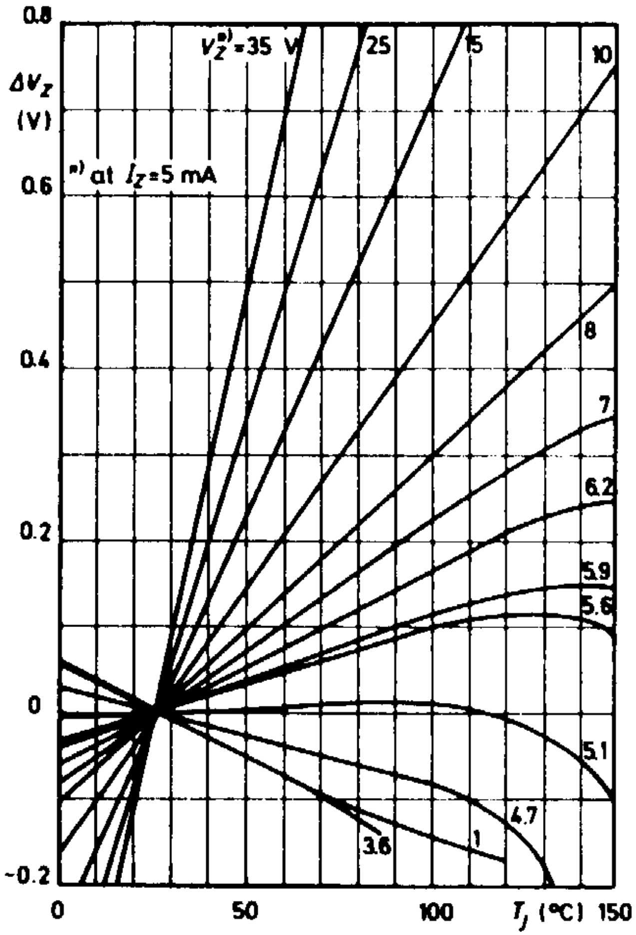
Voltage reference

Voltage stabilizer (at low power consumption)

Break-down phenomena

Temperature dependence of Zener-diodes

Operating voltage variation
versus junction temperature
$\Delta V_Z = f(T_j);\ I_Z = 5\ mA$



The best: diodes around 5V

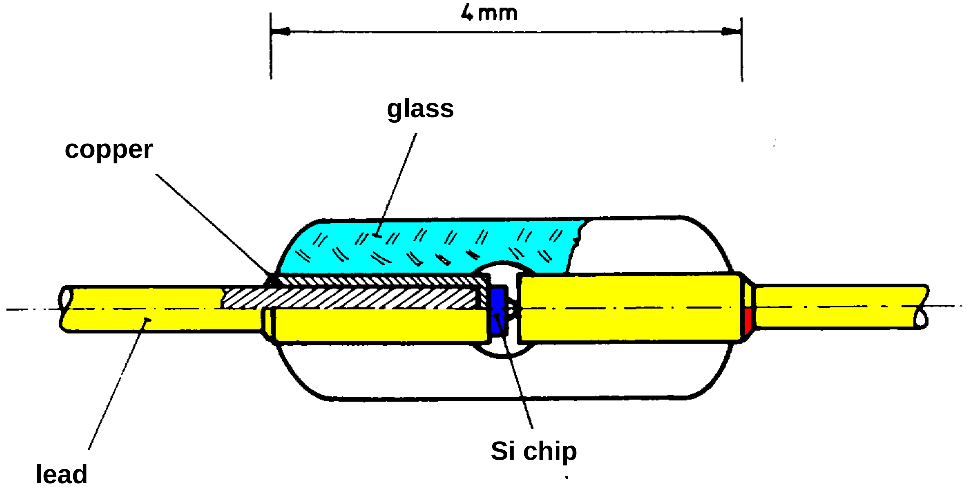
(Si diode)

