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University of
Applied Sciences

Fakultät für
Elektro- und
Informationstechnik

High-Performance Operational Amplifier with Rail-to-Rail Output for HPGe Radiation Detectors

IHP Workshop on OpenPDK, 27.06.2023

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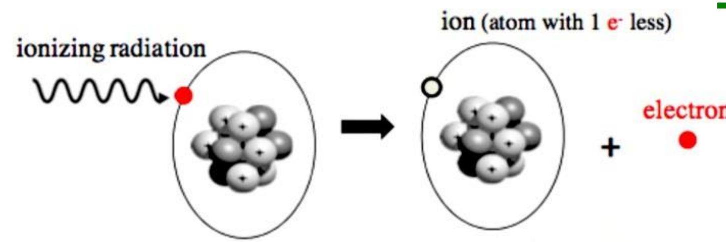
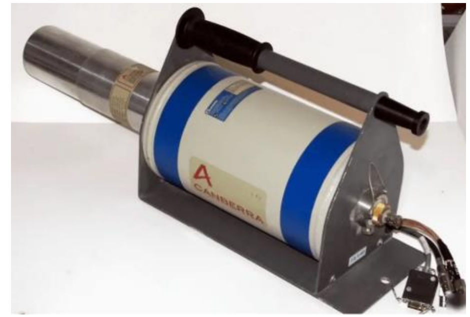
Outline

- Introduction
- HPGe Detector with Front-end Electronics
- Design Challenges in Modern CMOS Technology
- High Gain Folded-Cascode Operational Amplifier
- Simulation Results
- Design Concepts and Tools
- Funded Projects and Team
- Summary

Introduction - Semiconductor Detectors

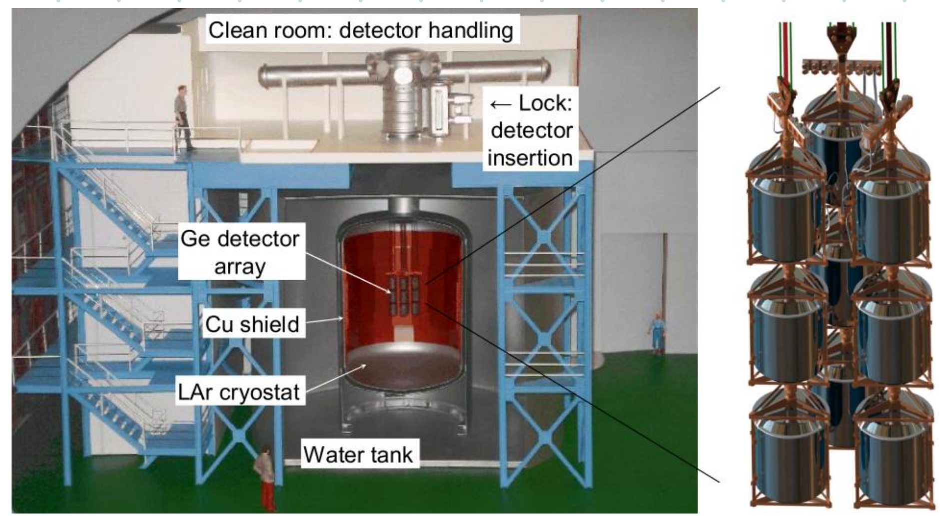
- Semiconductor is best suitable for detection and measurement of radiation energy.
- When elementary particles or photons interact with semiconductor material, charge carriers (electron-hole pairs) are created.
- Germanium detectors achieving highest resolution are used in a variety of applications including personnel and environmental monitoring for radioactive contamination, medical applications, space research/exploration.





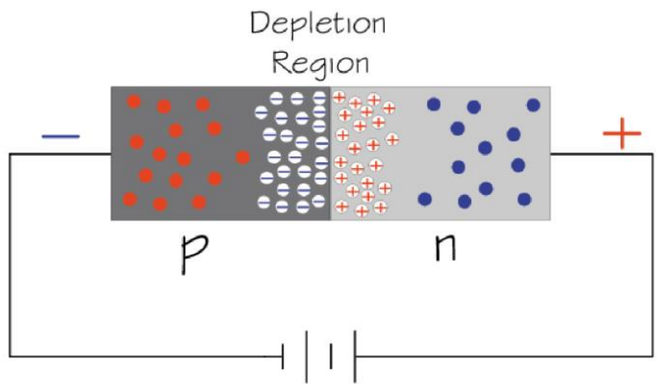
HPGe detector with LN_2 cryostat
Source: canberra.com

