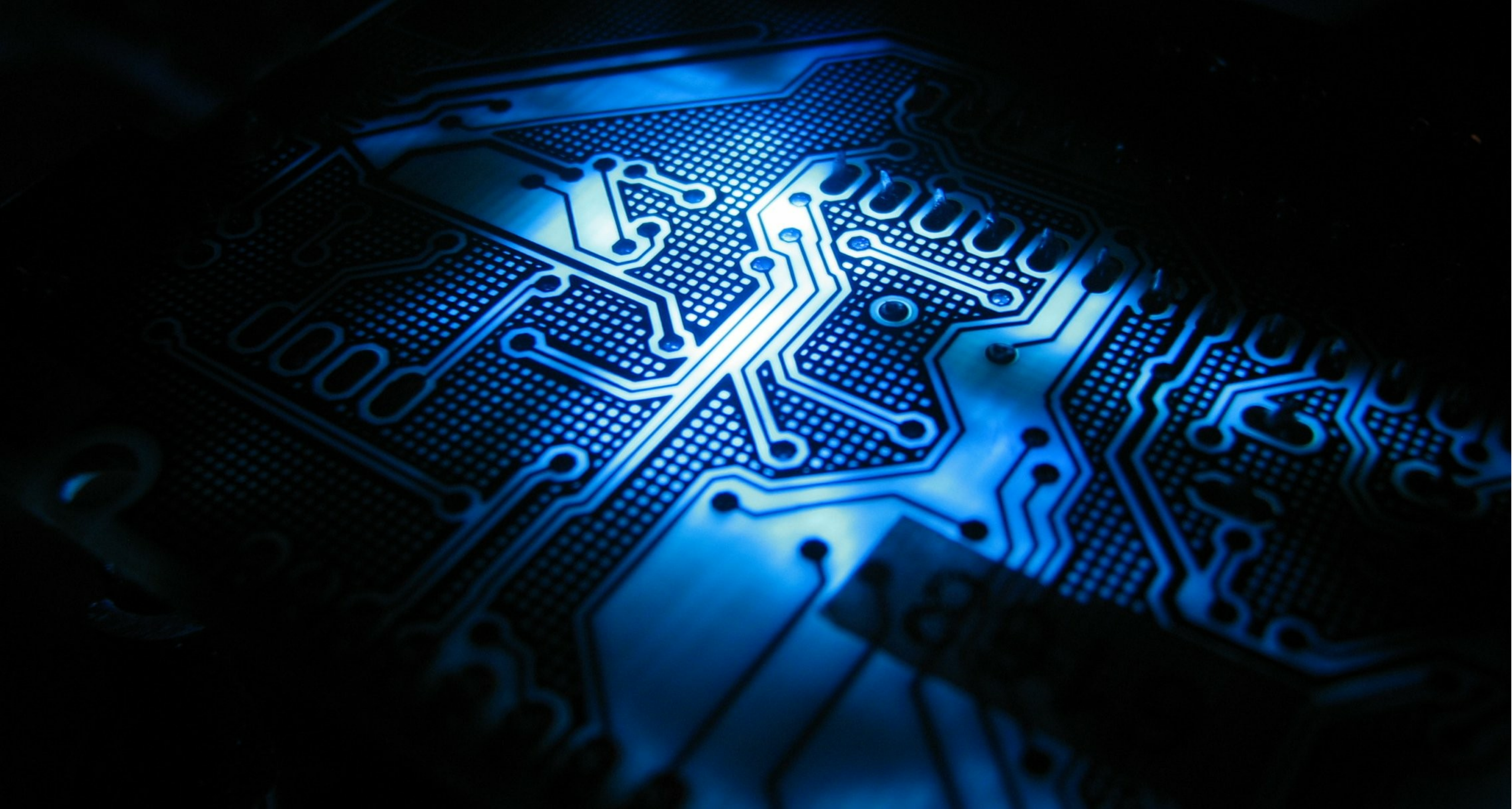
Electronics for Pedestrians
– Semiconductors & ICs –

Ralph J. Steinhagen, CERN



“In theory, 'theory' and 'praxis' are the same, in praxis they aren't”

Introduction

- Discussed passive components
- Now – semiconductor
  - Photodetectors, Diode, BJT, OpAmps, FETs
  - Noise

- Can cover only most basic concepts and high-light some of the interesting effects, common uses and pitfalls

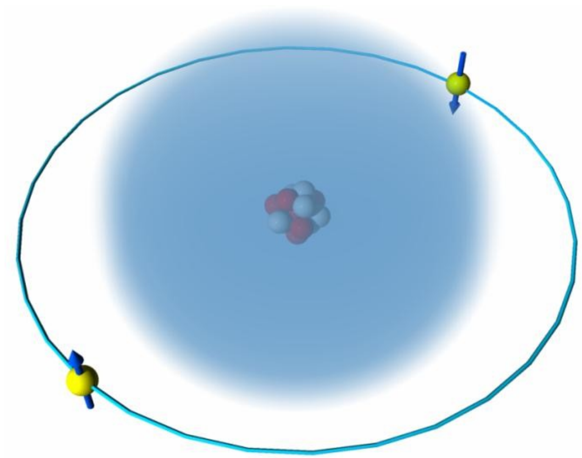
How do Semiconductor work?

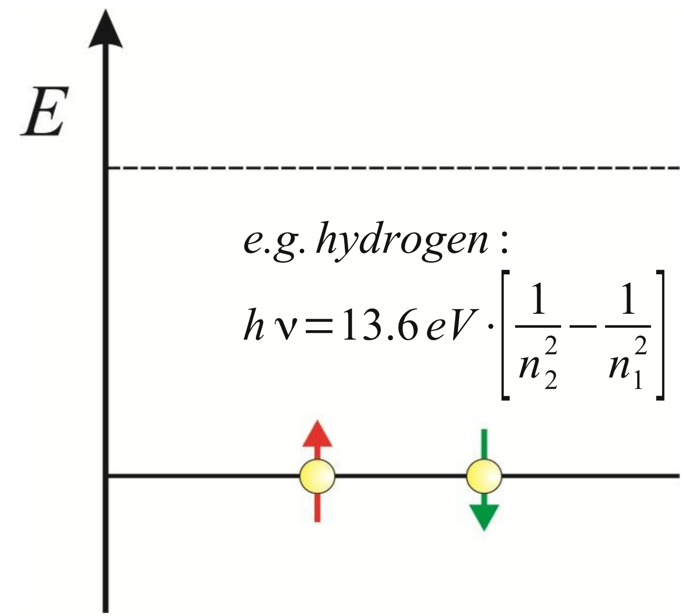
- Popular hypothesis of how electronics works: 'Magic Smoke'

  - source: http://en.wikipedia.org/wiki/Magic_smoke
- Will continue presenting an alternative theory ...

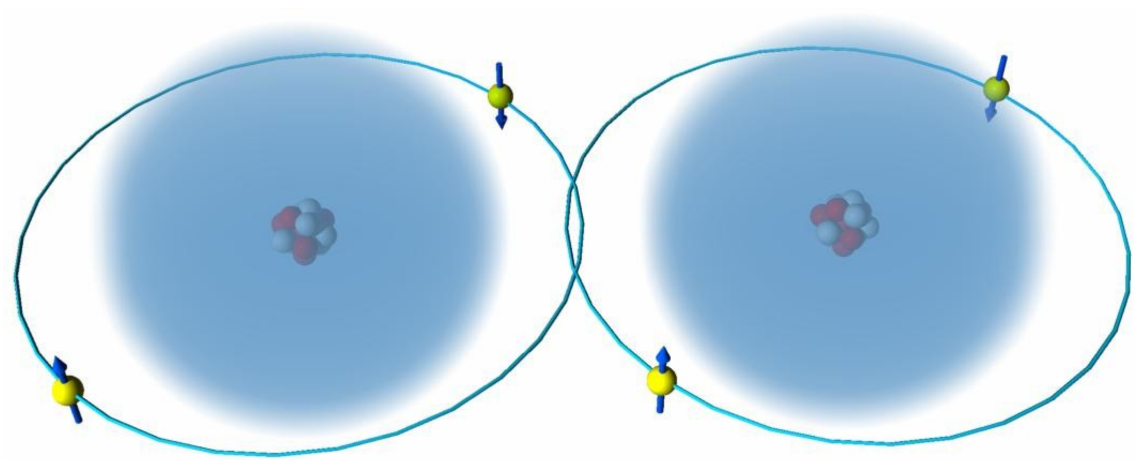
Semiconductor Basics I/IV

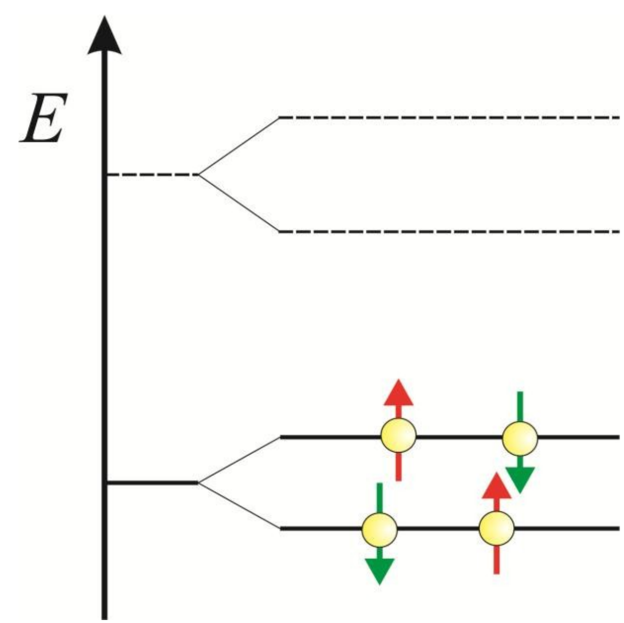
- single atom





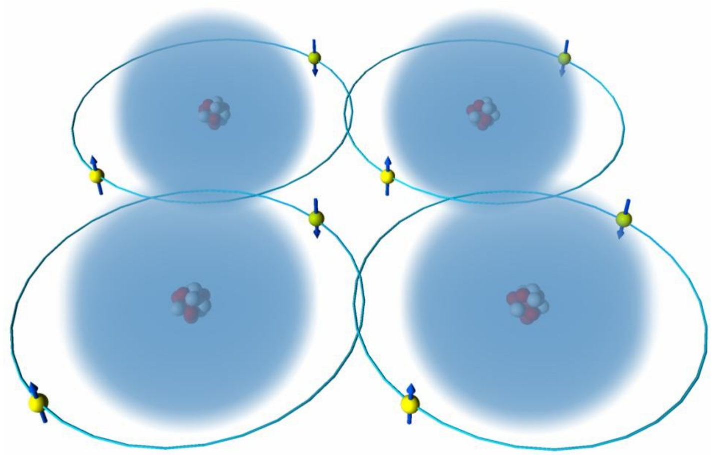
- two atoms

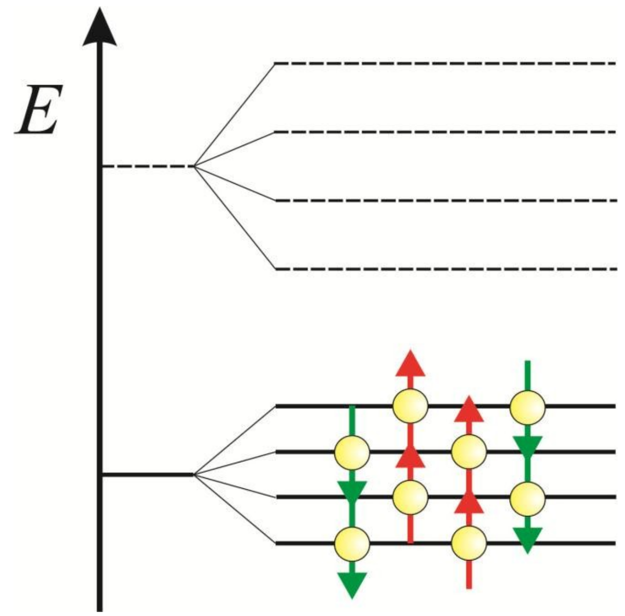




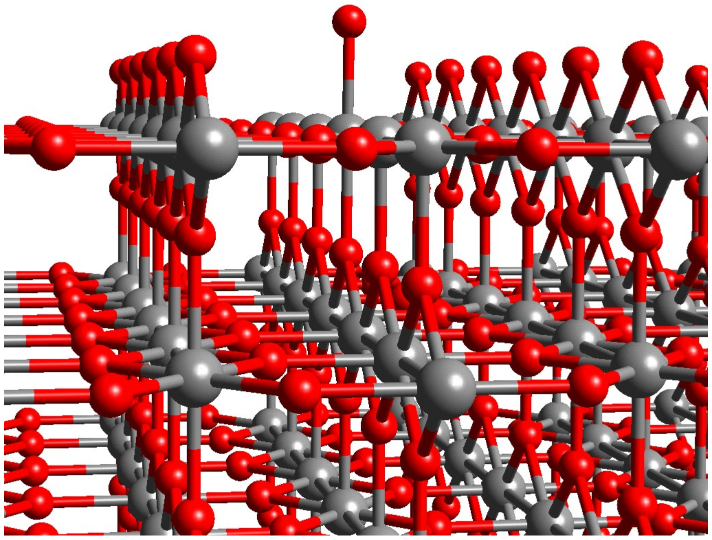
Semiconductor Basics II/IV

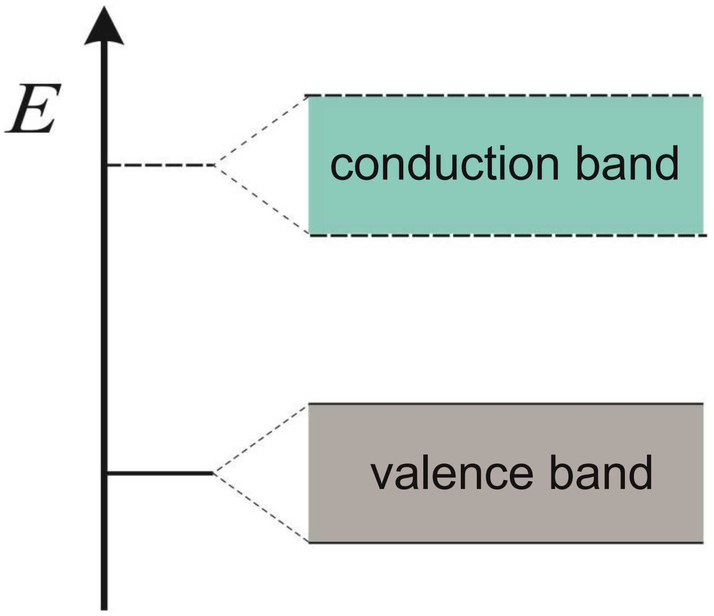
- four atom





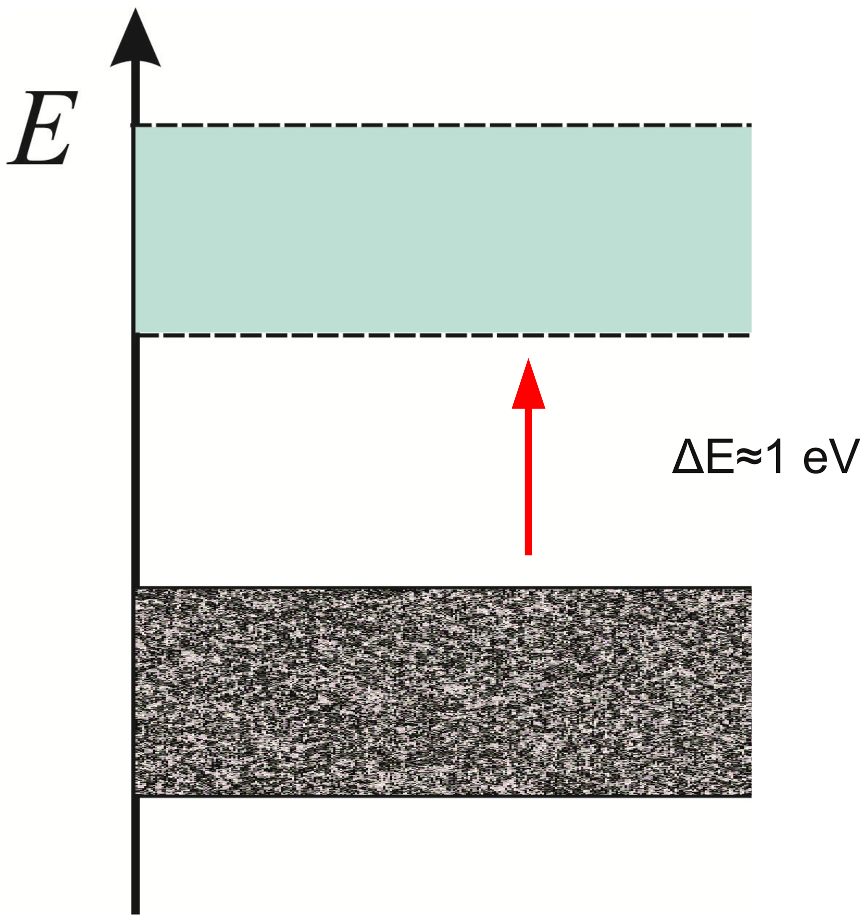
- crystal lattice (> 10^{20} atoms)



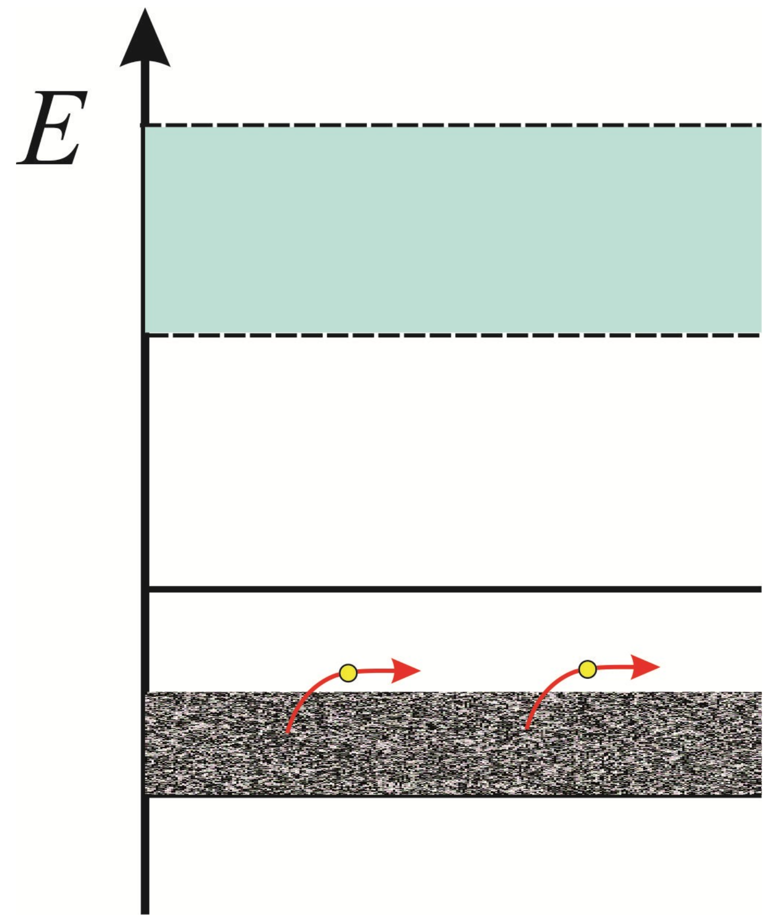


Two extremes...

- Insulator …
  - all slots in valence band filled.

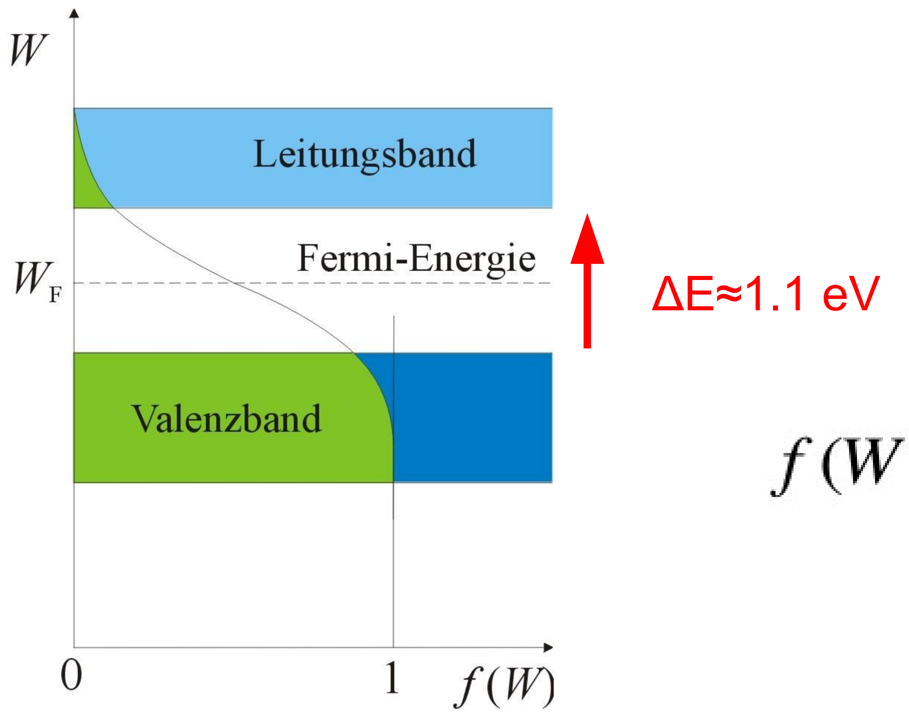


- Conductor …
  - valence band partially filled



Semiconductor Basics III/IV

- Pure silicon is an insulator!
  - particularly at low temperatures T



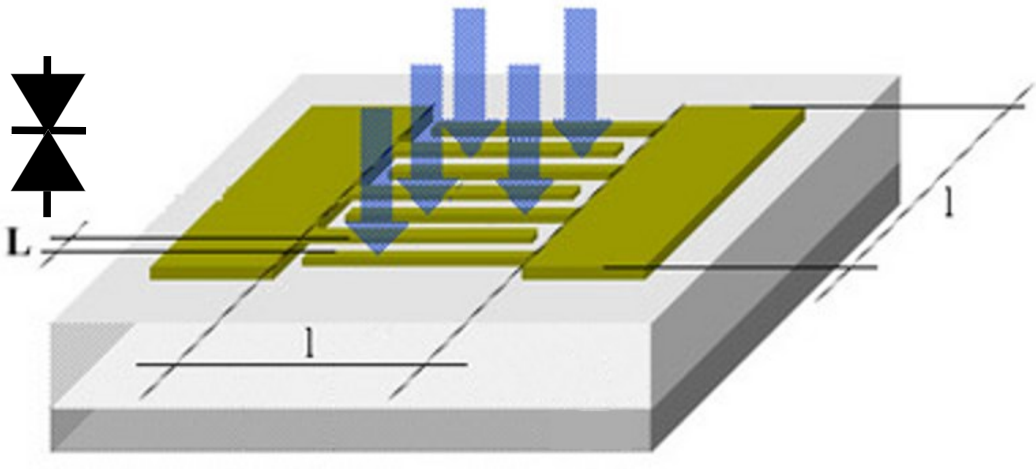
$$f(W) = \frac{1}{1 + \exp\left(\frac{W - W_F}{kT}\right)}$$

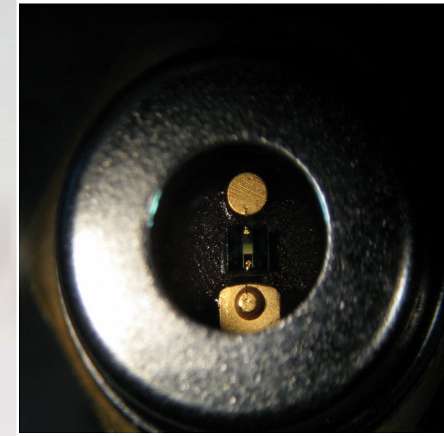
$$W_F = \frac{p_F^2}{2m} = \frac{h^2}{2m}\left(\frac{3}{8\pi}n\right)^{\frac{2}{3}}$$