Practical issues

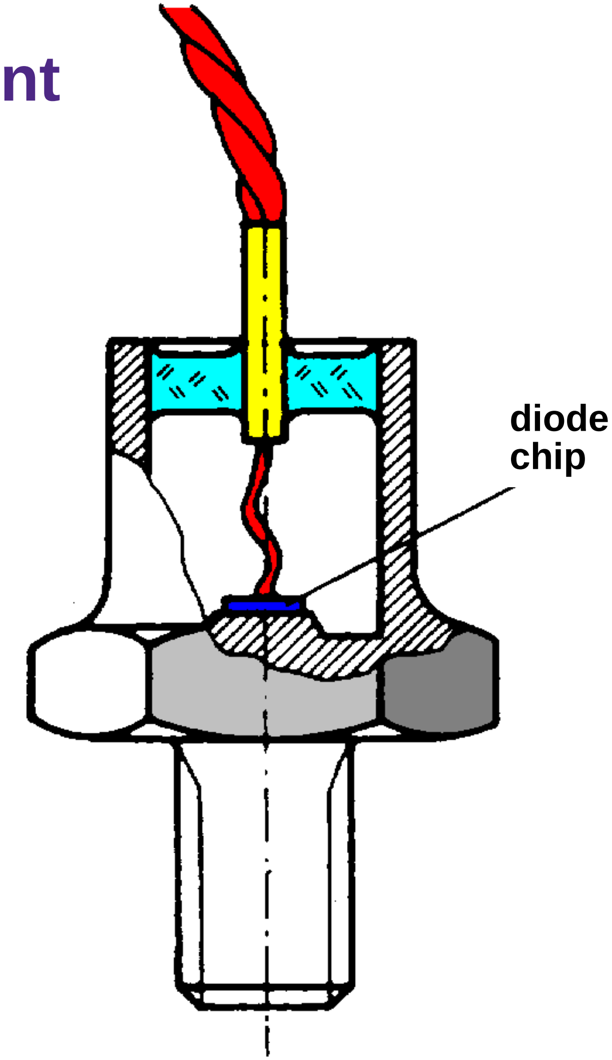
- Packaging
- Data sheets

Actual realization of diodes

Small current



Large current



(IC realizations will be discussed later)

Data sheets

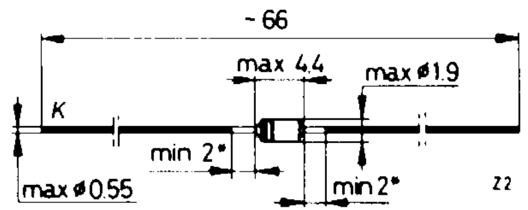
1N 4151 (BAY 95), 1N 4154 (BAY 94)

Silicon Epitaxial Planar Low-Capacitance Diodes

for very fast switching applications.

Dimensions in mm

Band: cathode



* not tinned

Case: DO-35

Mass: approx. 0.15 g

Absolute maximum ratings		**1N 4151**	**1N 4154**	
Reverse voltage	V_R	50	25	V
Peak reverse voltage	V_{RM}	75	35	V
Rectified current[1]	I_o	150		mA
Forward current	I_F	200		mA
Peak forward current	I_{FM}	450		mA
Surge peak forward current[2]	I_{FSM}	2		A
Junction temperature	T_j	200		°C
Storage temperature	T_s	–65 . . . + 200		°C
Total power dissipation	P_{tot}[4]	440		mW
	P_{tot}[5]	500		mW

Data sheets

Forward voltage				
$I_F = 30$ mA	V_F[6]	–	0.88 (≤ 1)	V
$I_F = 50$ mA	V_F[6]	0.88 (≤ 1)	–	V
Reverse current				
$V_R = 25$ V	I_R[6]	–	9 (≤ 100)	nA
$V_R = 50$ V	I_R[6]	14 (≤ 50)	–	nA
$V_R = 25$ V, $T_{amb} = 150\,°C$	I_R	–	≤ 100	µA
$V_R = 50$ V, $T_{amb} = 150\,°C$	I_R	≤ 50	–	µA
Breakdown voltage[6]				
$I_R = 5$ µA	$V_{(BR)}$	≥ 75	≥ 35	V