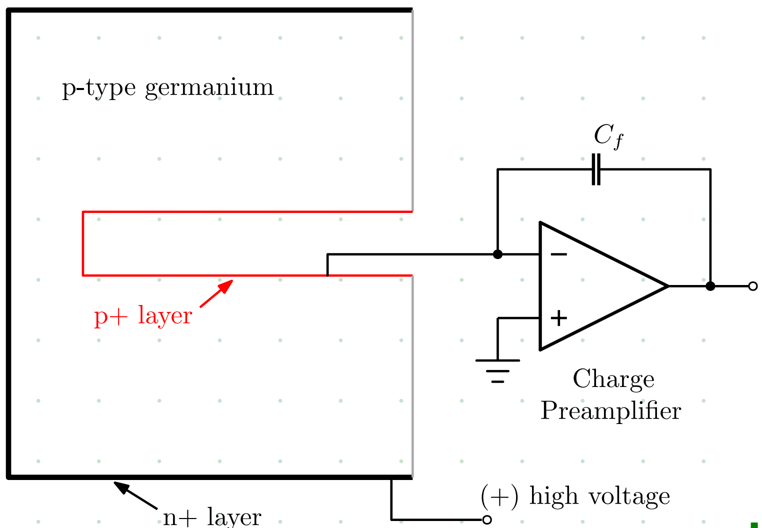
Setup of GERDA experiment in an underground laboratory
Source:mpi-hd.mpg.de/gerda/



HPGe Detector

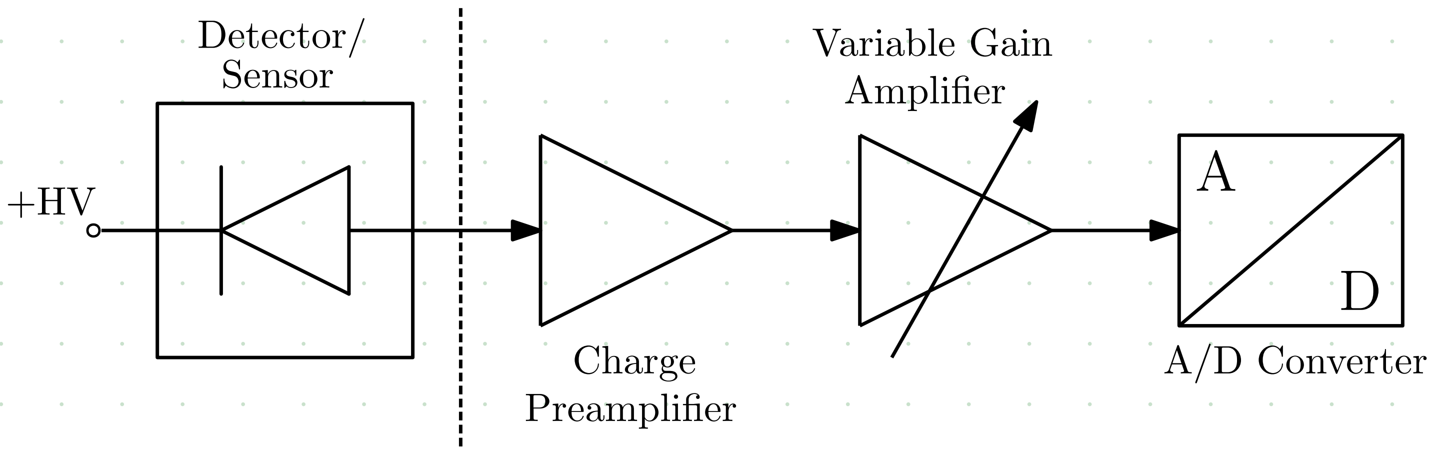
- In order for a semiconductor to act as a radiation detector, the active area to radiation must be free of excess electrical charges (depleted).
- A zone free of charge carriers can be established at p-n-junction, also known as charge depletion region
- By applying a voltage, the depletion zone can be extended to the entire diode → highly insulating layer.
- An ionizing particle produces free charge carriers in the diode, which drift in the electric field and induce an electrical signal on the metal electrodes.
- Electronic circuit is used to collect the charge carriers and convert them into voltage signal