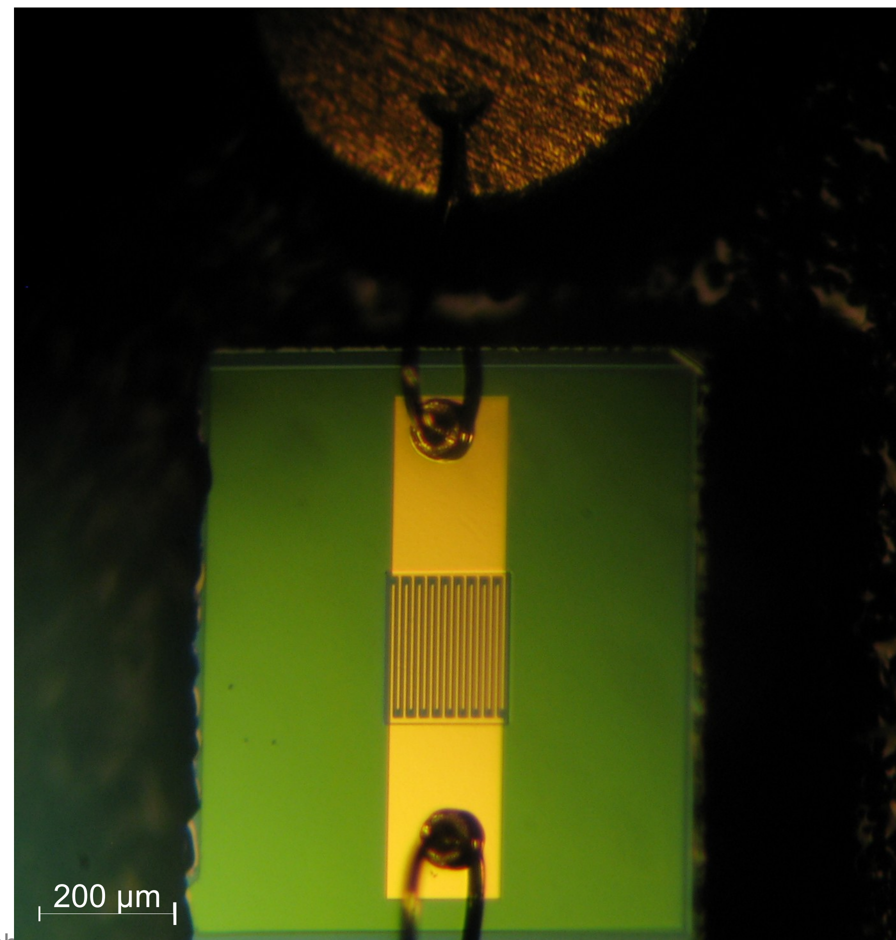
n: electron density, *m*: electron mass

↔ strong temperature dependence of all semi-conductor devices

Metal-Semiconductor-Metal (MSM) Photodetector



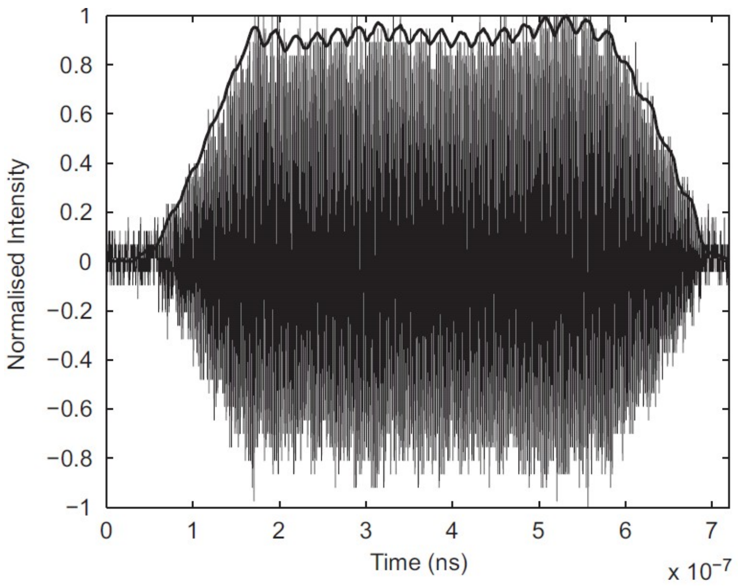


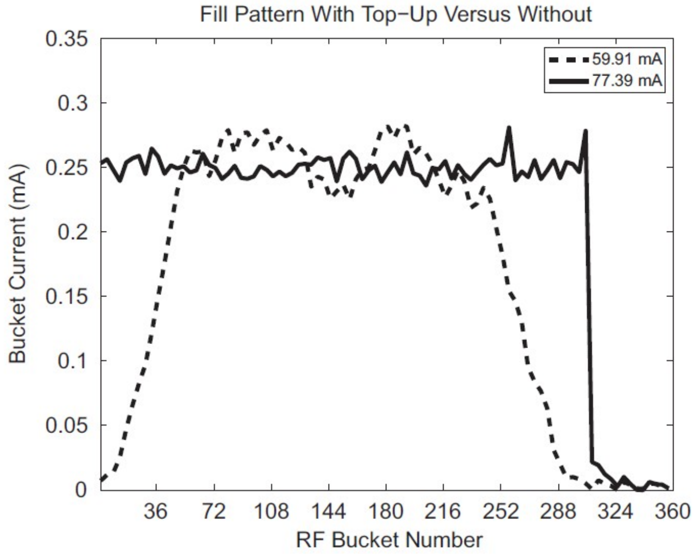


- >300 GHz bandwidth possible!

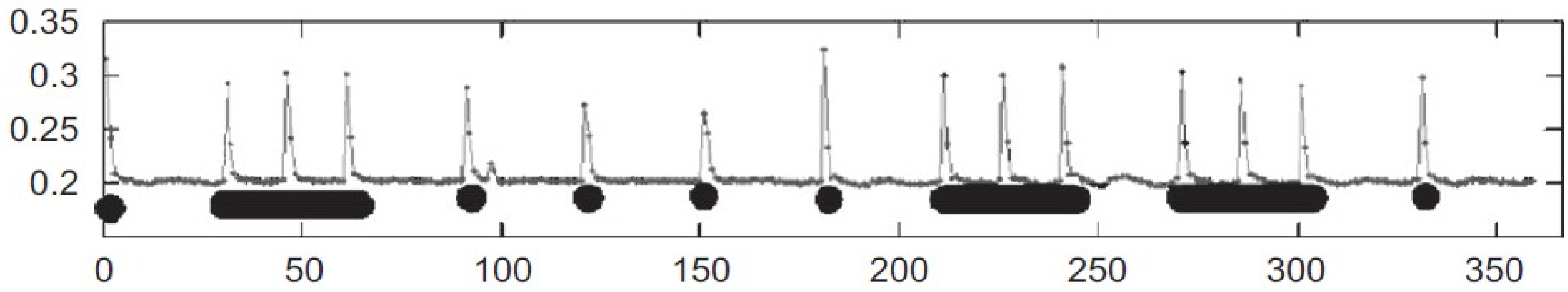
Synchrotron-Light based Fill-Pattern-Monitor

- ASLS's Fill Pattern Monitor (FPM)*





- ASLS fill pattern *a la carte*:

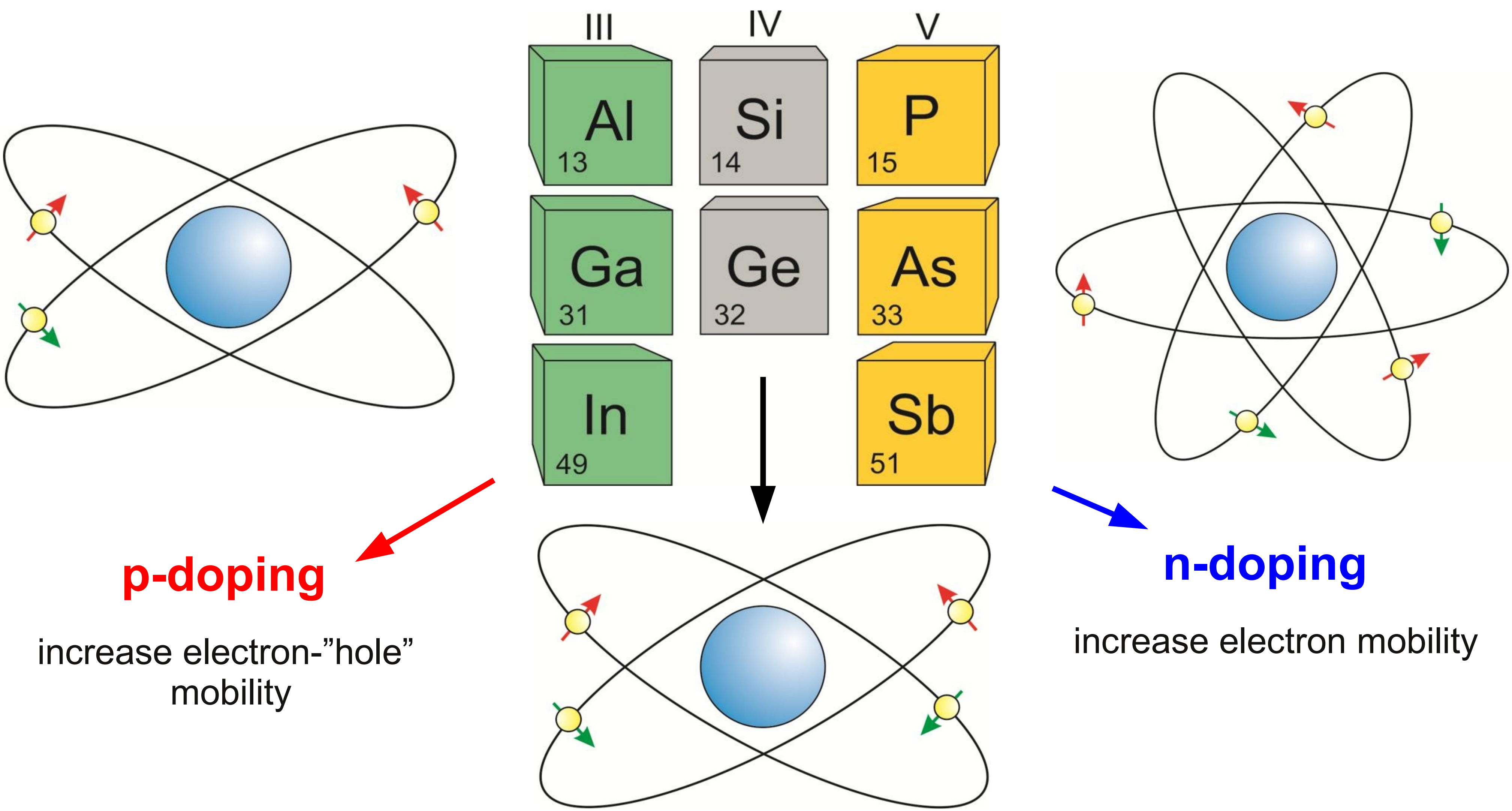


Australian Synchrotron Project

*D. Peak, M. Boland, R. Rassool, et. al., "Measurement of the real time fill-pattern at the Australian Synchrotron", NIMA, 2008

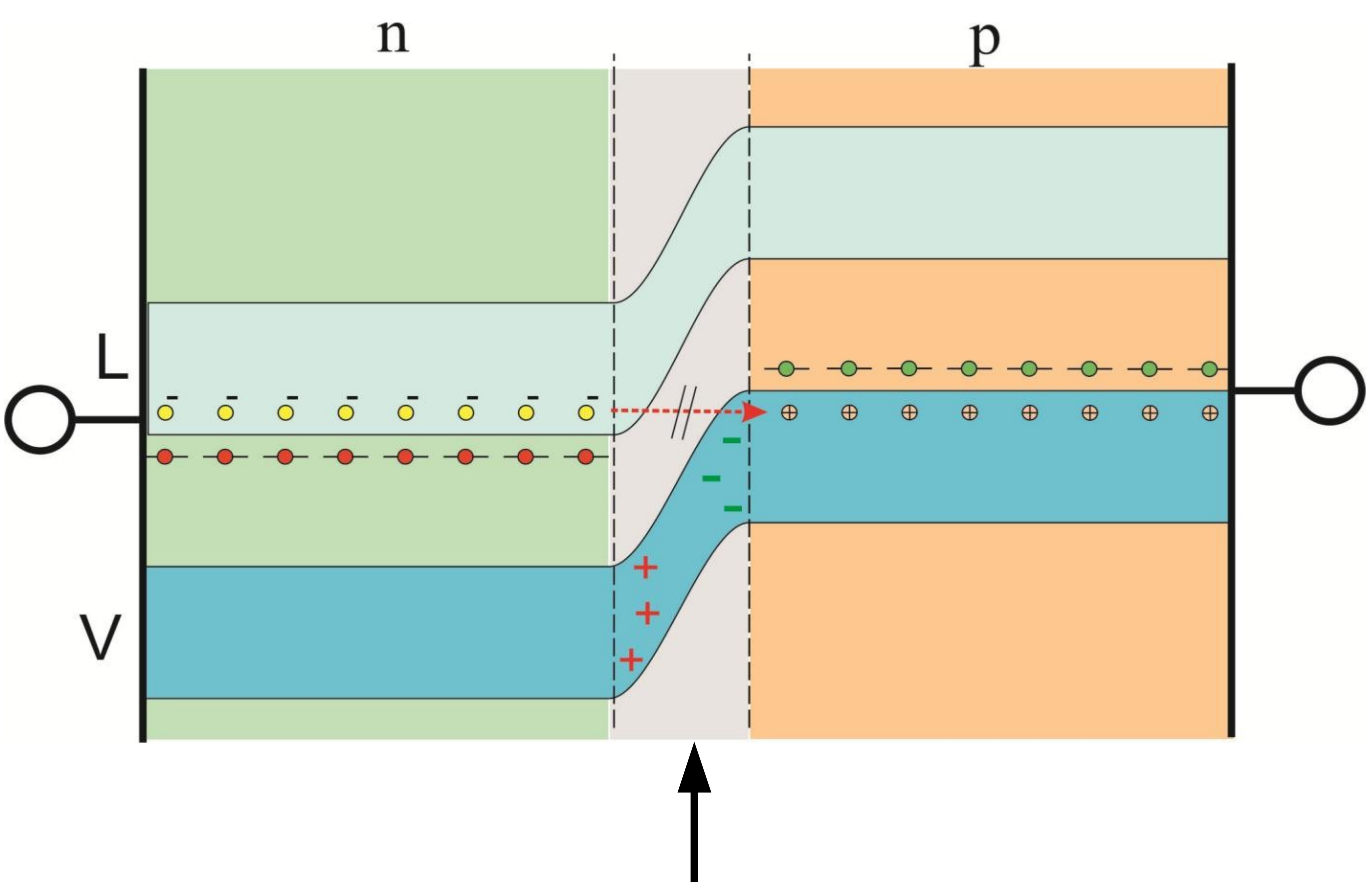
Semiconductor Basics IV/IV

- Smallest crystal lattice impurities can change the conducivity significantly → “doping”



Diode

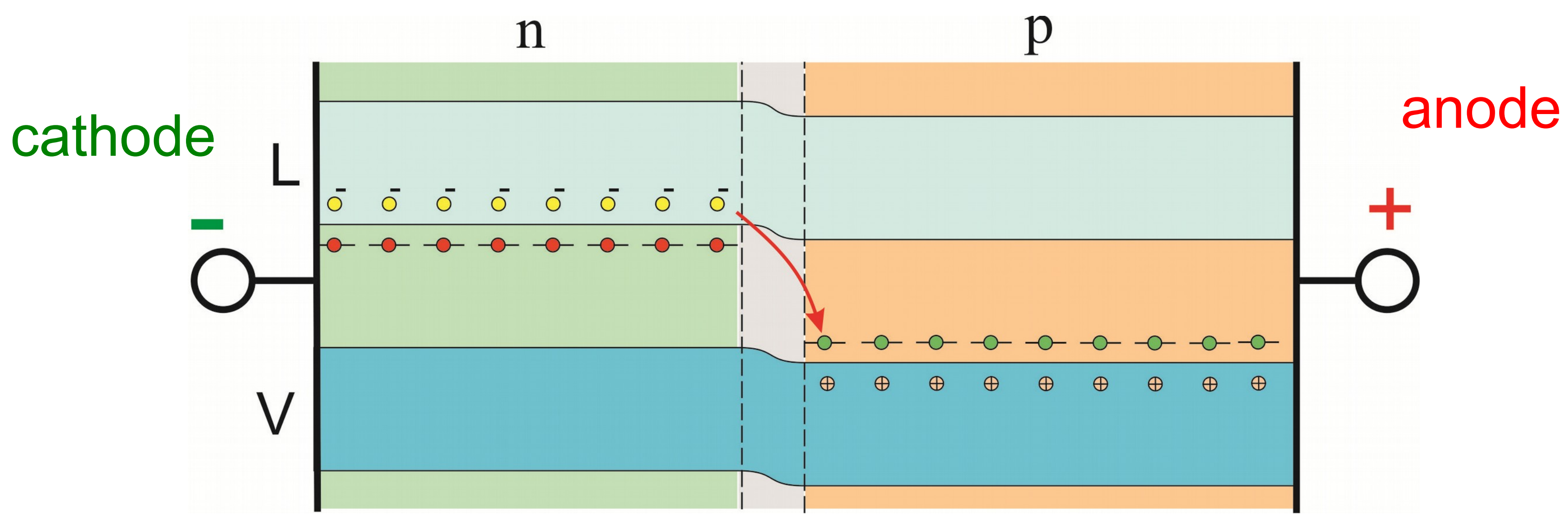
- Connecting n/p-doped semiconductor form 'intrinsic' region



intrinsic region
(non-conducting)