Dynamic characteristics

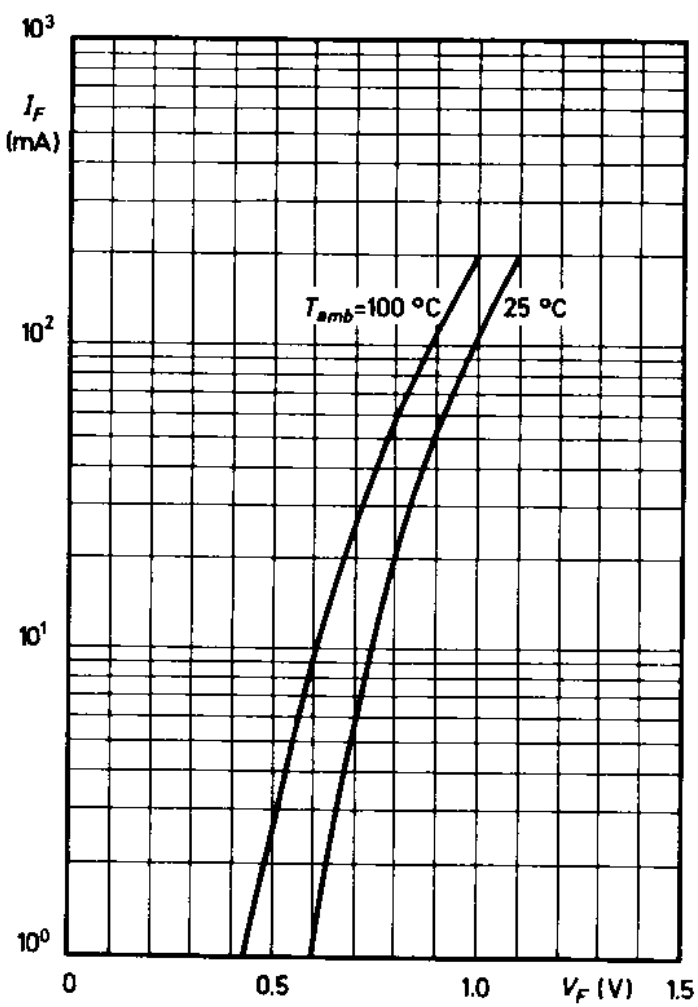
$T_{amb} = 25\,°C$		1N 4151	1N 4154	
Diode capacitance				
$V_R = 0$ V, f = 1 MHz, $V_{HF} = 50$ mV	C_D	1.7 (≤ 2)	≤ 4	pF
Reverse recovery time	t_{rr}[1]	≤ 4	≤ 4	ns
	t_{rr}[2]	≤ 2	≤ 2	ns

[1] measured at switching from $I_F = 10$ mA through $I_R = 10$ mA to $I_R = 1$ mA