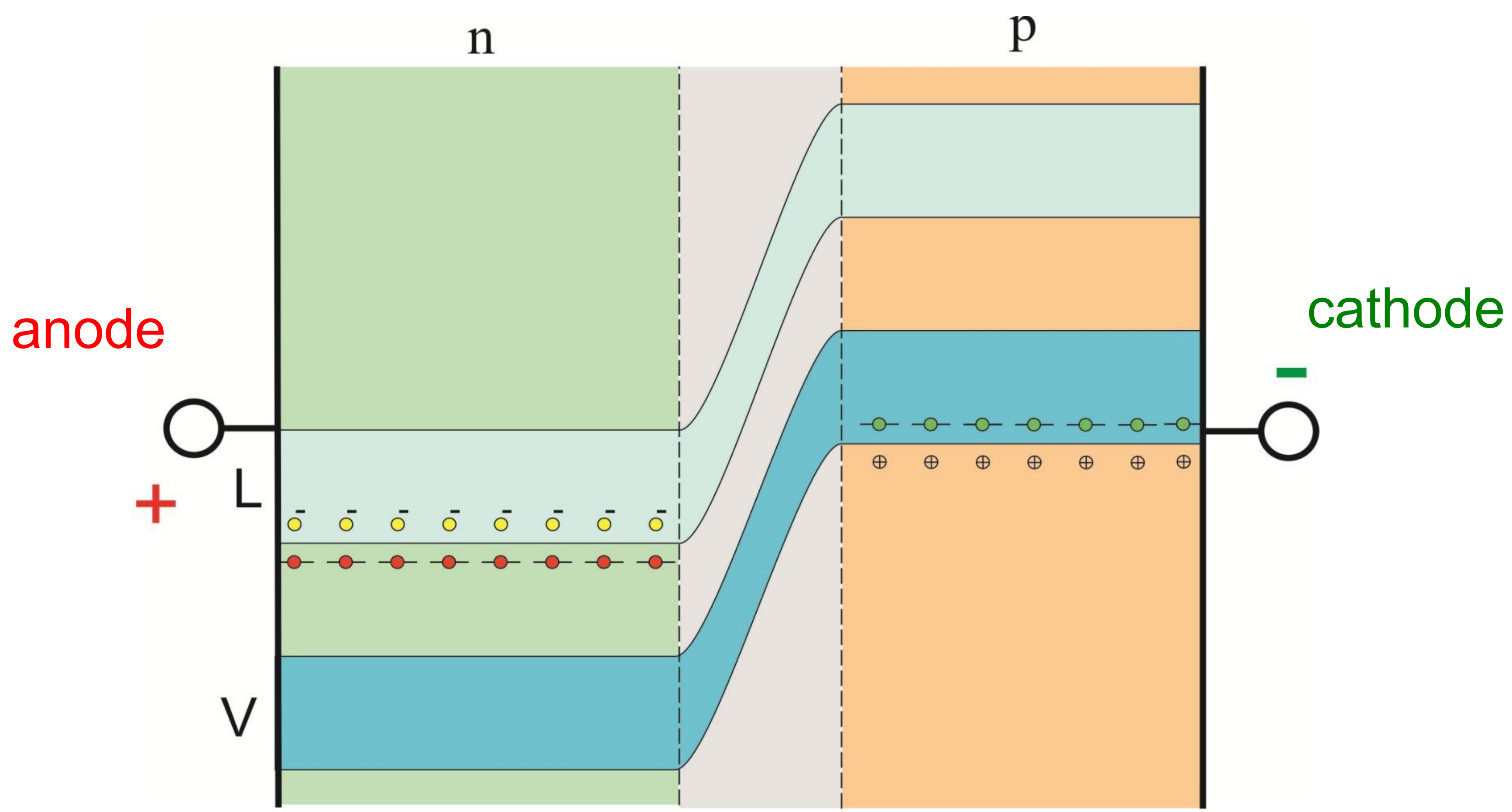
Diode – Forward Polarity

- conducts current

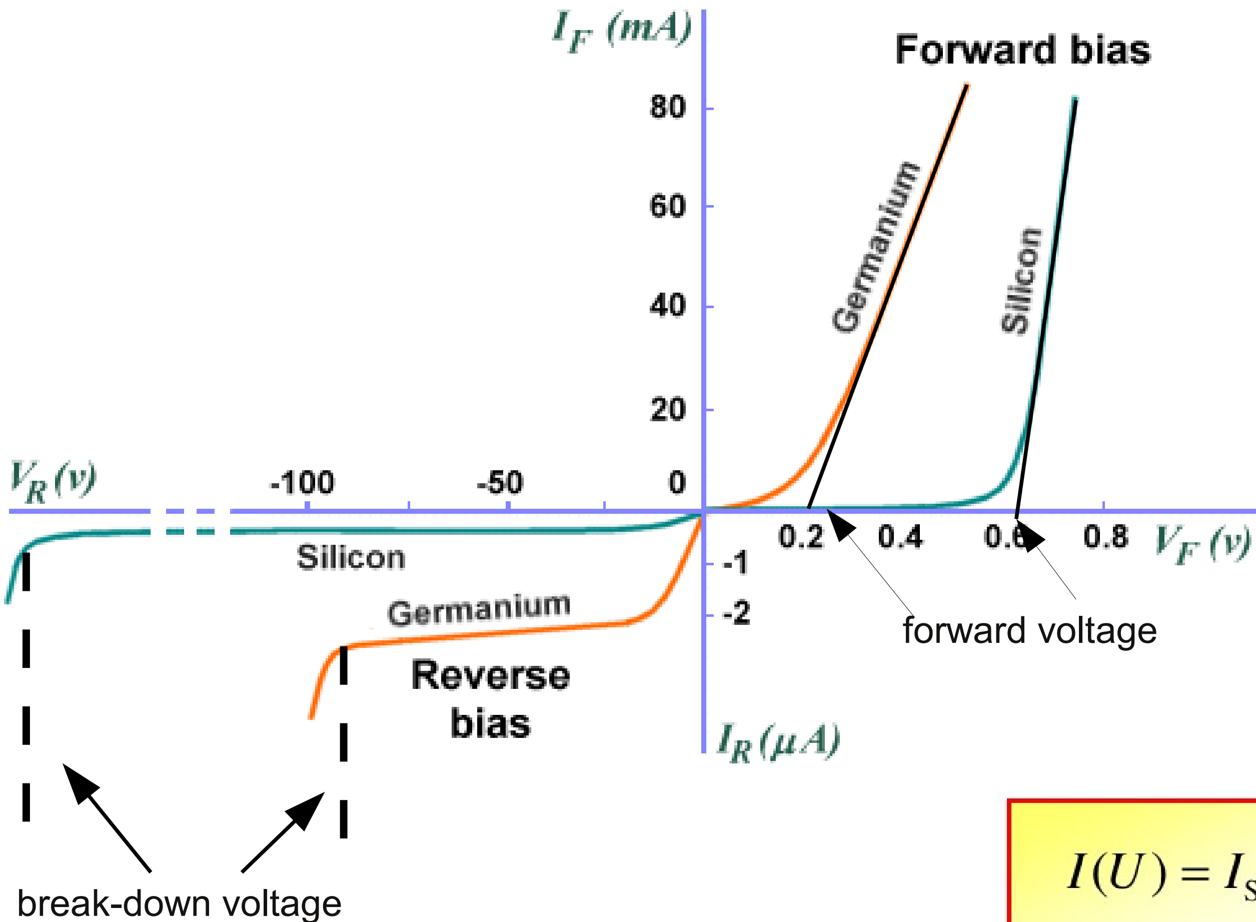


Diode – Reverse Polarity

- blocks current



Diode – Shockley Equation

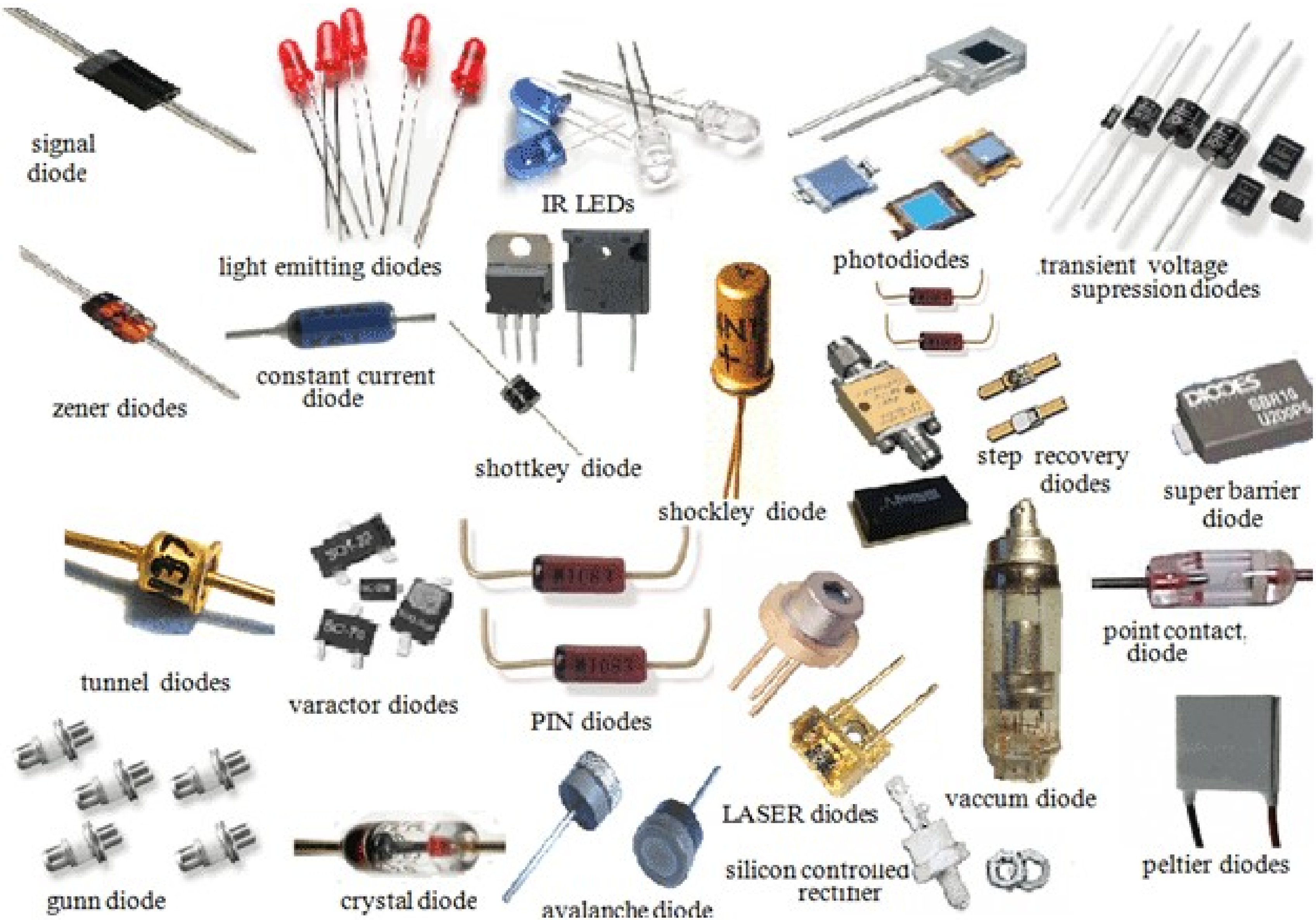


$$I(U) = I_S\left(\exp\left(\frac{eU}{mkT}\right) - 1\right) = I_S\left(\exp\left(\frac{U}{mU_T}\right) - 1\right)$$

- Material properties
  - Silicon: $I_s = 10^{-11}$ A, mU_T=0.03V
  - Germanium: $I_s = 10^{-7}$ A, mU_T=0.03V

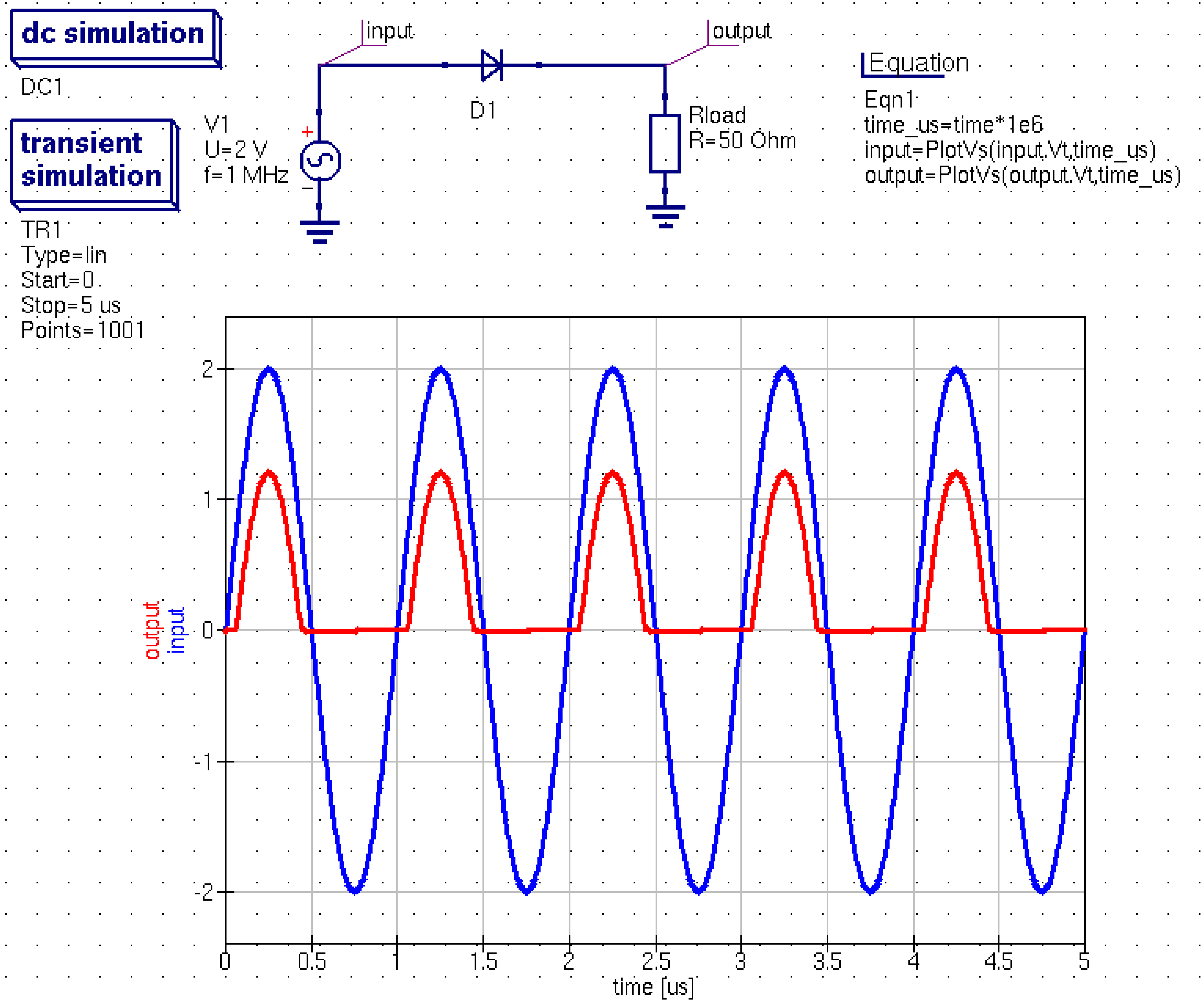
$$U_T = \frac{kT}{e} = 25.5\text{ mV}$$

Diode Types I/II

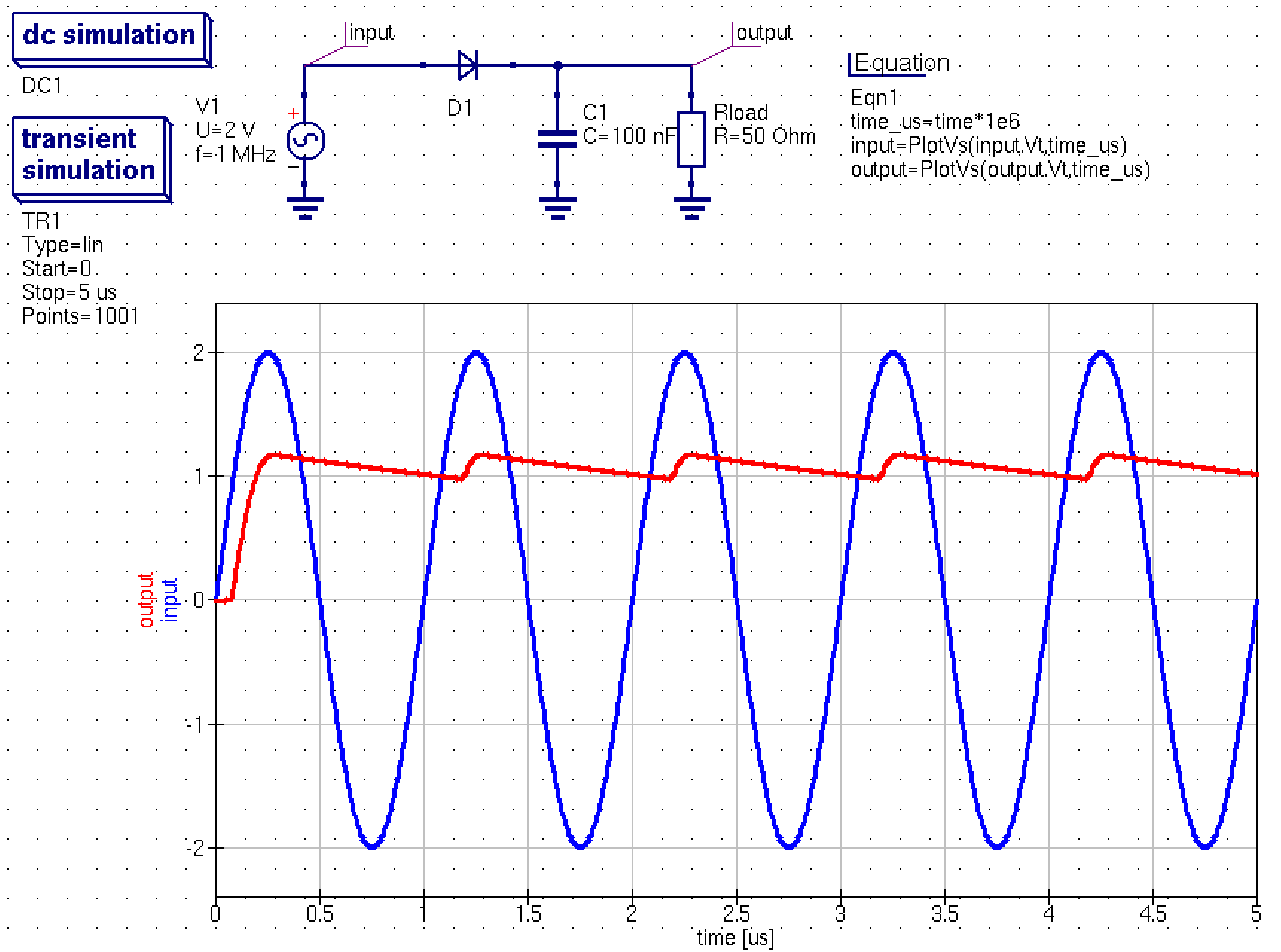


Types of Diode

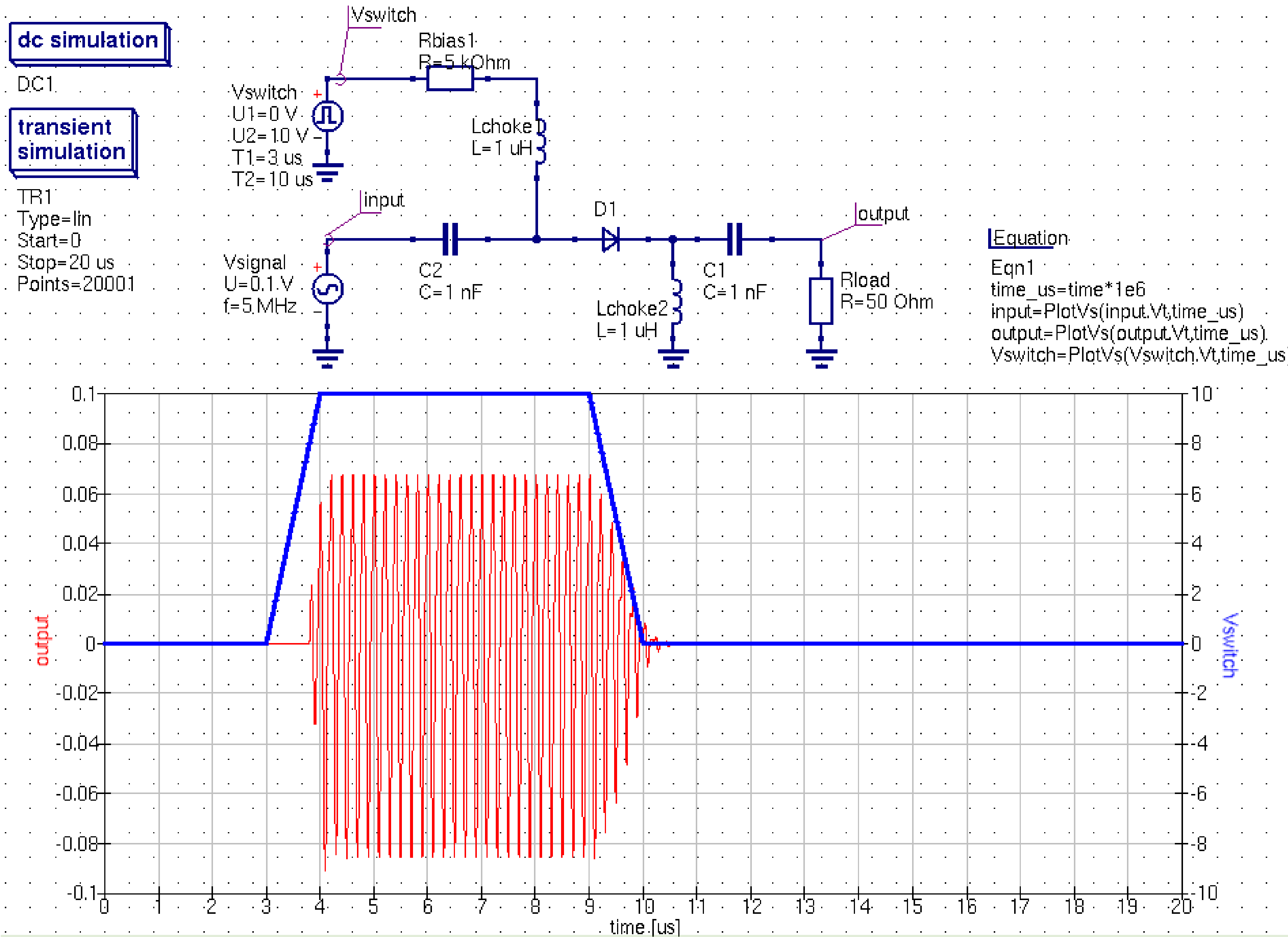
Diode as a Rectifier I/II



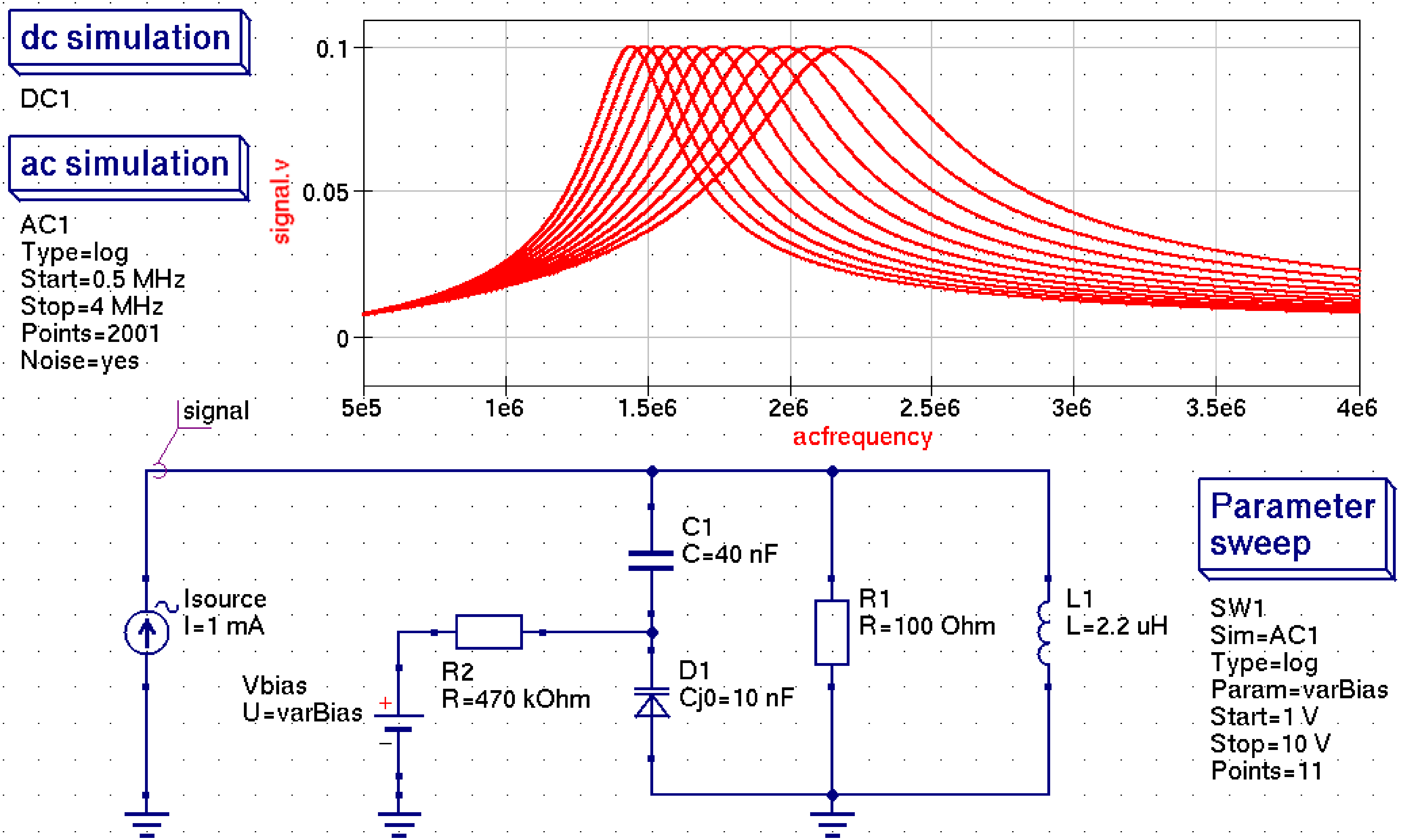
Diode as a Rectifier II/II



Fast RF Switch using Diodes



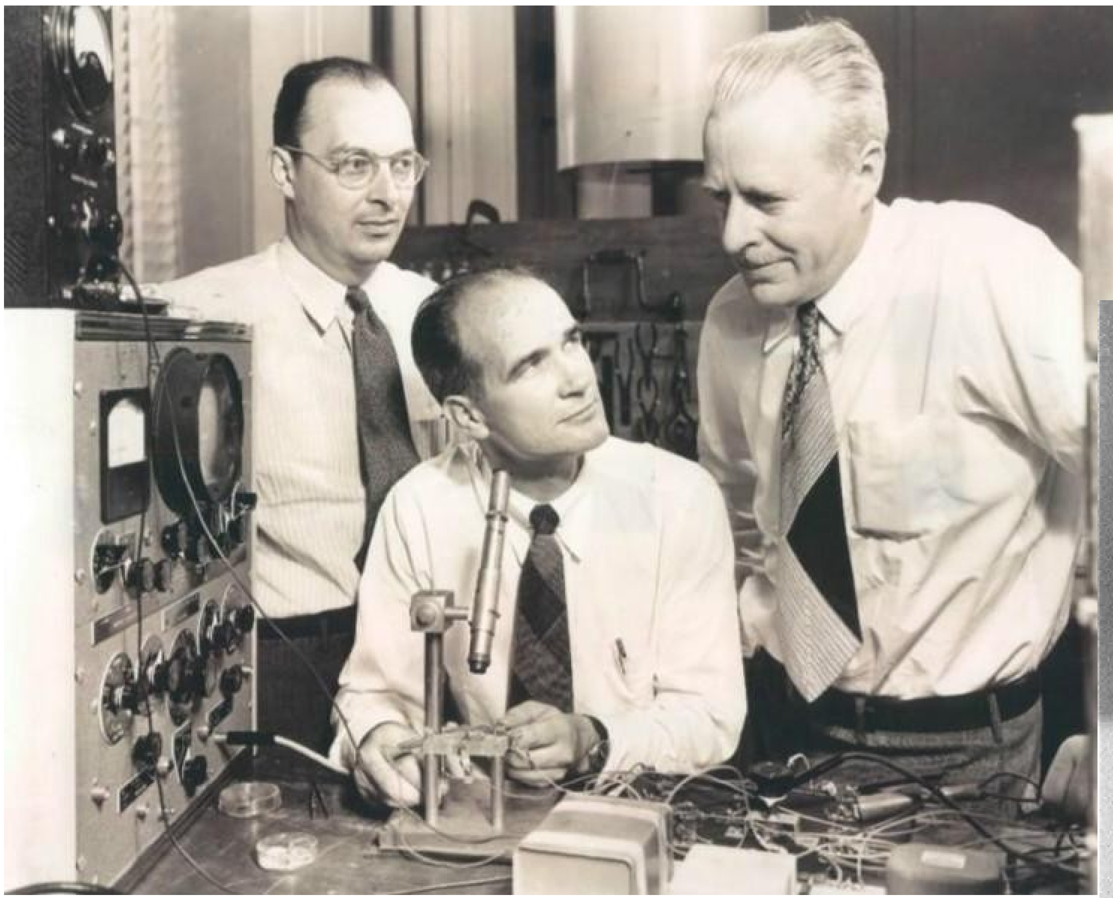
Diodes as Variable Capacitors

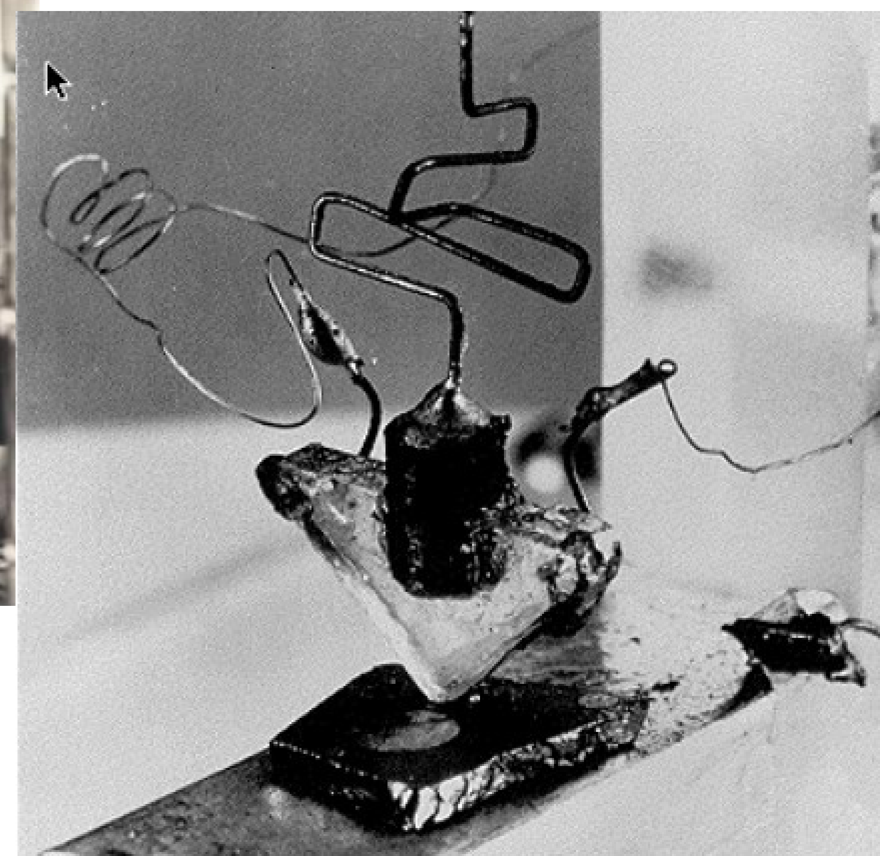


L.E.D. Zeppelin

First (working) Transistor (23.12.1947)

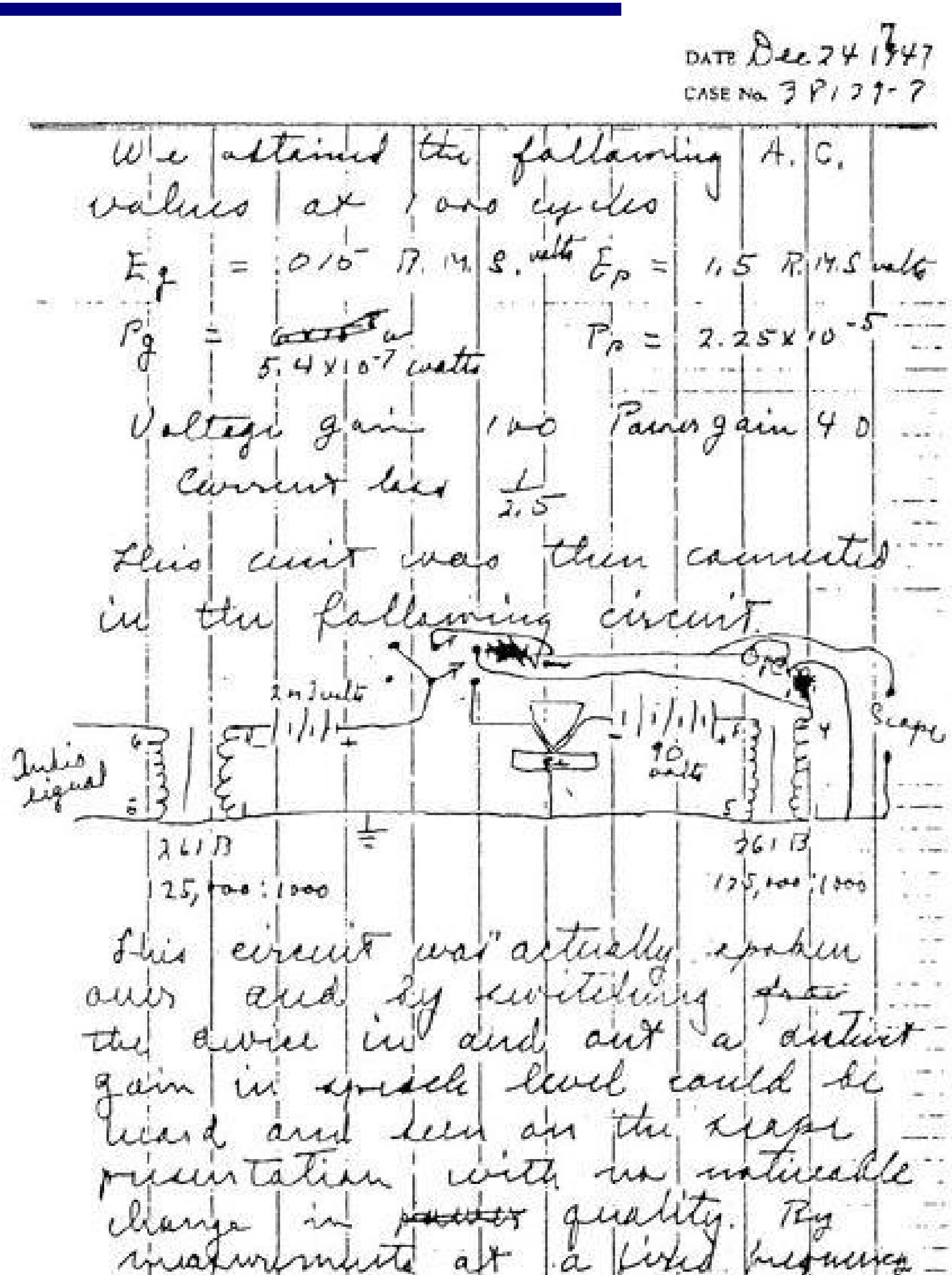
- John Bardeen, William Shockley & Walter Houser Brattain





- 1956 Nobel prize for Physics

… and Extract from their Notes (24.12.1947!)



DATE Dec 24 1947
CASE No. 38139-7

We obtained the following A.C. values at 1000 cycles

E_g = .015 R.M.S. volts E_p = 1.5 R.M.S. volts

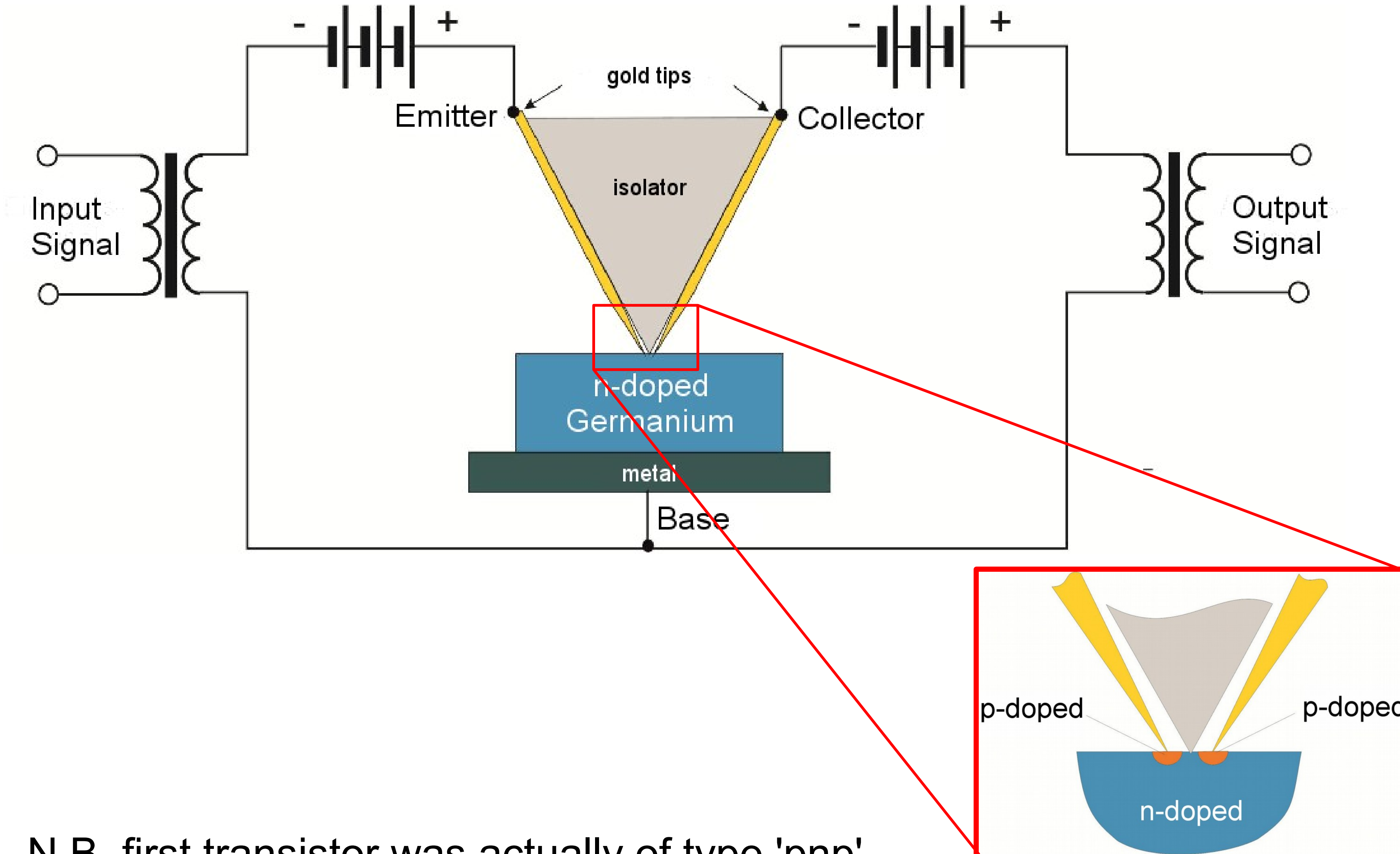
P_g = 5.4×10^{-7} watts P_p = 2.25×10^{-5}

Voltage gain 100 Power gain 40
Current loss $\frac{1}{2.5}$

This circuit was then connected in the following circuit.

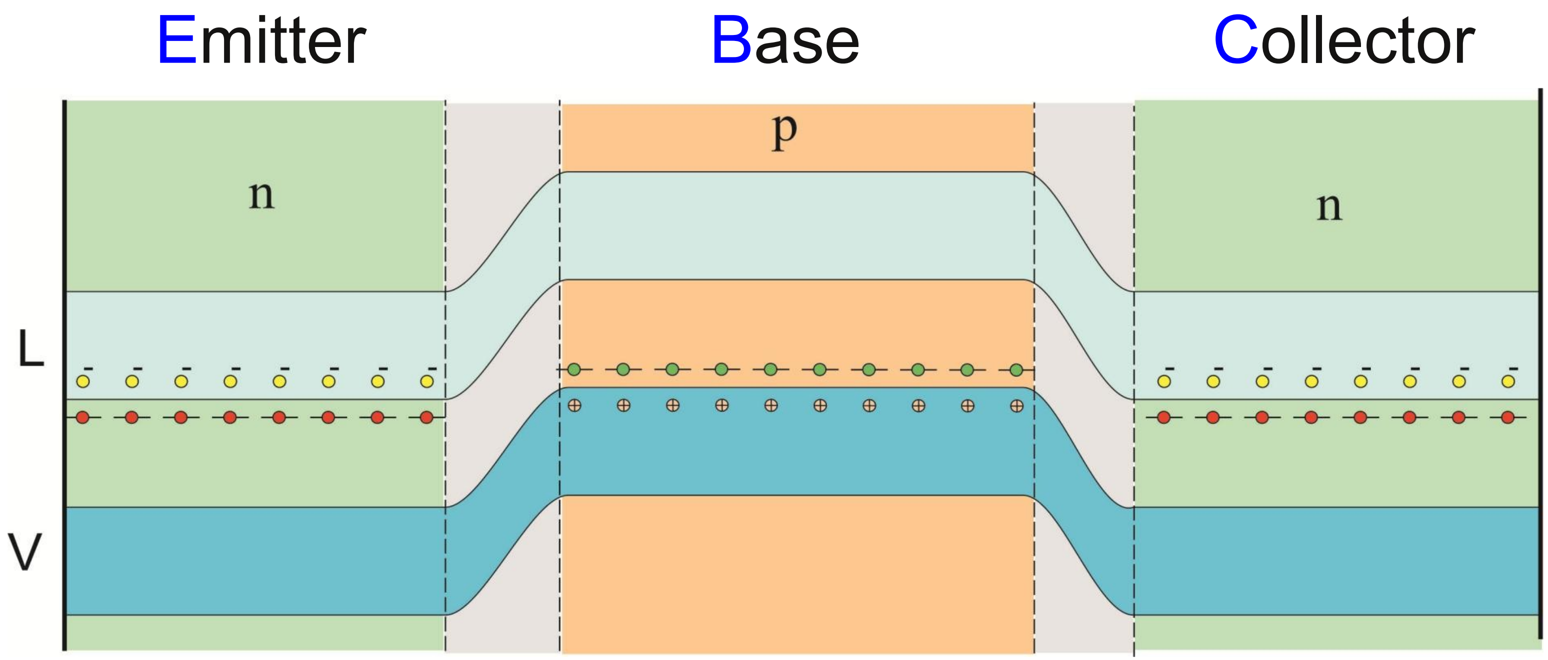
This circuit was actually spoken over and by switching the device in and out a distinct gain in speech level could be heard and seen on the scope presentation with no noticeable change in quality. By measurements at a fixed frequency

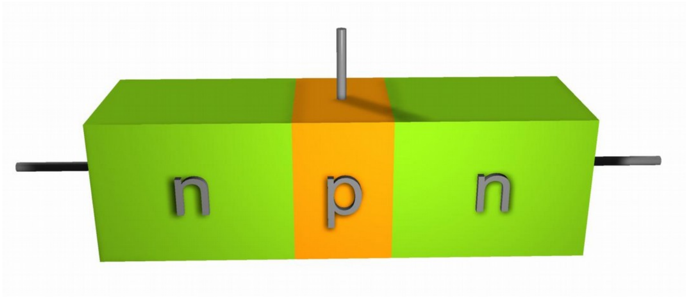
First Transistor Schematic

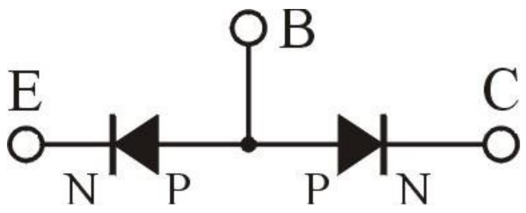


- N.B. first transistor was actually of type 'pnp'
  → will discuss npn (similar but inverse polarities)

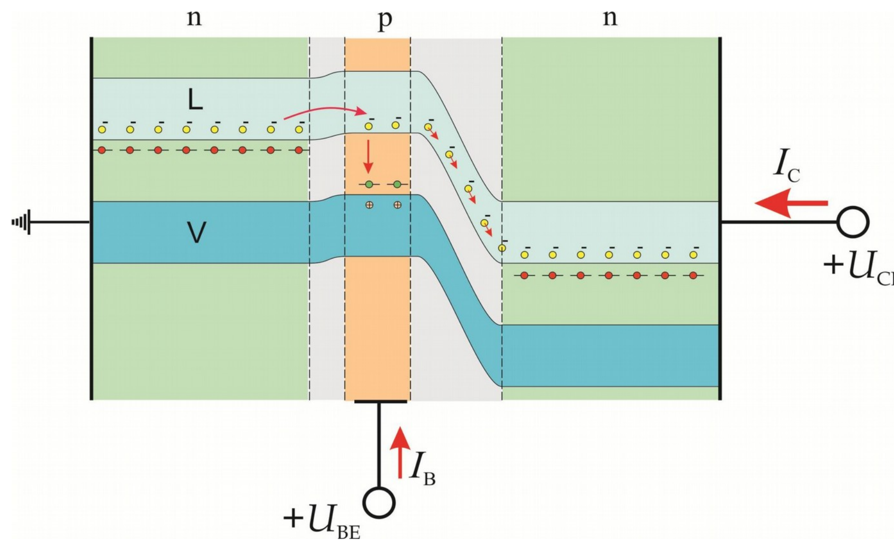
Transistor Band Model

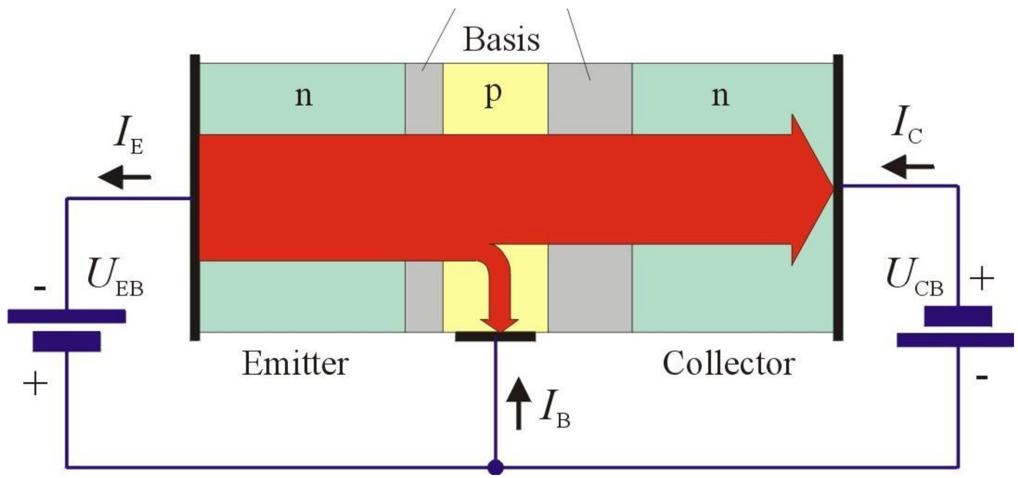






Transistor – Basic Use

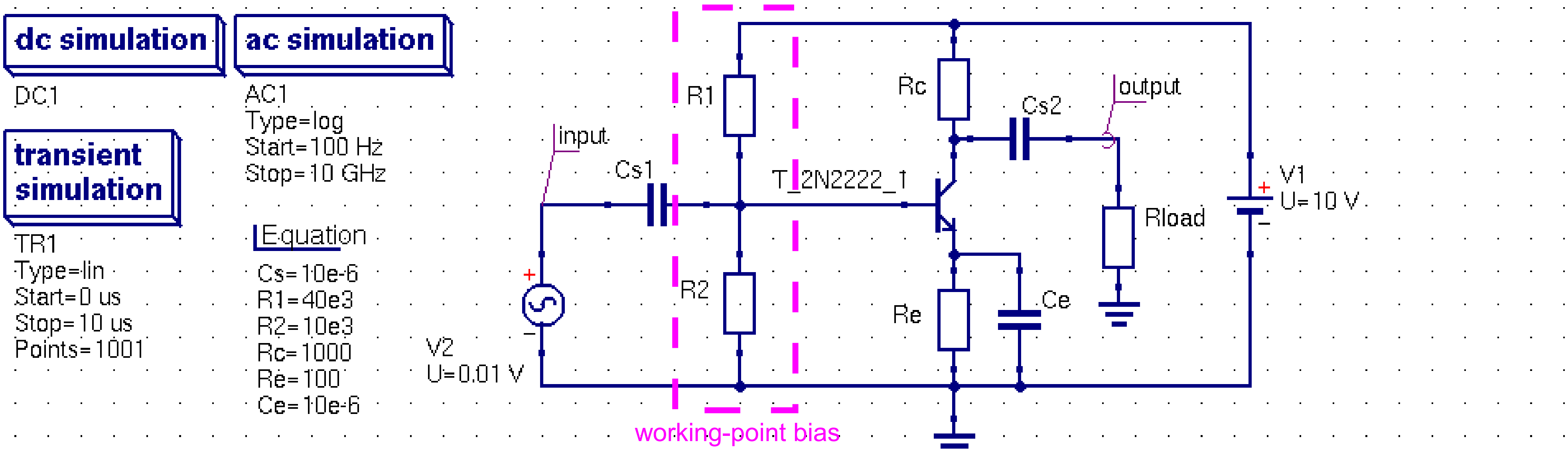


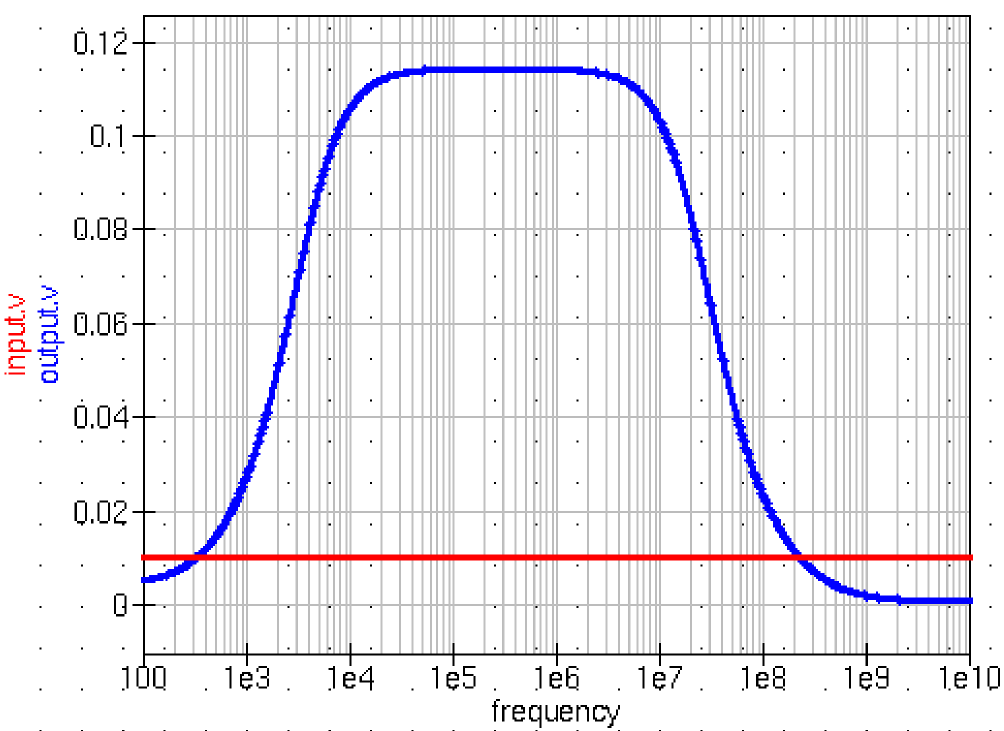


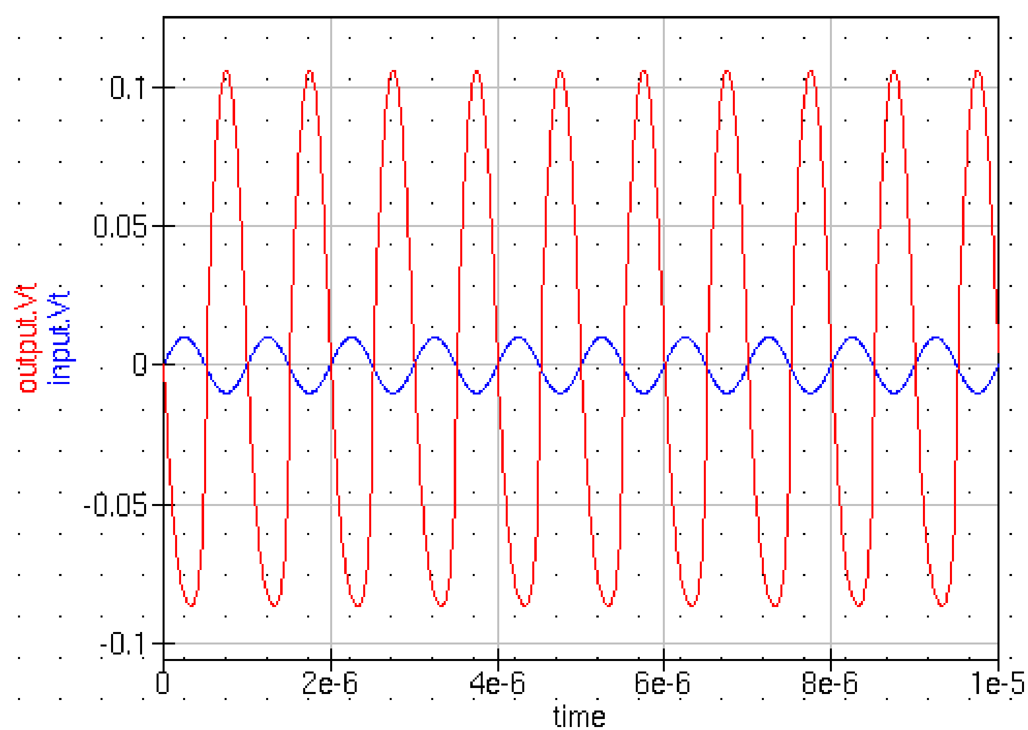
$$I_C = \beta \cdot I_b$$
$$\beta \approx 100$$