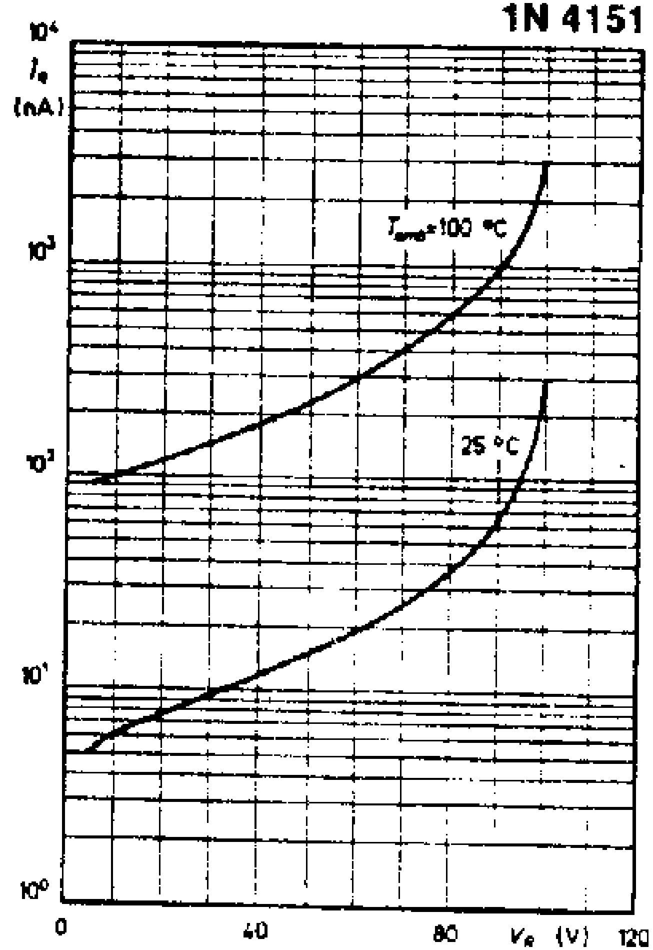
[2] measured at switching from $I_F = 10$ mA through $V_R = 6$ V to $I_R = 1$ mA, R_L