- Bottom-line: … can control a large collector current with a small current

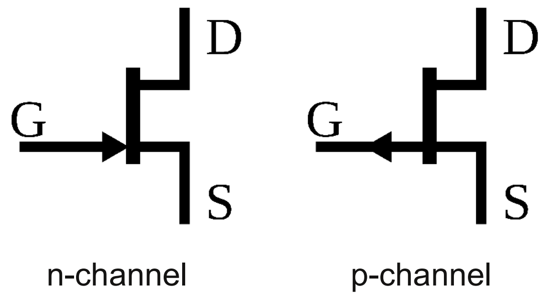
Transistor Voltage Amplifier Example

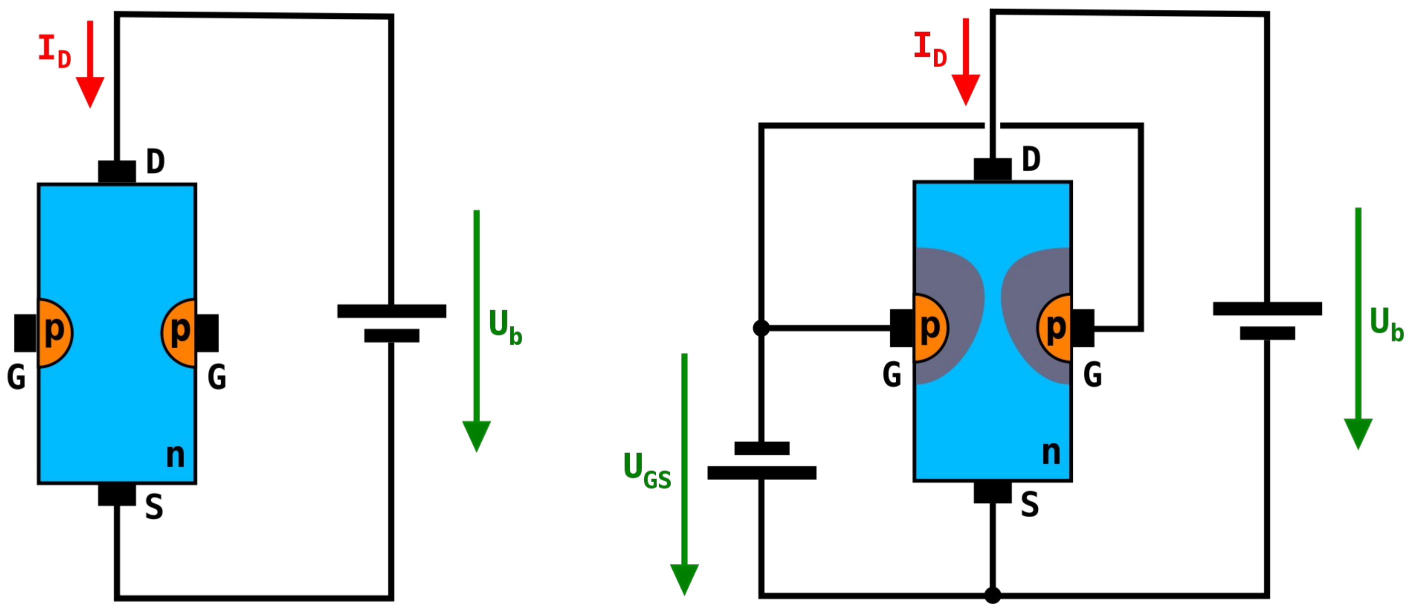






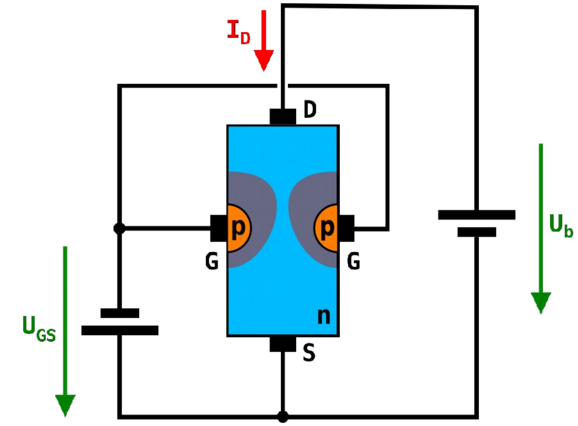
FET I/III



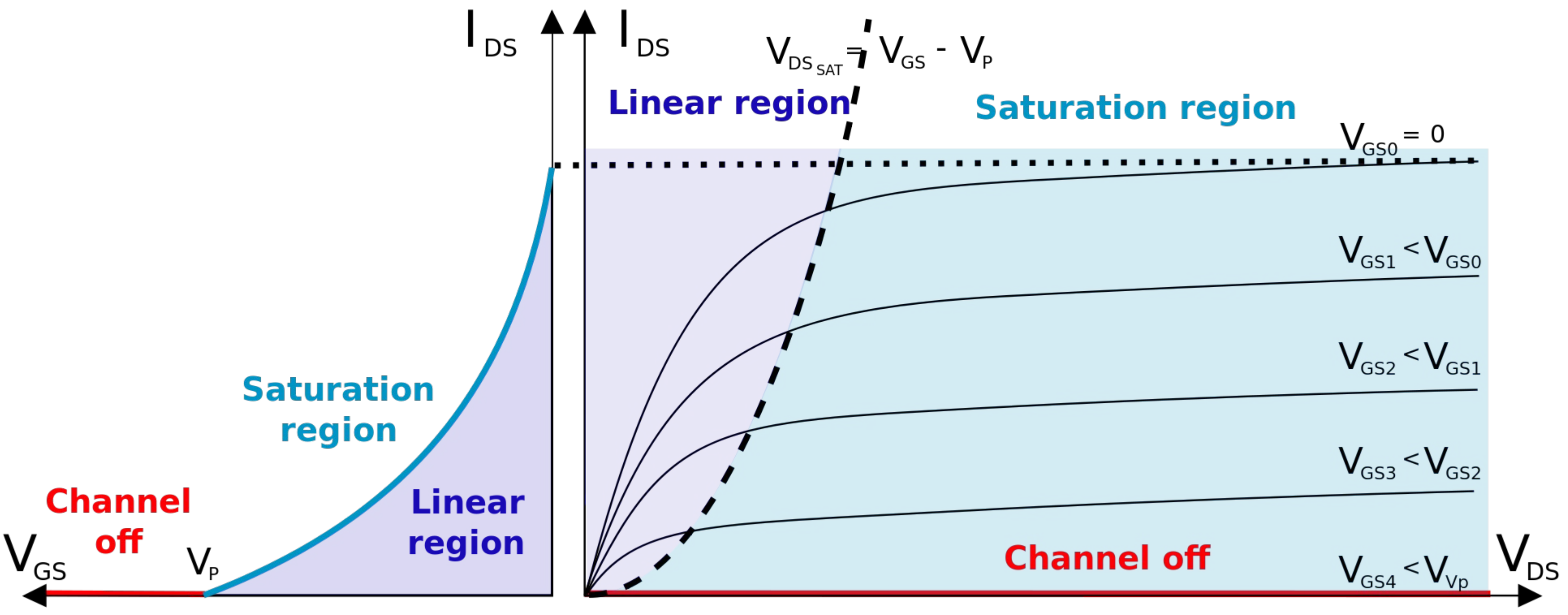


Nice-online demo:http://www-g.eng.cam.ac.uk/mmg/teaching/linearcircuits/jfet.html

FET II/III



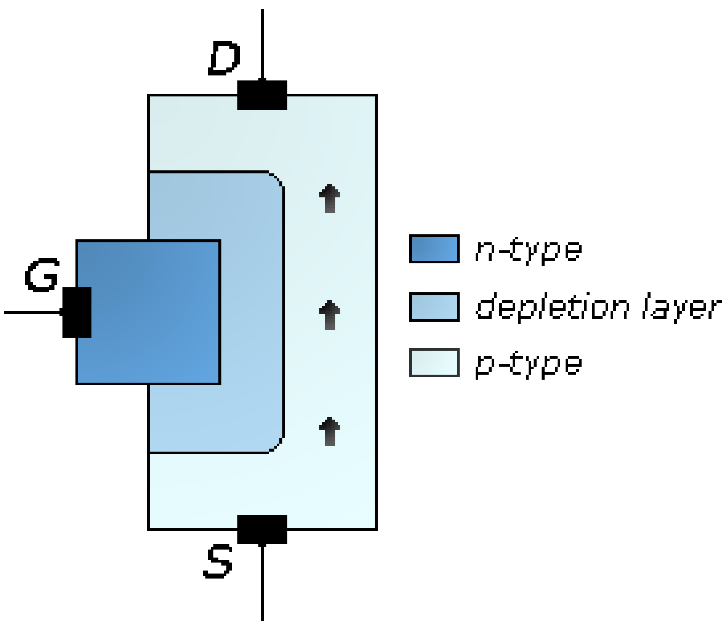
I_D
D
p
p
G
G
n
S
U_b
U_{GS}

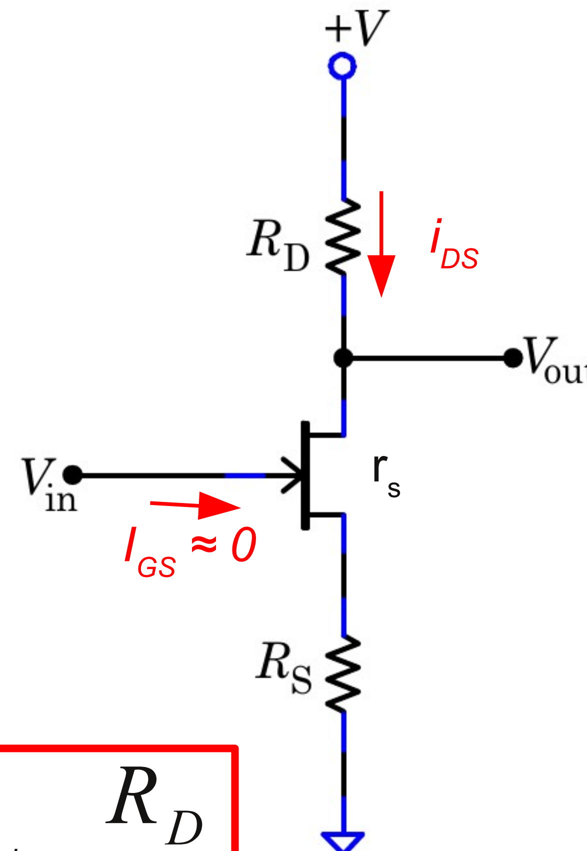


I_{DS}
I_{DS}
$V_{DS\,SAT} = V_{GS} - V_P$
Linear region
Saturation region
$V_{GS0} = 0$
$V_{GS1} < V_{GS0}$
$V_{GS2} < V_{GS1}$
$V_{GS3} < V_{GS2}$
$V_{GS4} < V_{Vp}$
Saturation region
Linear region
Channel off
V_{GS}
V_P
Channel off
V_{DS}

FET – Example

- Simple FET amplifier
  - The gate-source current is extremely small
    ↔ high-input impedance
    ↔ doesn't draw current (/power) from the input





$$G \approx -\frac{R_D}{R_S}$$

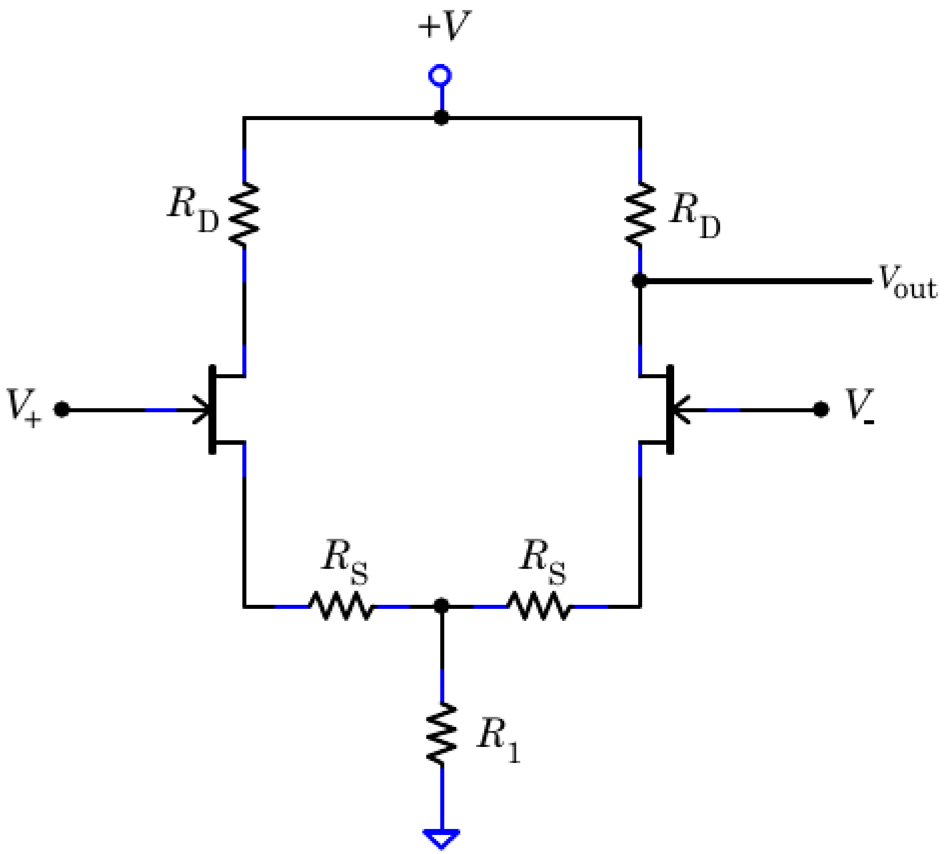
- Very useful if small current/charges need to be measured

JFET Differential Amplifier

- Idea can be extended to a differential amplifier

$$U_{out} = G \cdot \left(V_p - V_m \right)$$

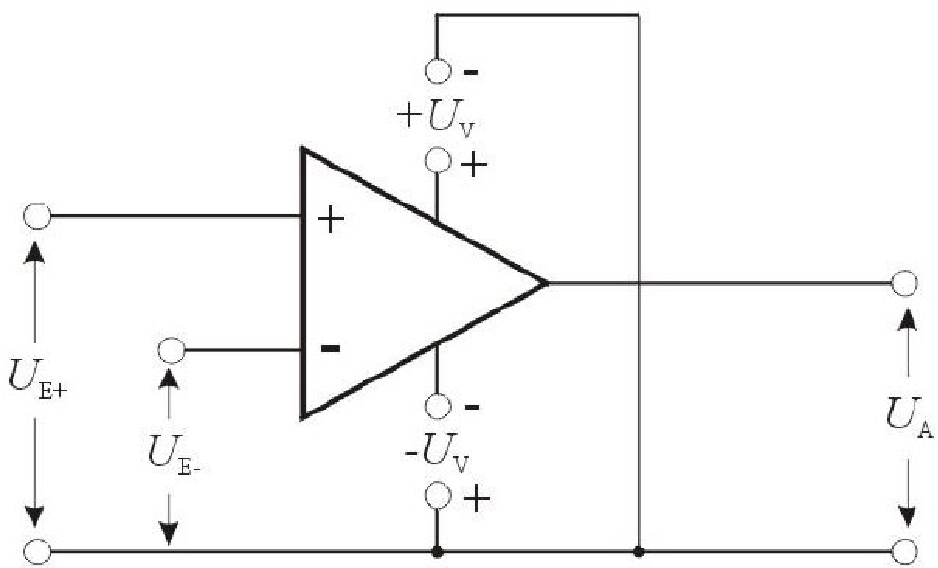
$$with: G \approx -\frac{R_D}{R_S}$$



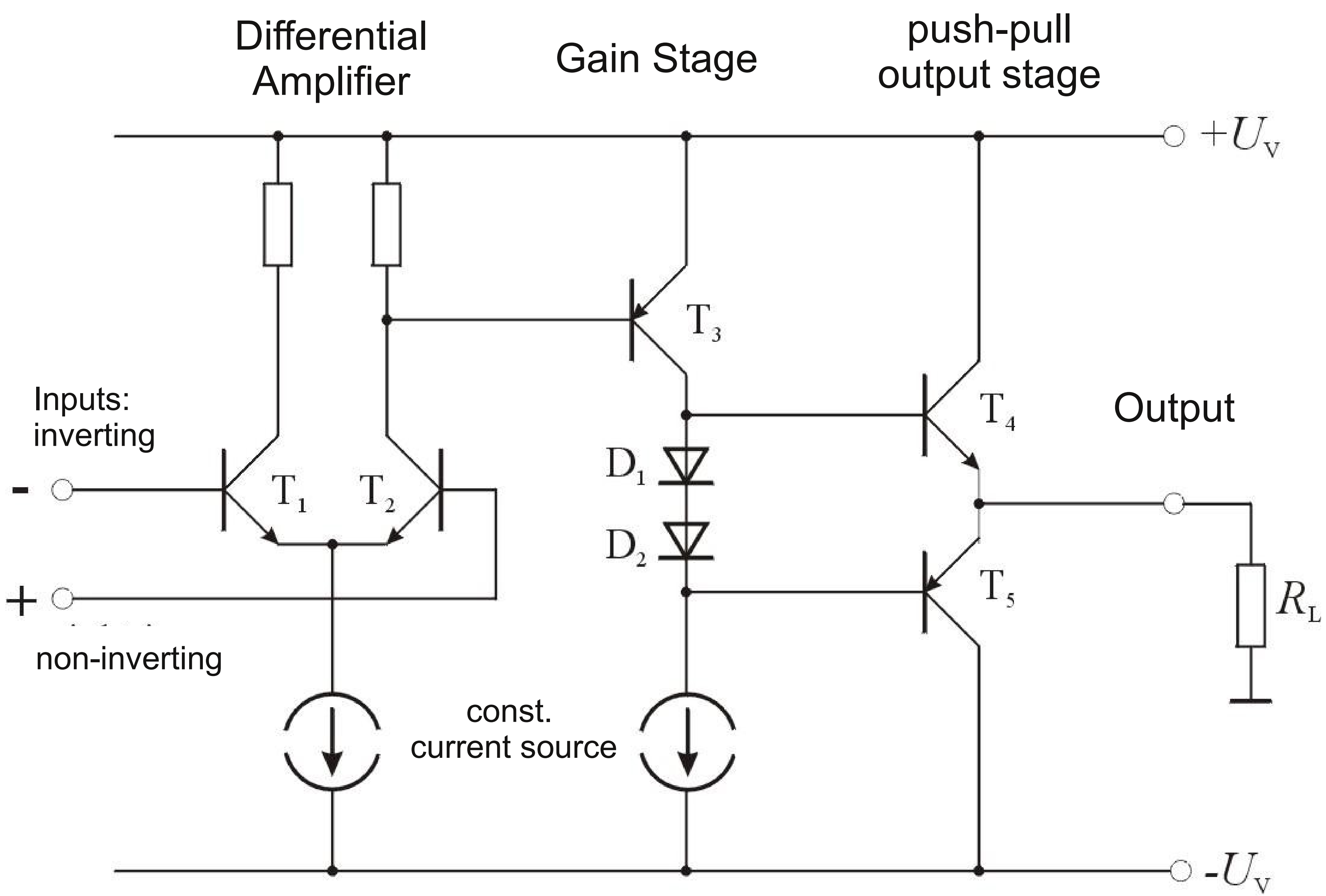
Integrated Circuit: Operational Amplifier

- … or "OpAmps": most popular differential amplifier (typ. f_{RF} <500 MHz)
  - DC-coupled, high-gain electronic voltage amplifier
  - differential input
    - large input impedance (particular with JFETs → good voltage monitors)
    - large 'common-mode' suppression of the inputs
  - typically single-ended output
    - very-low output impedance (i.e. good voltage source)
  - … an important building block of analog electronics

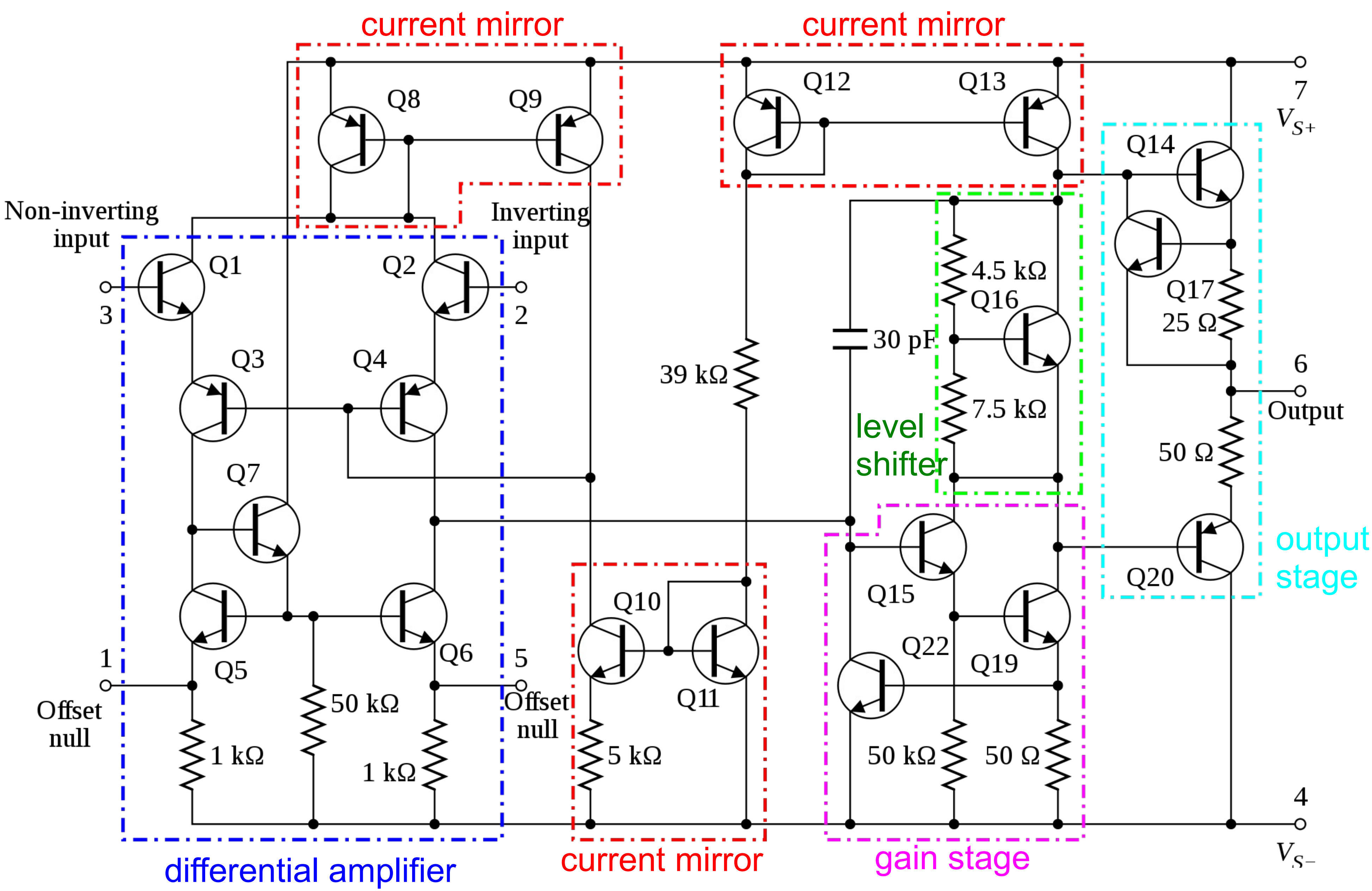
$$U_{out} = G \cdot \left(U_{Ep} - U_{Em} \right)$$
$$with: G \approx 10^5 \ldots 2 \cdot 10^6$$



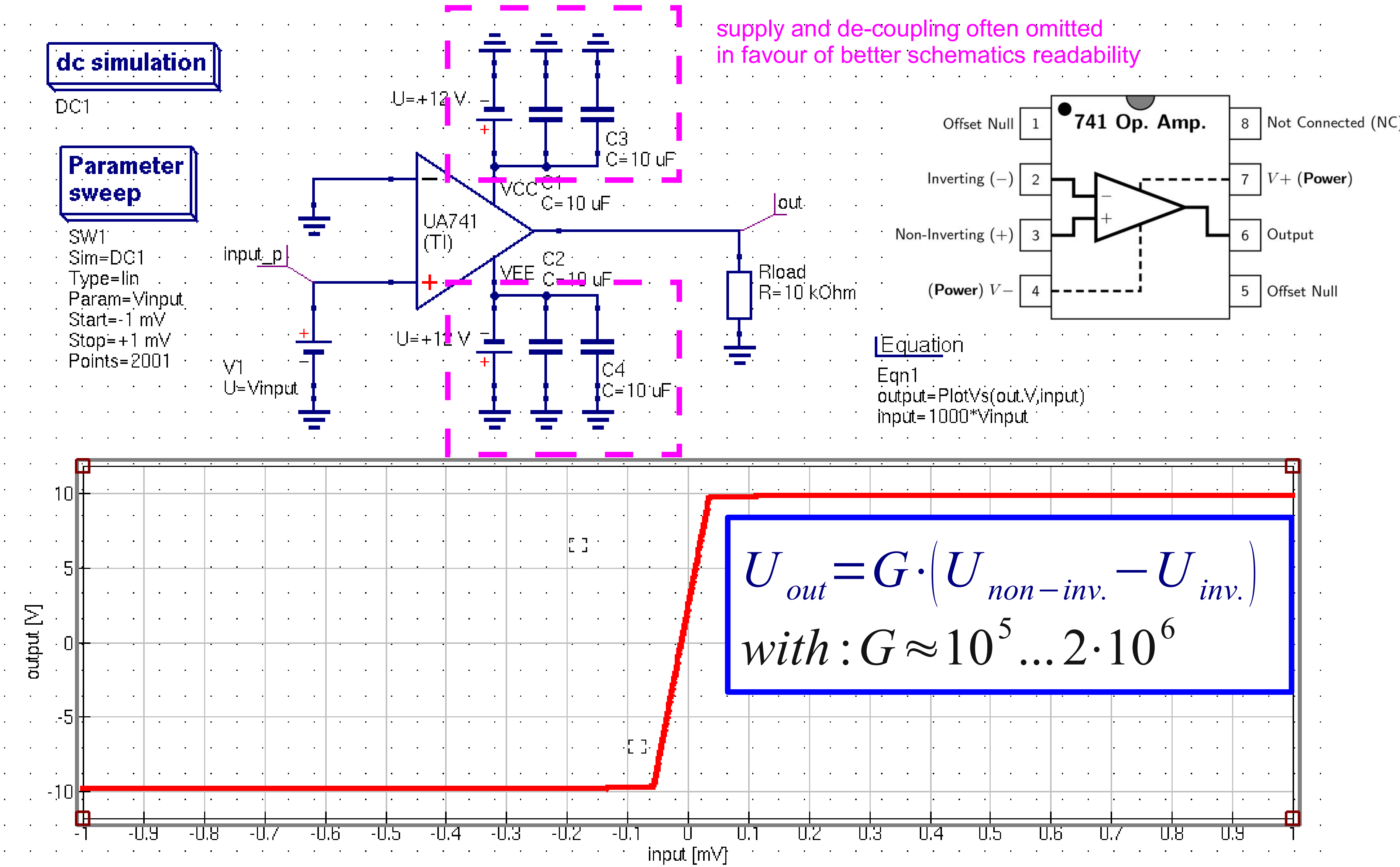
OpAmp – Simplified Internals



Classic 741 OpAmp Topology



OpAmp Open-Loop Gain



$$U_{out} = G \cdot \left(U_{non-inv.} - U_{inv.} \right)$$
$$with: G \approx 10^5 \ldots 2 \cdot 10^6$$

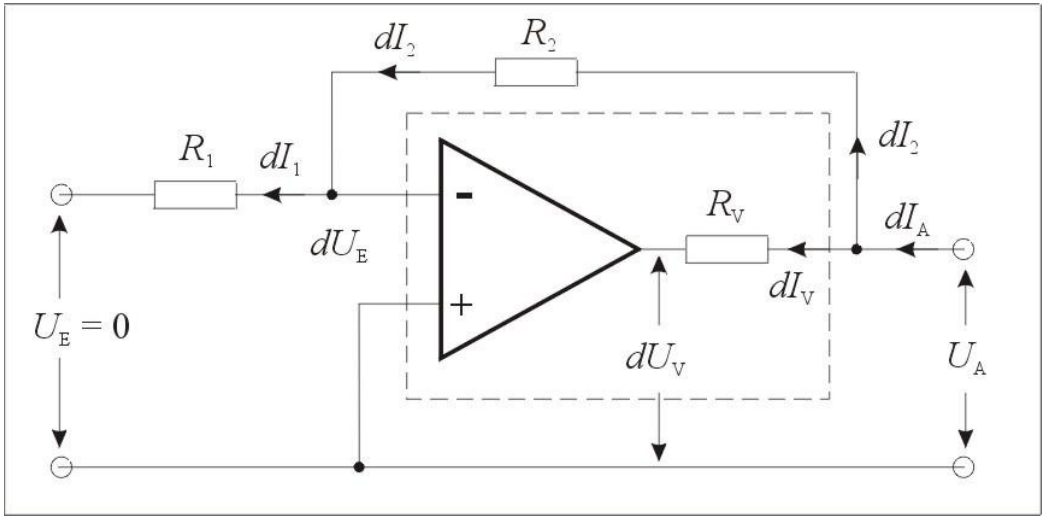
- large open-loop gains facilitates feedback loops

Inverting Amplifier

- Using KCL:

$$I_1 = I_2 + I_E$$

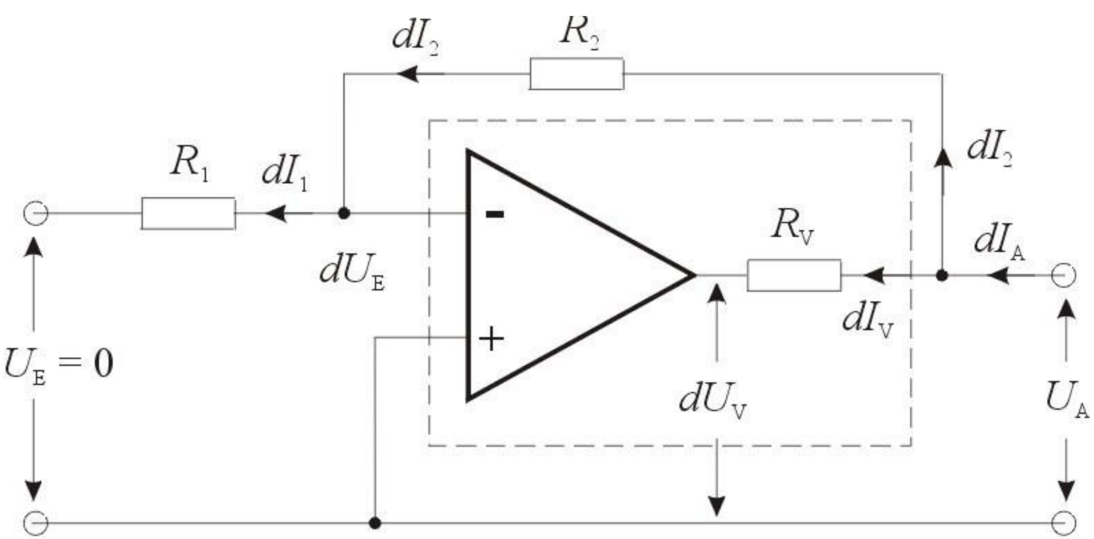
- Simple derivation...

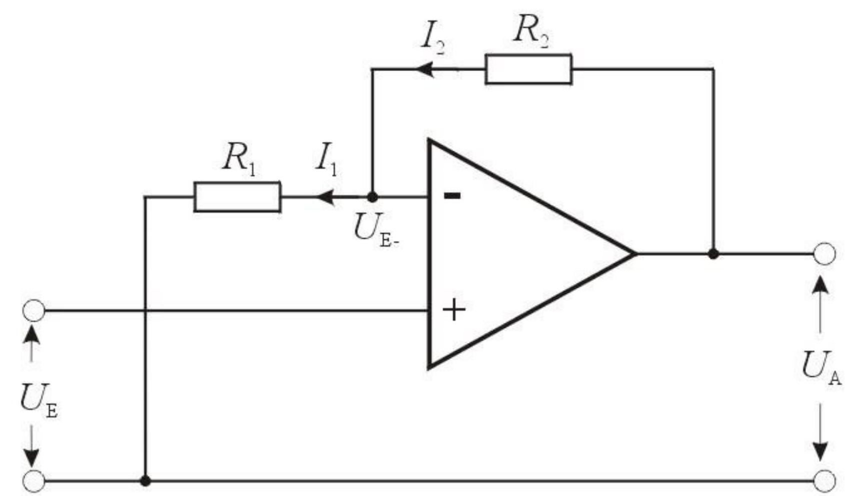


For v >>> 1

$$U_A = -\frac{R_2}{R_1} U_E$$

Common OpAmp Circuits I/II





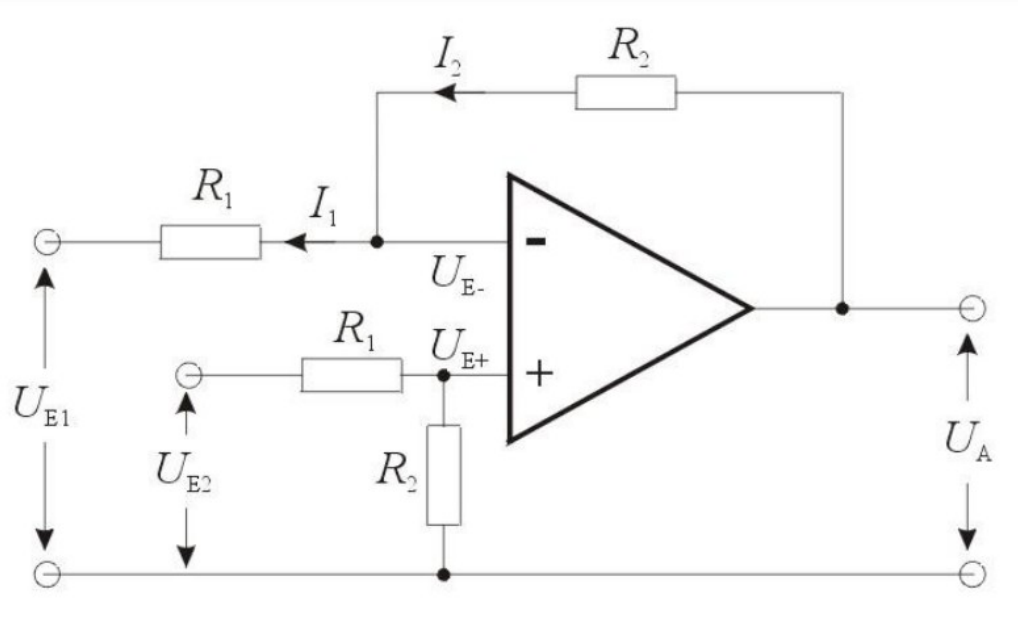
For v >>> 1

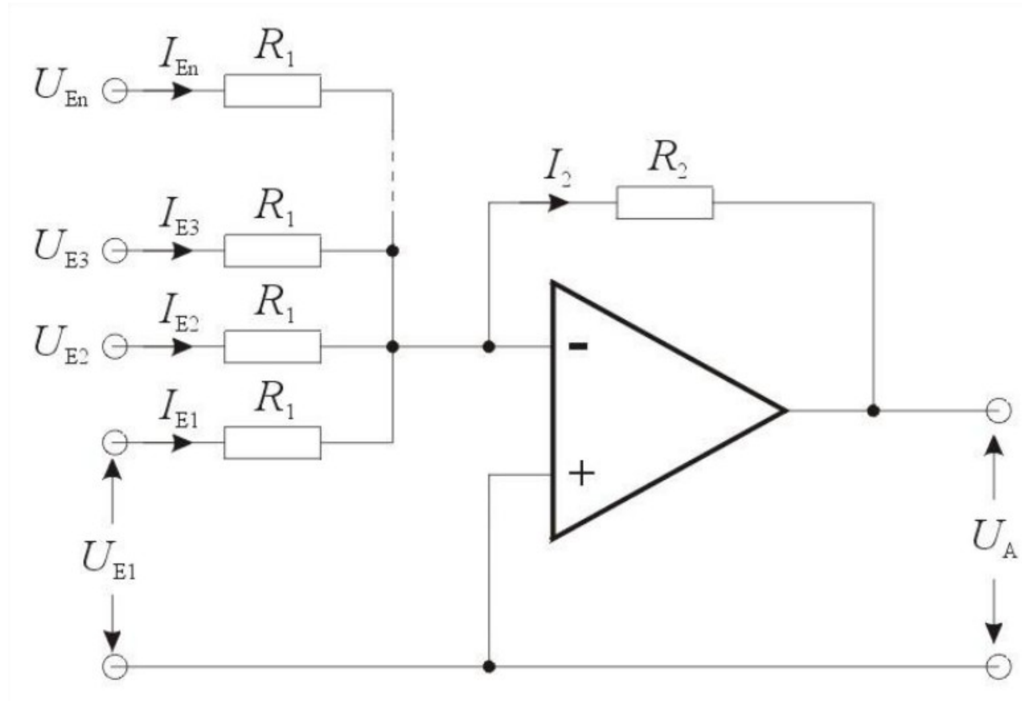
$$U_A = -\frac{R_2}{R_1} U_E$$

$$U_A = \frac{R_1 + R_2}{R_1} U_E$$

http://en.wikipedia.org/wiki/Operational_amplifier_applications
http://www.ti.com/ww/en/bobpease/assets/AN-31.pdf

Common OpAmp Circuits II/II



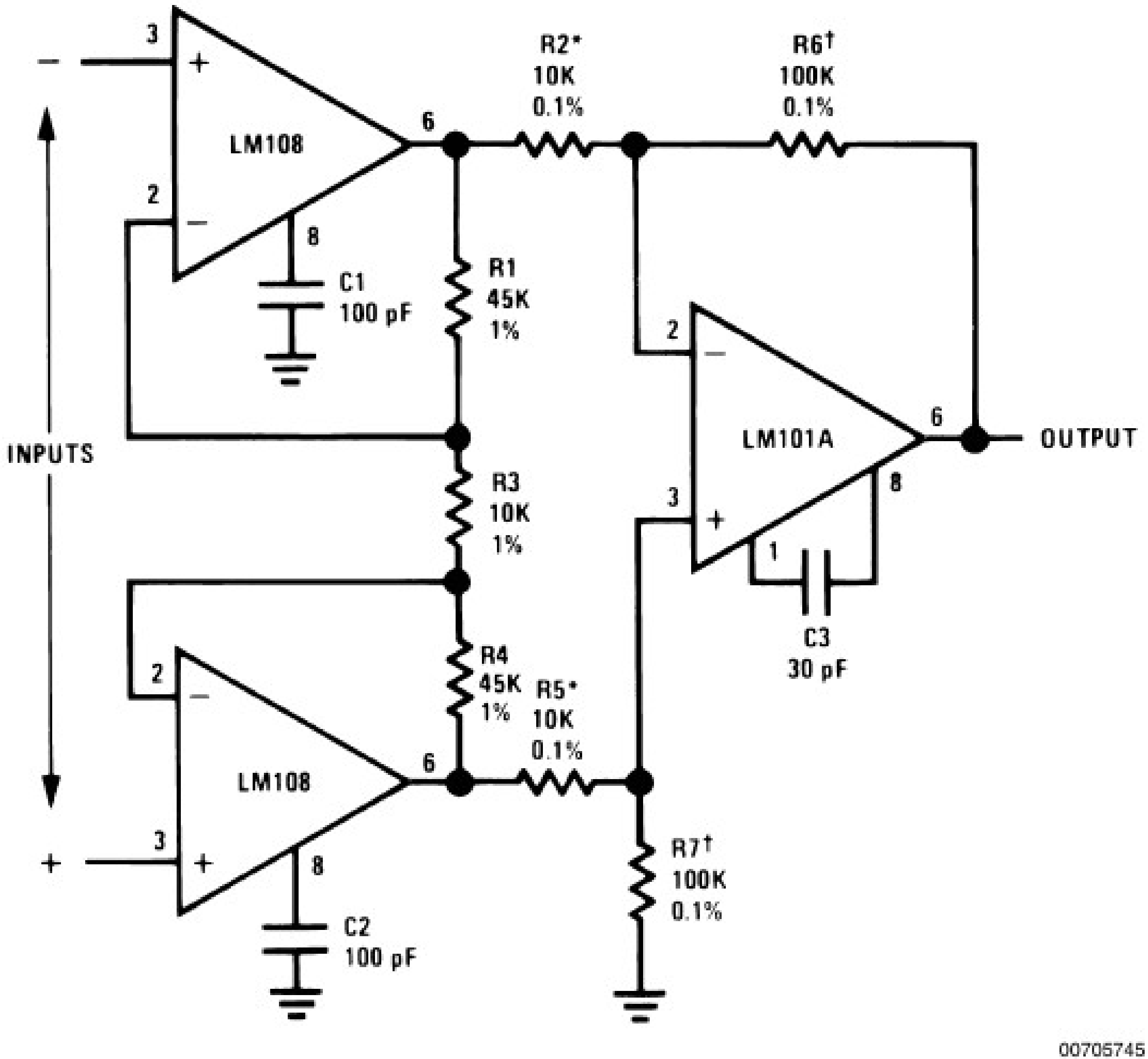


$$U_A = \frac{R_2}{R_1}(U_{E2} - U_{E1})$$

$$U_A = -\frac{R_2}{R_1}\sum_{i=1}^{n} U_{Ei}$$

http://en.wikipedia.org/wiki/Operational_amplifier_applications
http://www.ti.com/ww/en/bobpease/assets/AN-31.pdf

Instrumentation Amplifier



R1 = R4

R2 = R5

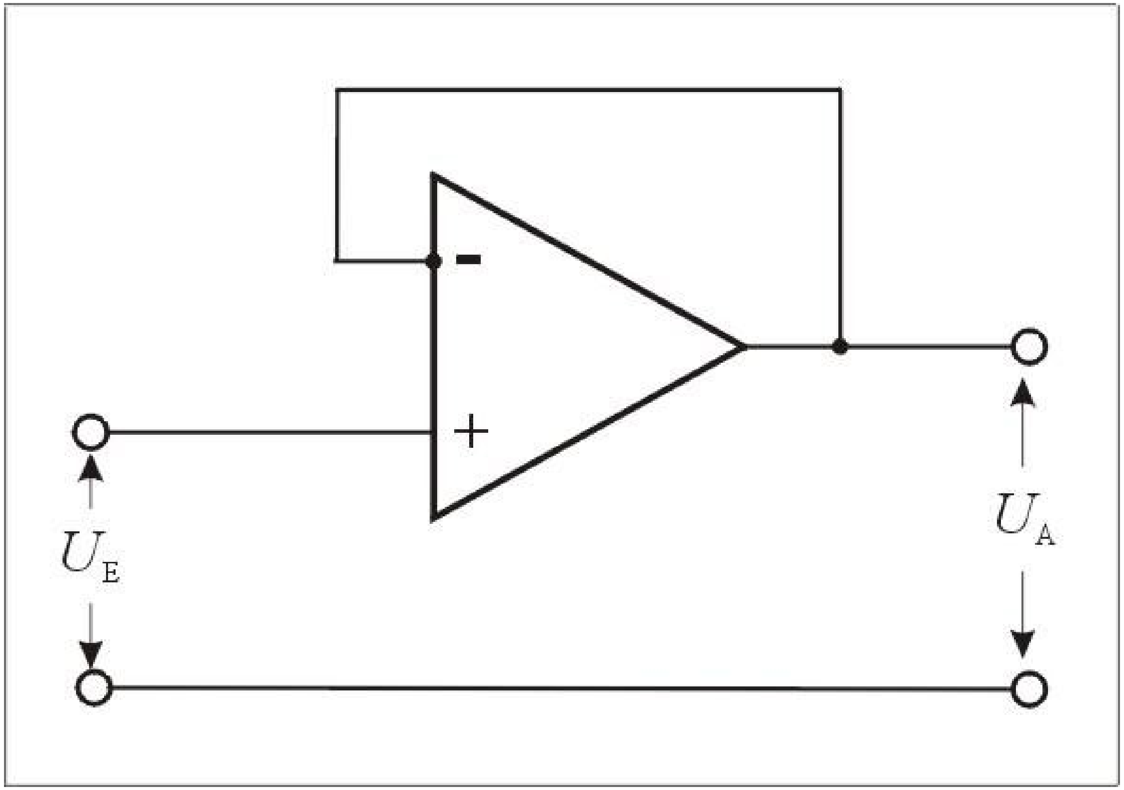
R6 = R7

†*Matching Determines CMRR

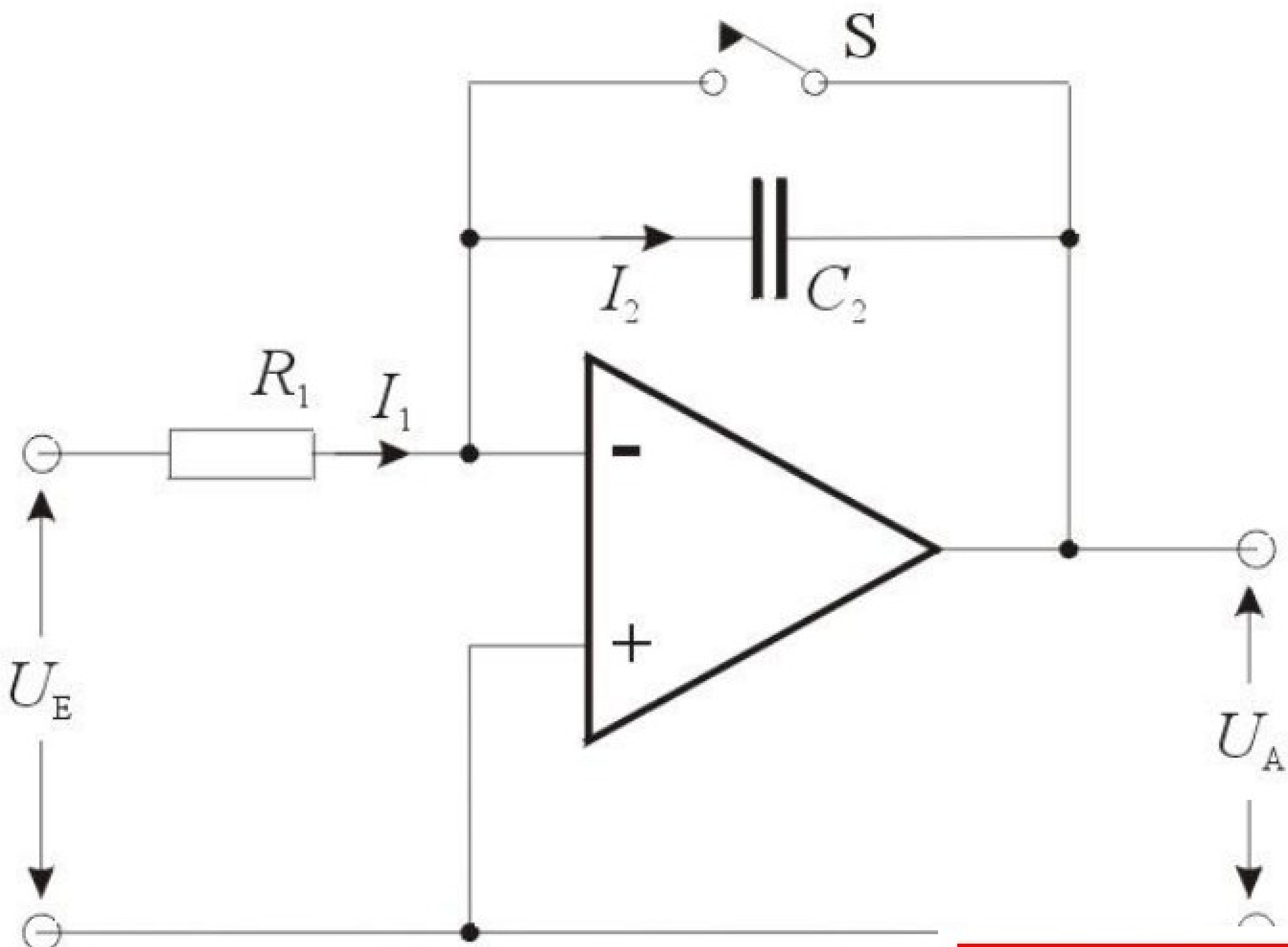
$$A_V = \frac{R6}{R2}\left(1 + \frac{2R1}{R3}\right)$$

Special Case: Voltage Follower

- Buffer: decouples input from output
  - e.g. high-impedance input
  - "drive" low-impedance loads (ie. provide large currents)