Data sheets

Forward characteristics $I_F = f(V_F)$



Reverse characteristics



Data sheets

0 → 100 °C

6.5 → 1200 nA

(1200/6.5)^0.01=1.054

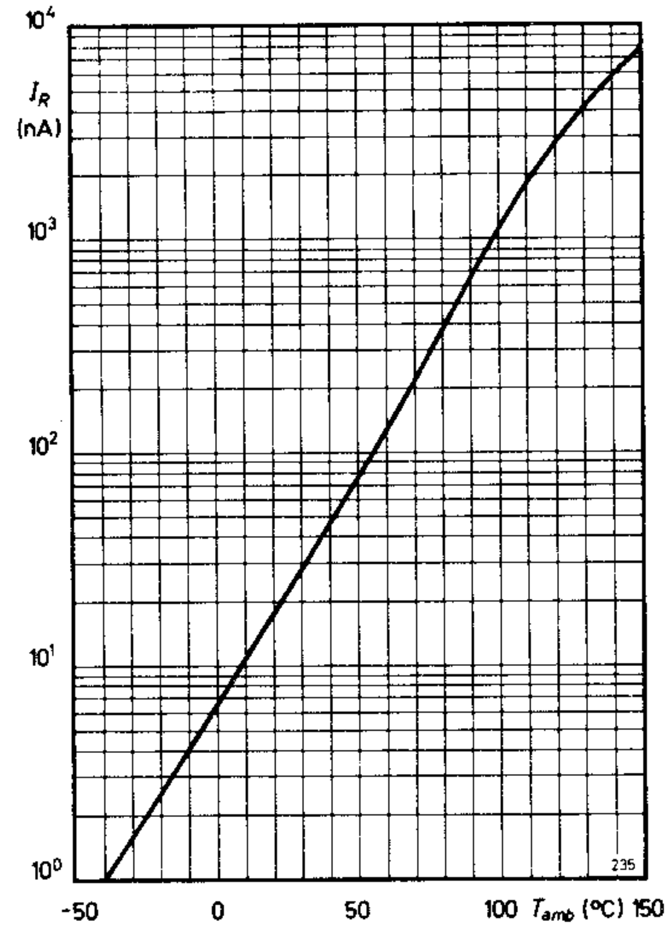
5.4 %/°C

Reverse current versus ambient temperature

$I_R = f(T_{amb})$

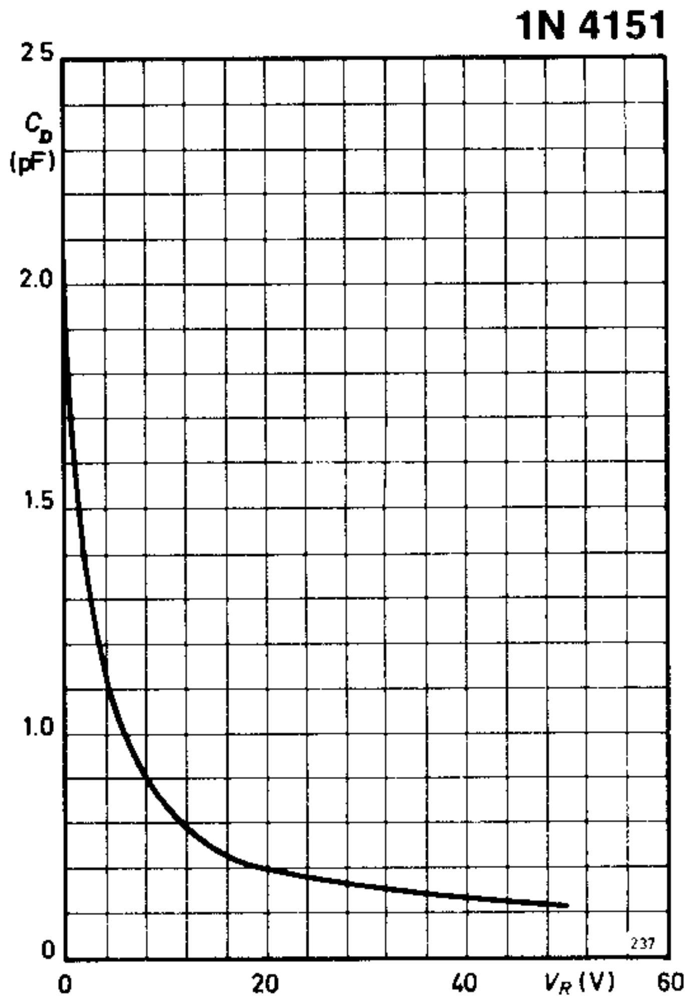
$V_R = 50$ V: **1N 4151**

$V_R = 25$ V: **1N 4154**



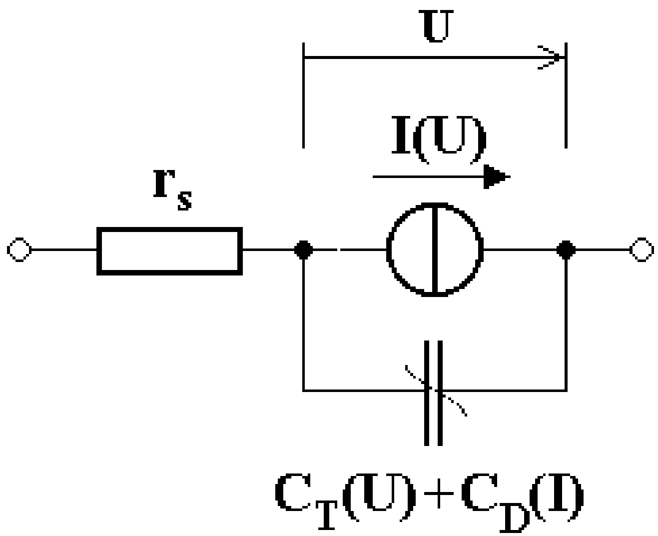
Data sheets

Diode capacitance versus reverse voltage
$C_D = f(V_R)$, $f = 1$ MHz



Simulation model of the diode

Large signal, non-linear model of the diode**:**



Modelling equations are coded in the simulation program!

$$I = I_0\left(\exp(U/mU_T)-1\right)$$

$$C_T = C_{T0}\left(\frac{U_D}{U_D-U}\right)^n$$

$$C_D = I\frac{\tau}{U_T}$$

Modell parameter are from a catalgue file!