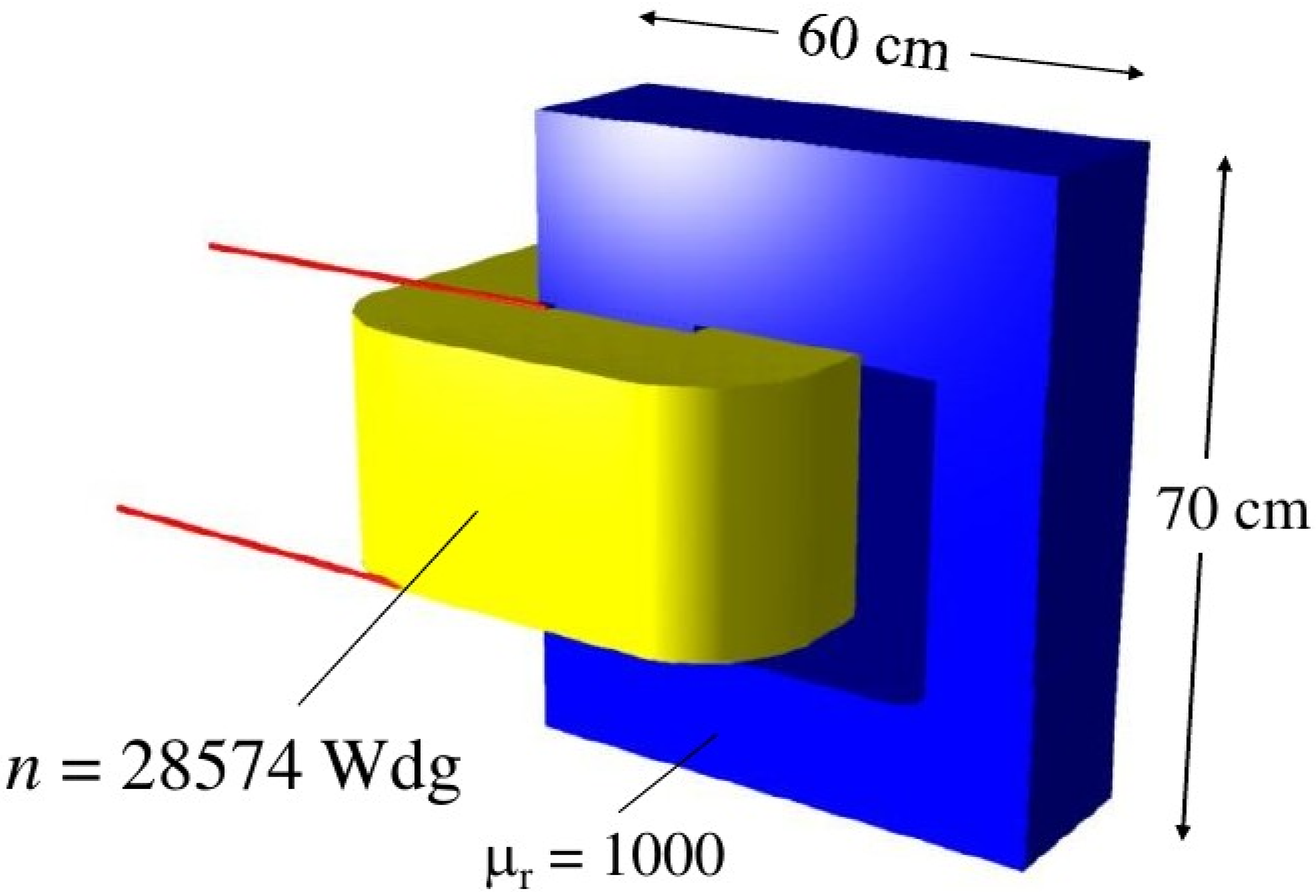
Special Case: Integrator



$$U_A(t) = \frac{1}{R_1 C_2} \int_0^t U_E(\tau)\, d\tau + U_0$$

Inductances for very low-Frequencies

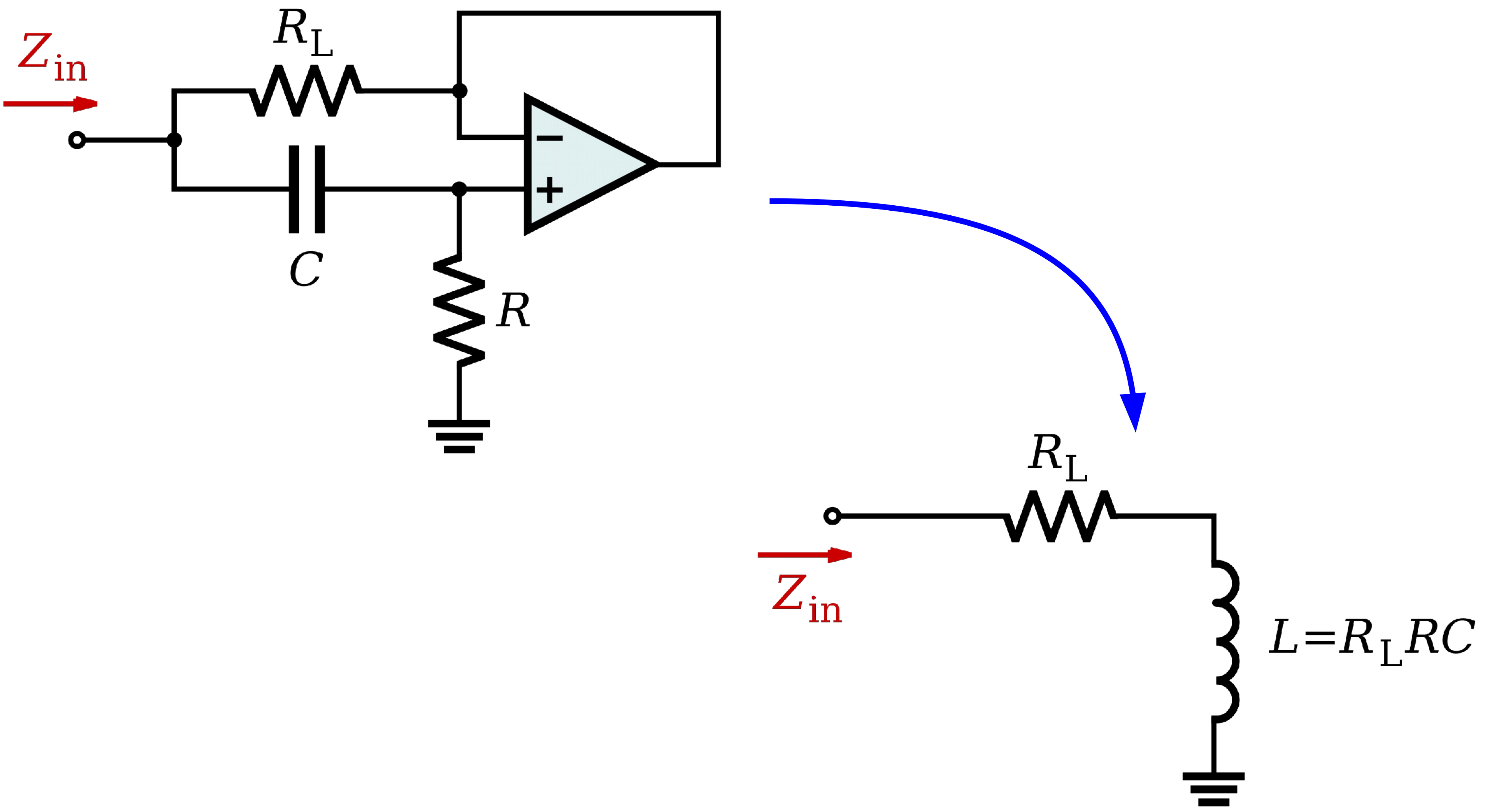
- If you'd need a RLC circuit with e.g. f_0 = 1/3 Hz and C_2=10 μF
  → you'd need an inductance of:



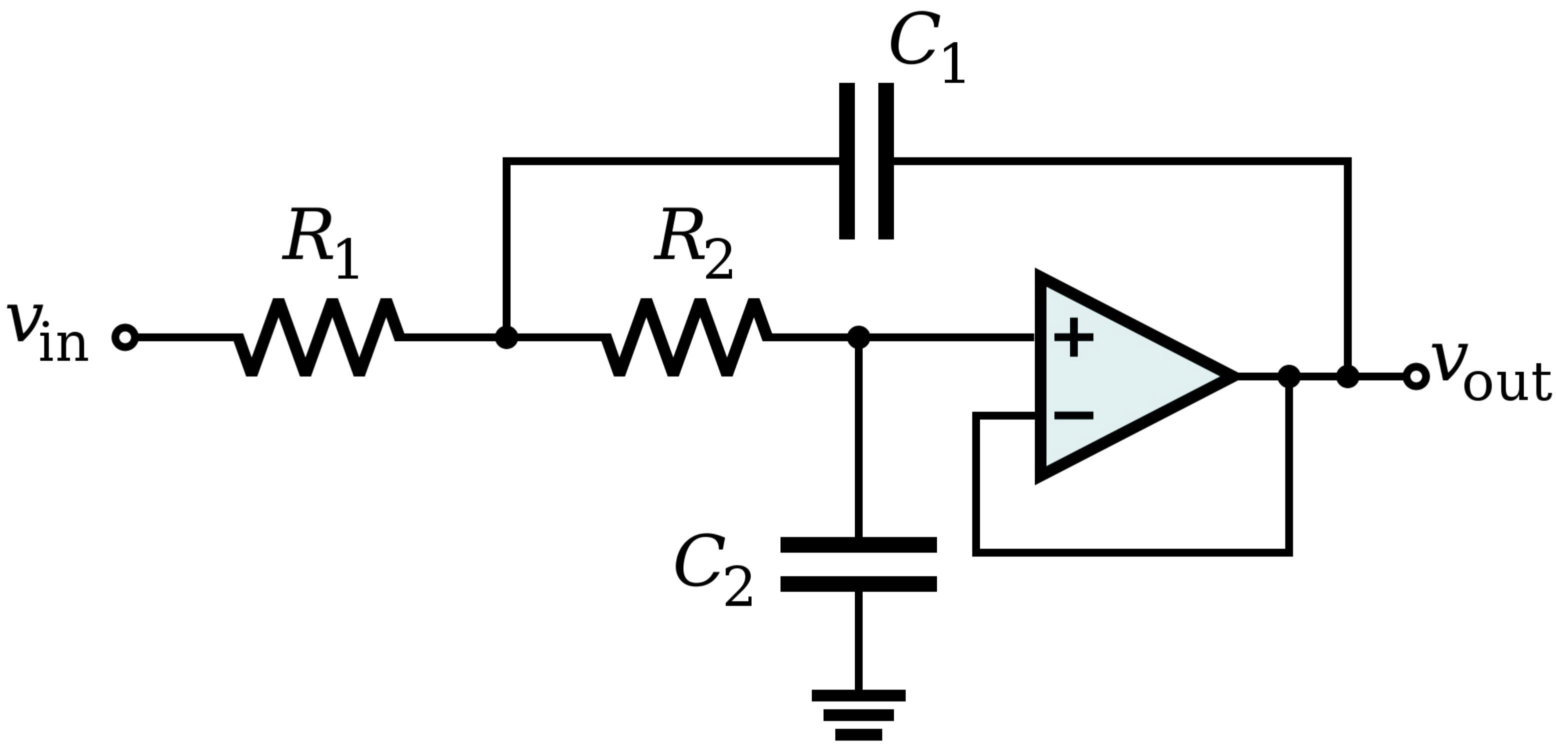
$$L = \frac{1}{\omega_0^2 C_2} = \frac{1}{(2\pi)^2 f_0^{\,2} C_2} = 22800\,\mathrm{H}\,(!)$$

Large Inductances

- Good news: can be simulate using OpAmps (aka. Gyrators)



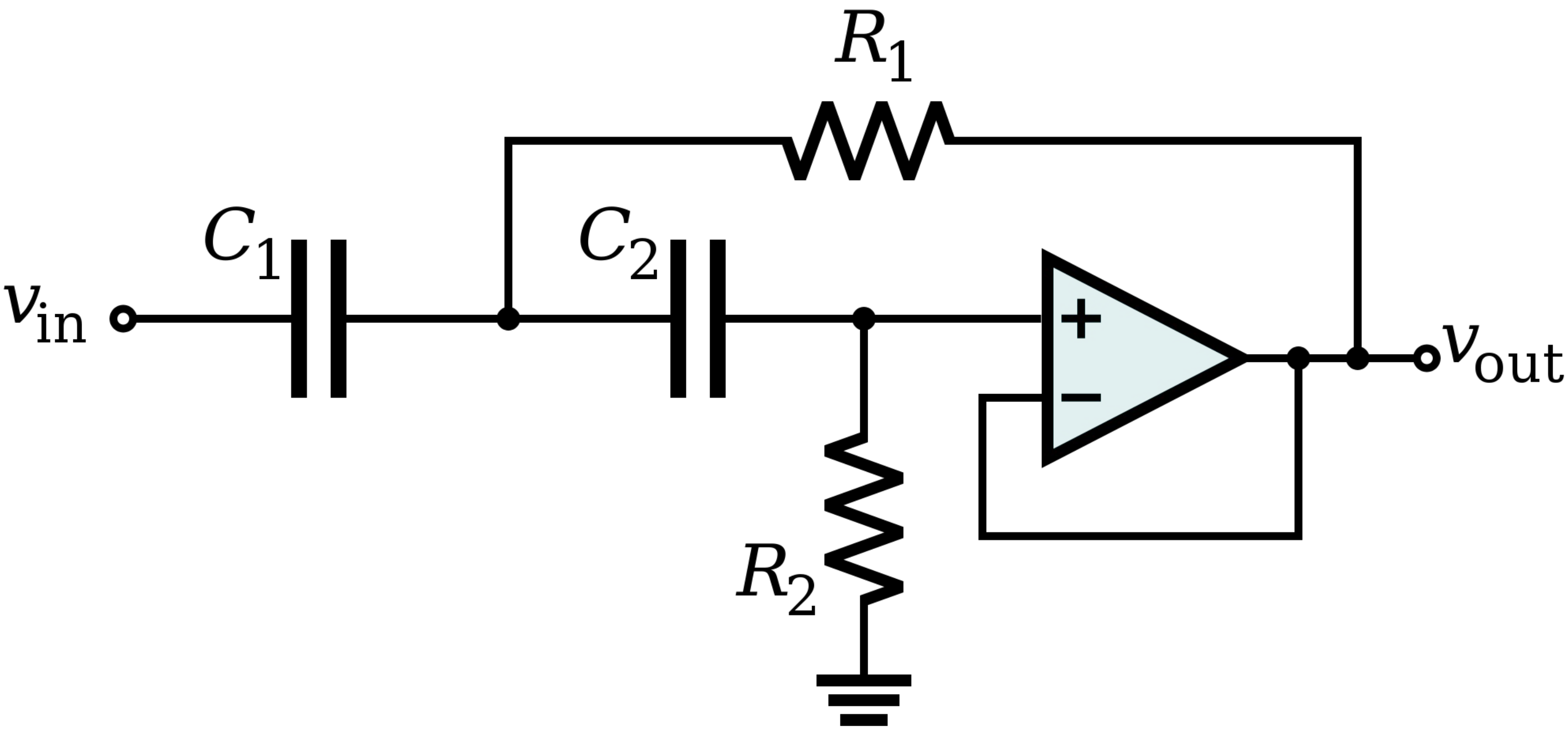
Active Low-Pass Filter (Butterworth)



$$f_{BW} = \frac{1}{2\pi RC}$$

$$assuming: C = C1 = C2 \wedge R = R1 = R2$$

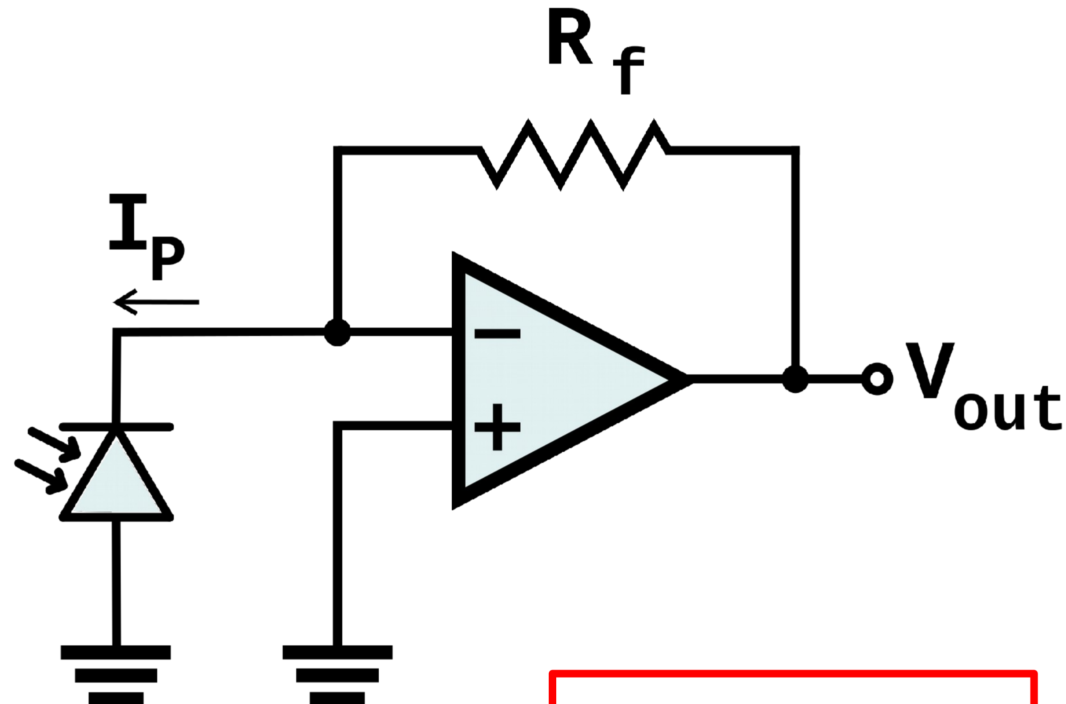
Active High-Pass Filter (Butterworth)



$$f_{BW} = \frac{1}{2\pi RC}$$

$$assuming: C = C1 = C2 \wedge R = R1 = R2$$

Transimpedance Amplifier



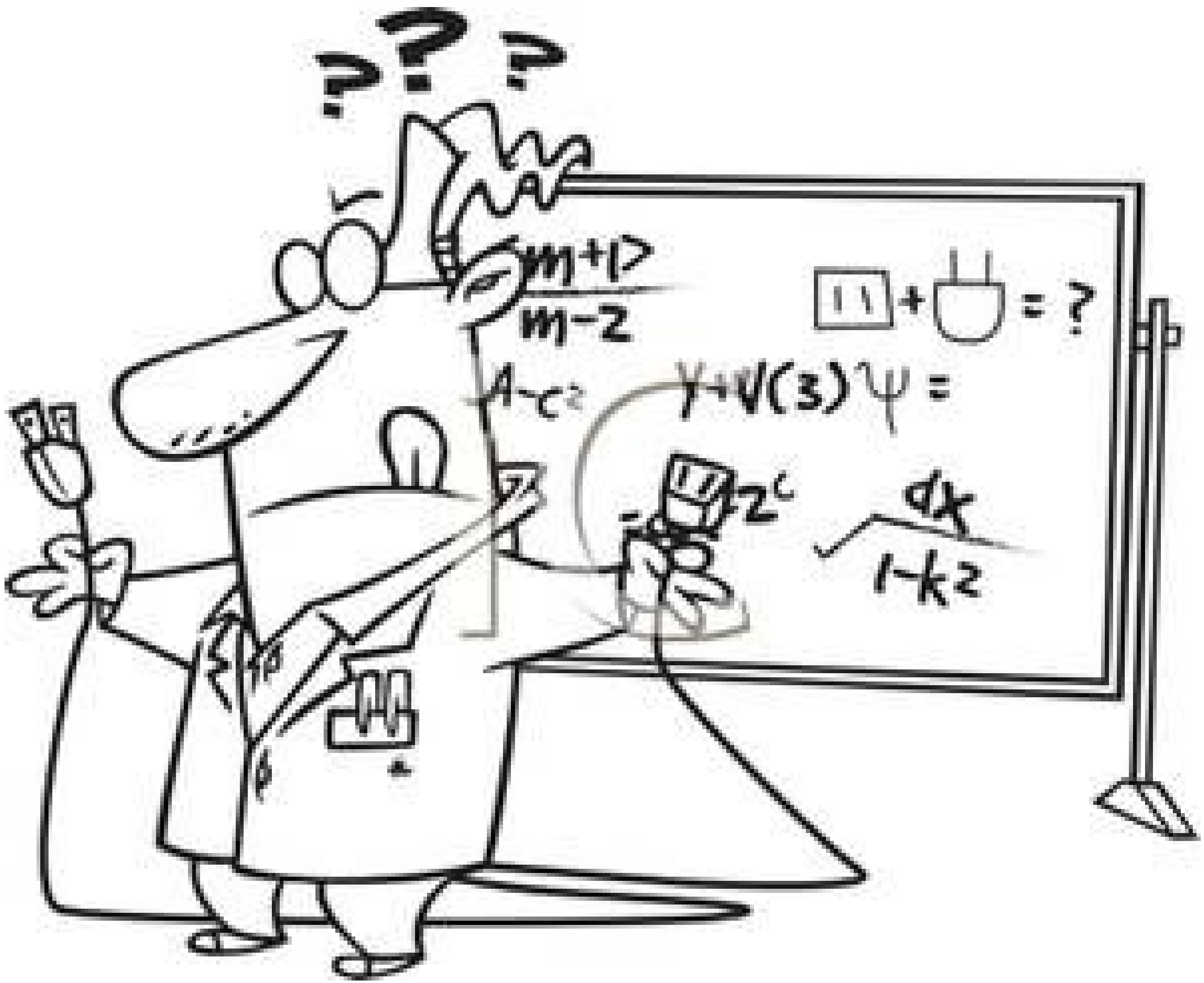
$$V_{out} = R_f \cdot I_P$$

$$f_{BW} = \sqrt{\frac{GBW}{2\pi R_f C_d}}$$

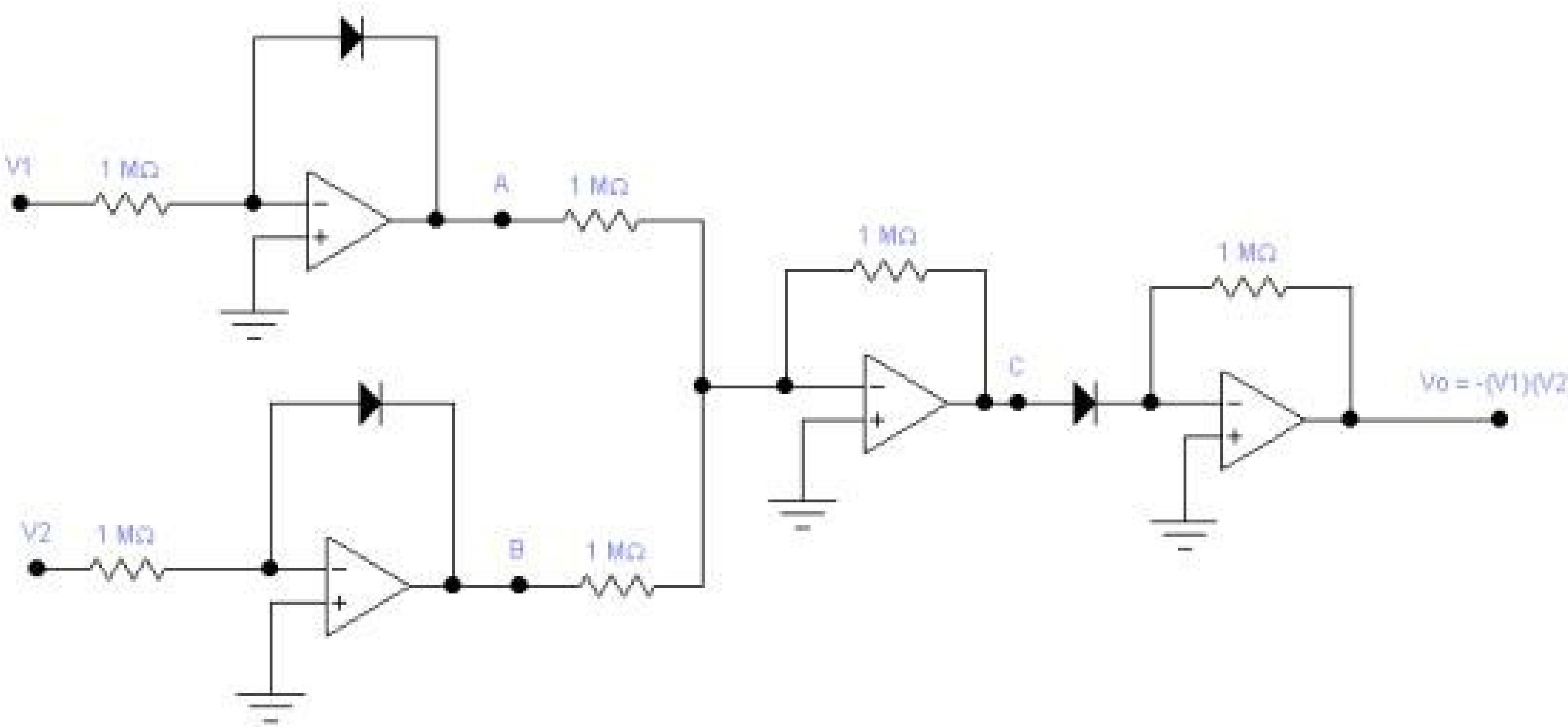
Transimpedance Amplifier with Noise

- TIA with noise sources and imperfections
- Comparison between photodetector receiver using simple R (RC low-pass limit) vs. TIA

Questions?

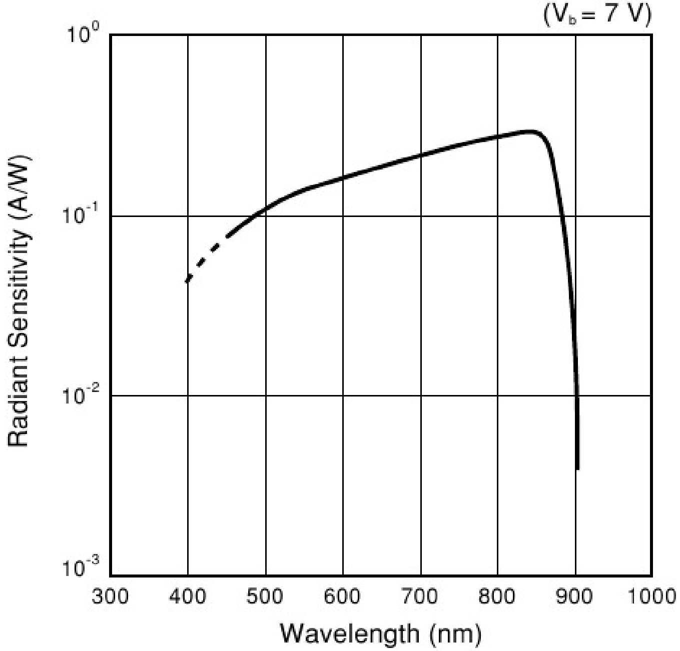


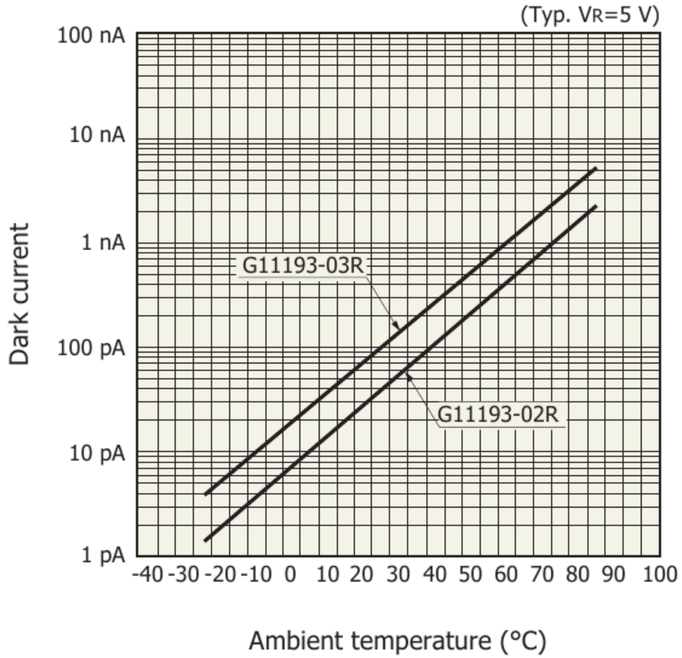
What does this Circuit do?



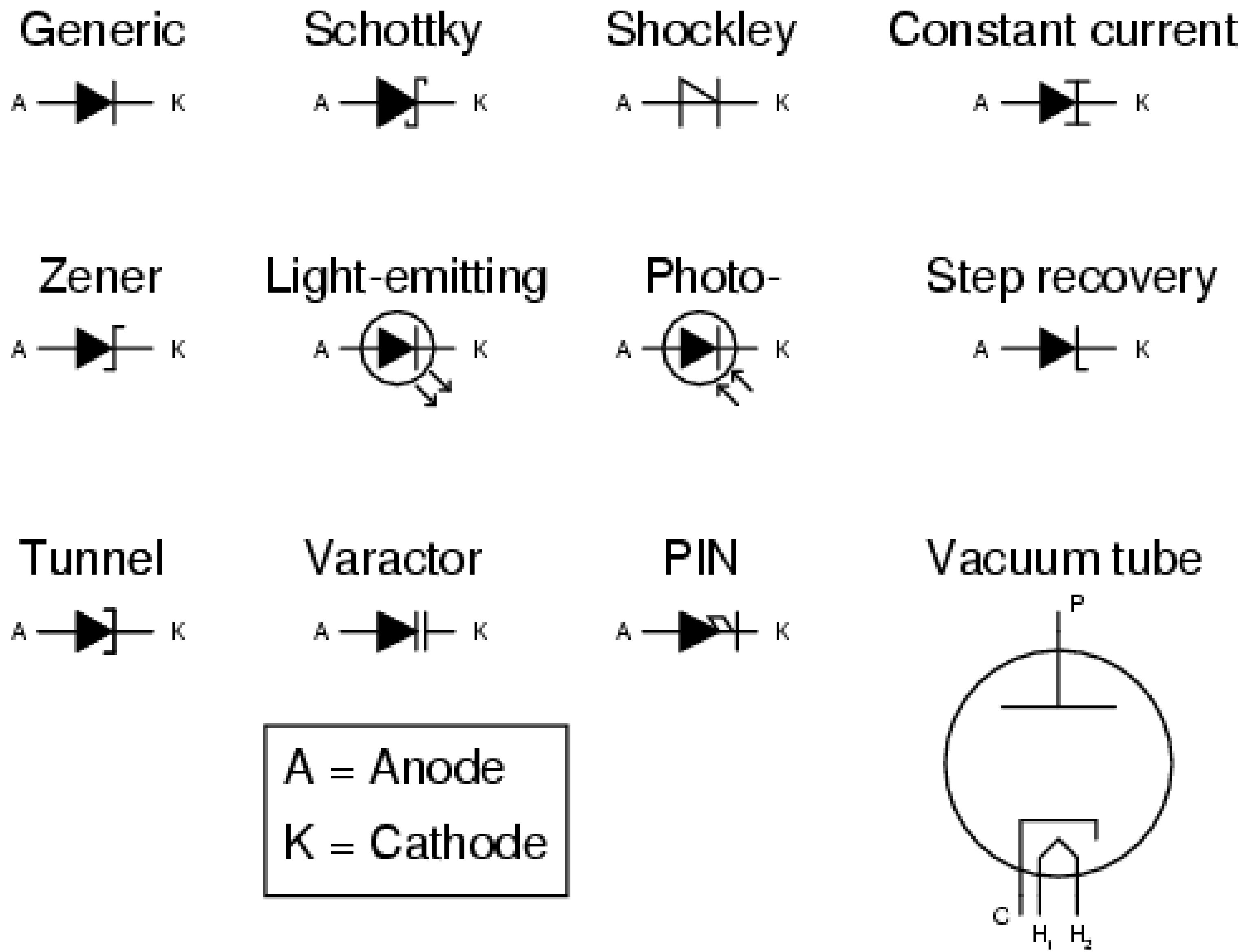
Metal-Semiconductor-Metal (MSM) Photodetector

- Hamamatsu's G4176-03
  - $t_r \approx$ 30 ps ↔ nom. 50% atten. @12GHz
  - 0.3 pF for active area of 0.2 x 0.2 mm²
  - typ. light input power ~5-10 mW (50% duty-cycle)
  - dark-current: 100 pA @23°C
  - max. est. S/N: ~150 dB (w/o cooling)

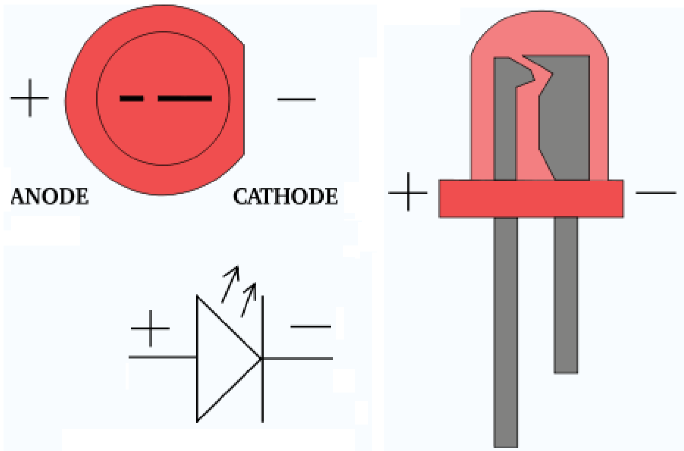


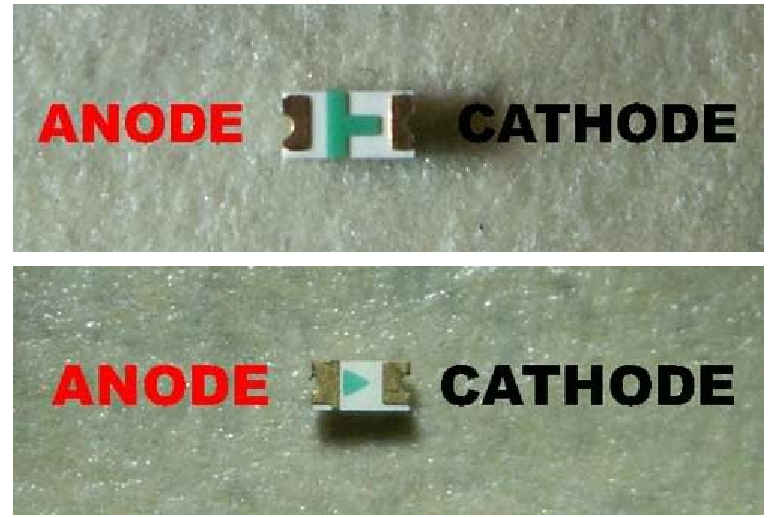


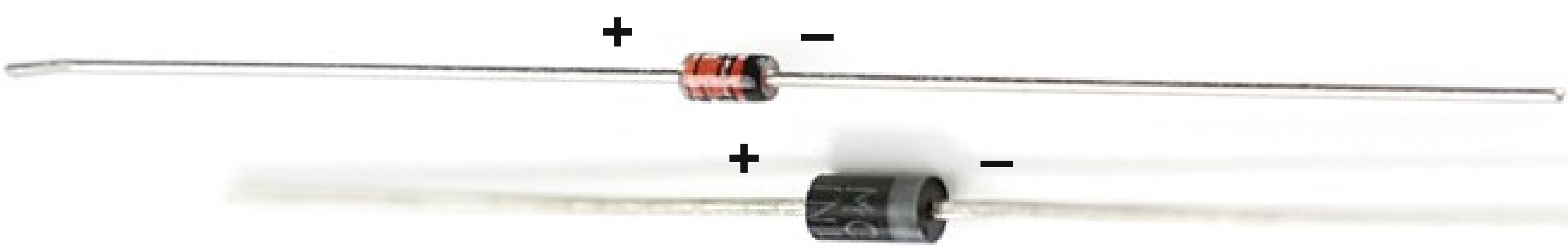
Diode Types II/II



Diode – Polarity



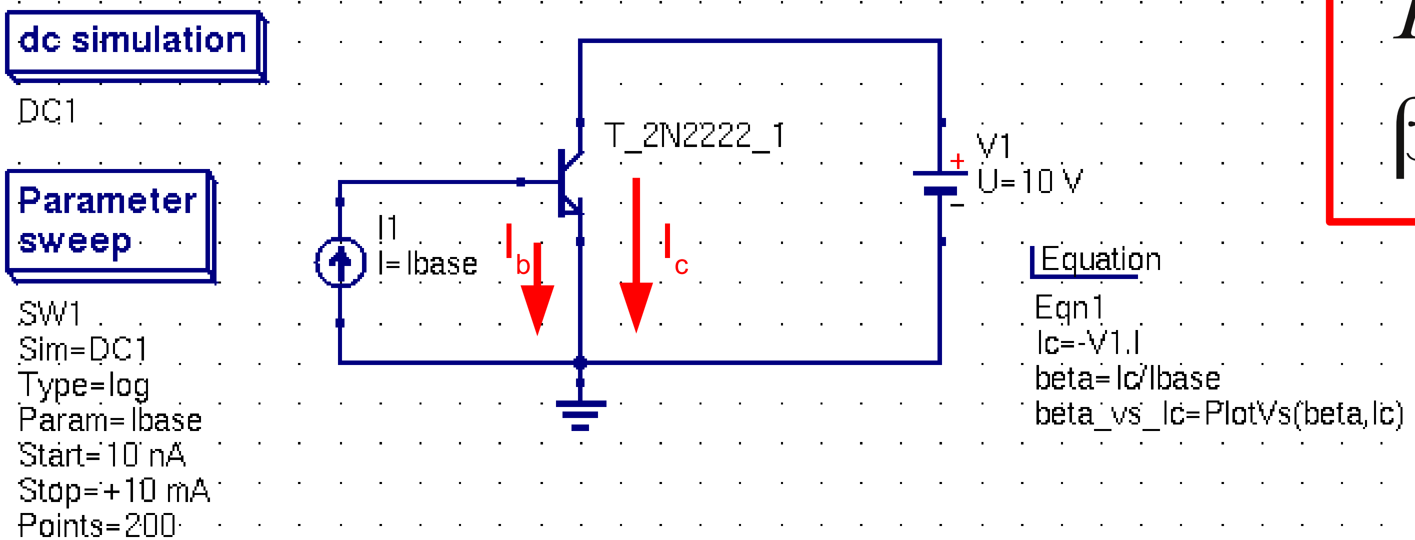


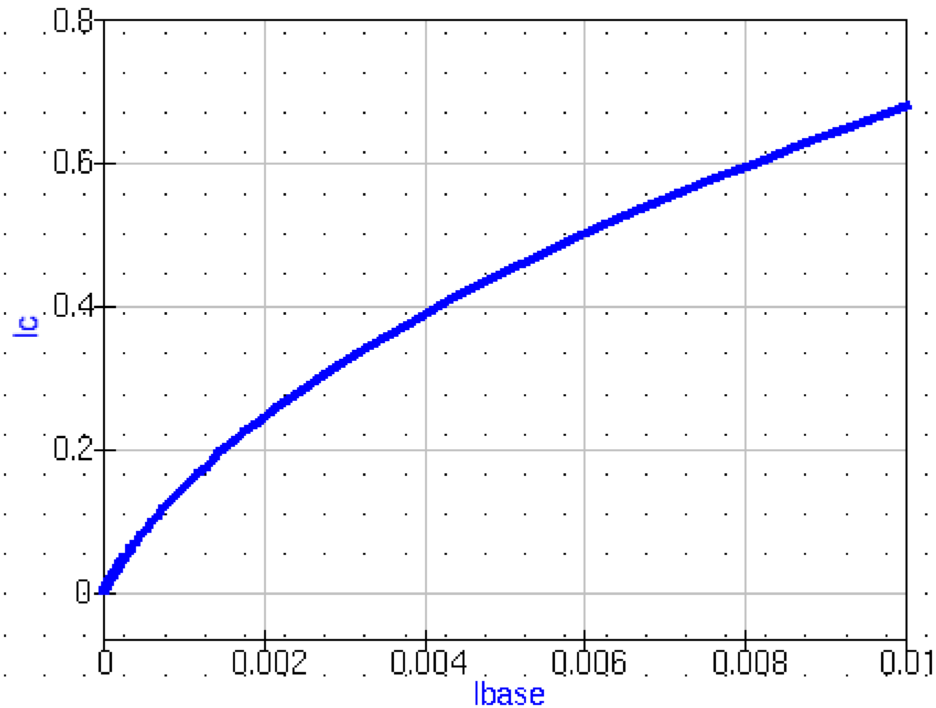


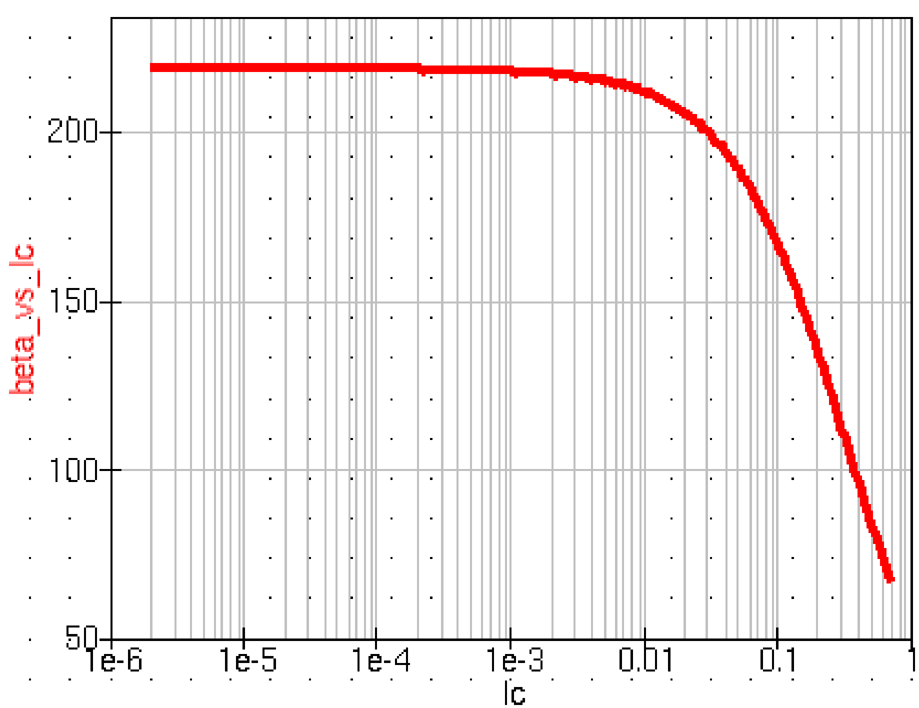
Transistor – Example I/II

$$I_C = \beta \cdot I_b$$

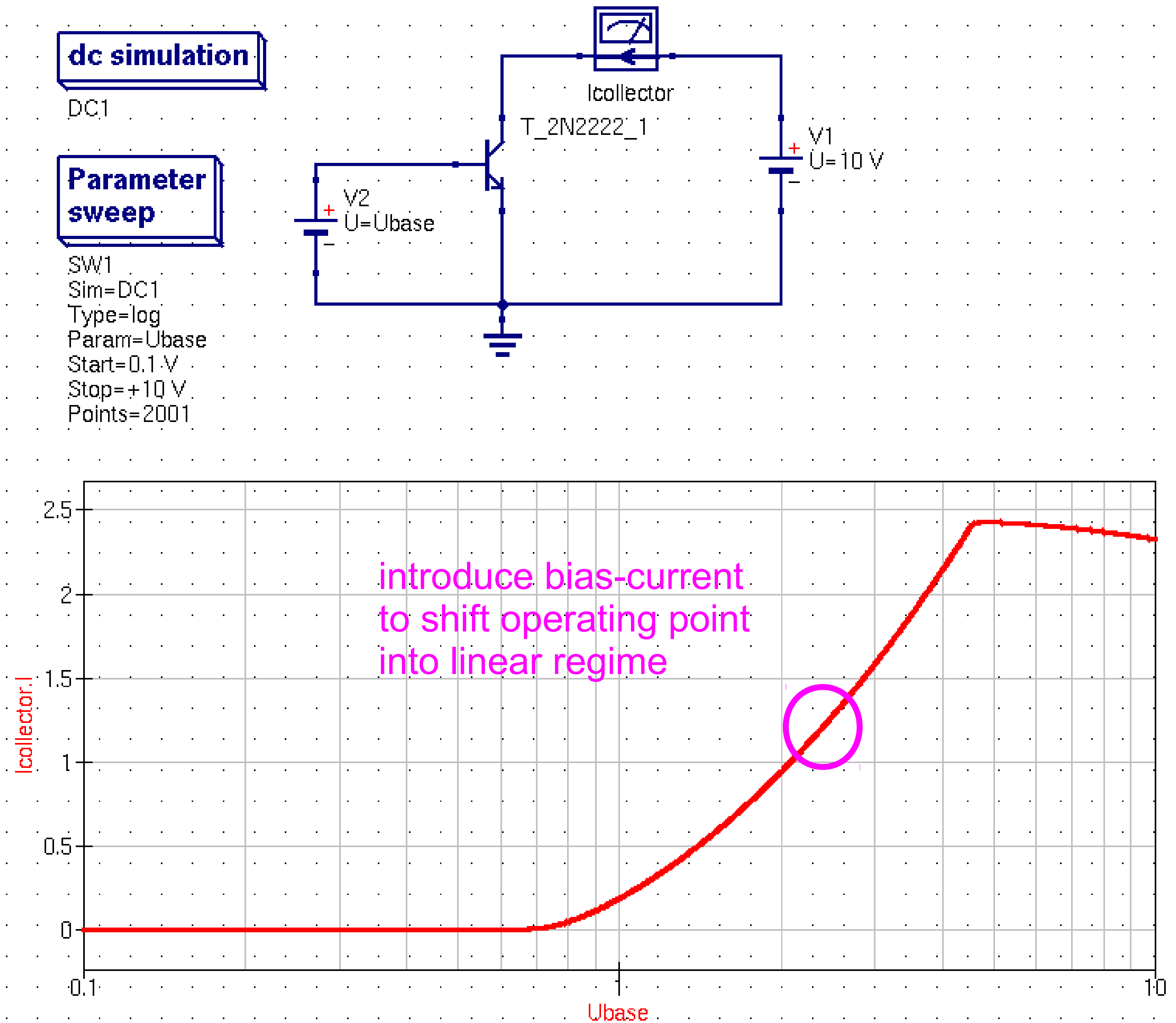
$$\beta \approx 100$$



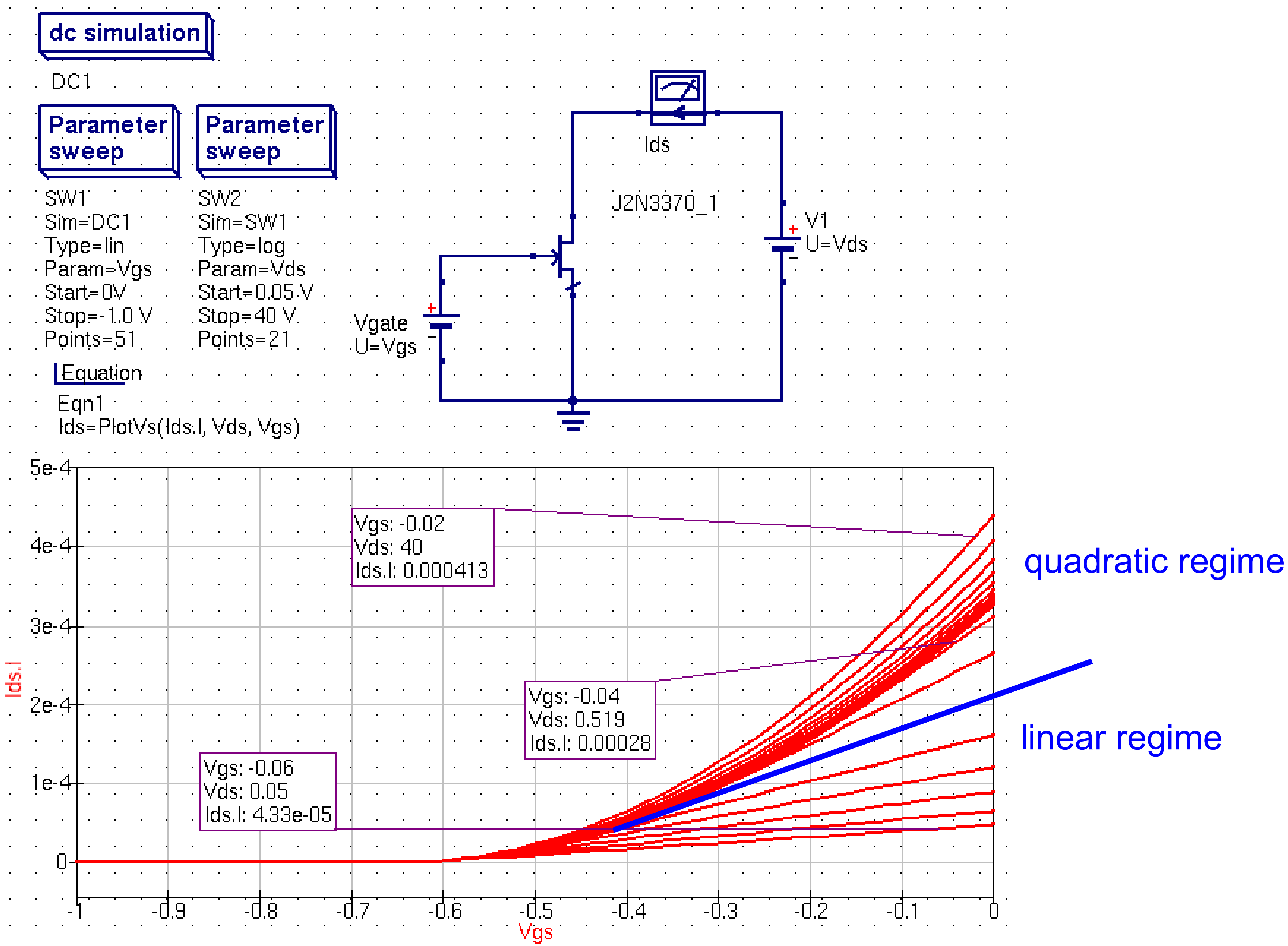




Transistor – Example II/II



FET III/III


dc simulation
DC1
Parameter sweep
SW1
Sim=DC1
Type=lin
Param=Vgs
Start=0V
Stop=-1.0 V
Points=51
Parameter sweep
SW2
Sim=SW1
Type=log
Param=Vds
Start=0.05 V
Stop=40 V
Points=21
Equation
Eqn1
Ids=PlotVs(Ids.I, Vds, Vgs)
Ids
J2N3370_1
V1
U=Vds
Vgate
U=Vgs
Vgs: -0.02
Vds: 40
Ids.I: 0.000413
Vgs: -0.04
Vds: 0.519
Ids.I: 0.00028
Vgs: -0.06
Vds: 0.05
Ids.I: 4.33e-05
Ids.I
Vgs
quadratic regime
linear regime