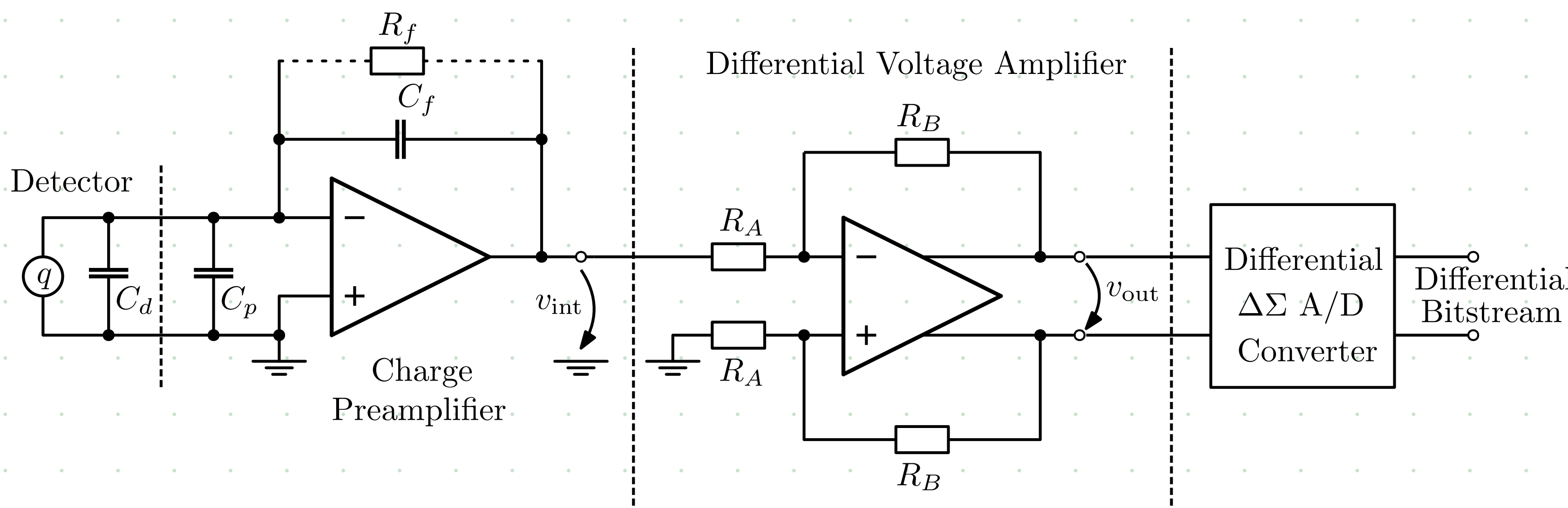
Front-end Electronics for Semiconductor Detector

- Charge generated by the radiation interaction is very small and has to be amplified before any further signal processing.
- Charge preamplifier must be placed very close to detector and has to provide a high-degree of radio-purity
  - Discrete front-end electronics is undesired due to the large amount of copper of PCB that can falsify the radiation information.
  - Integrated miniaturized charge amplifier is crucial



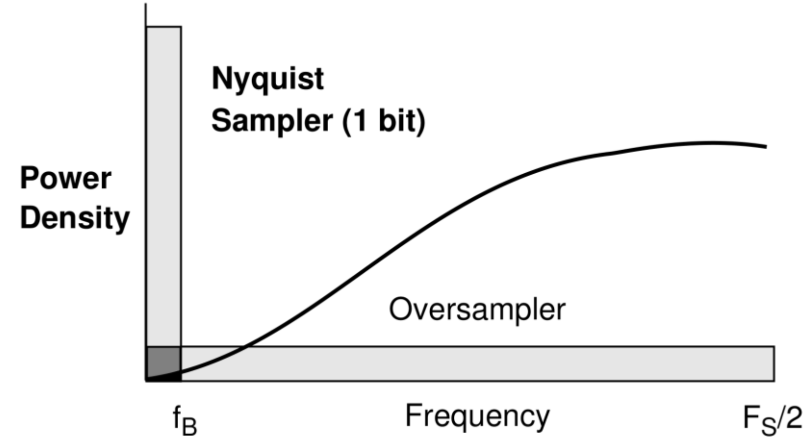
Charge Amplifier

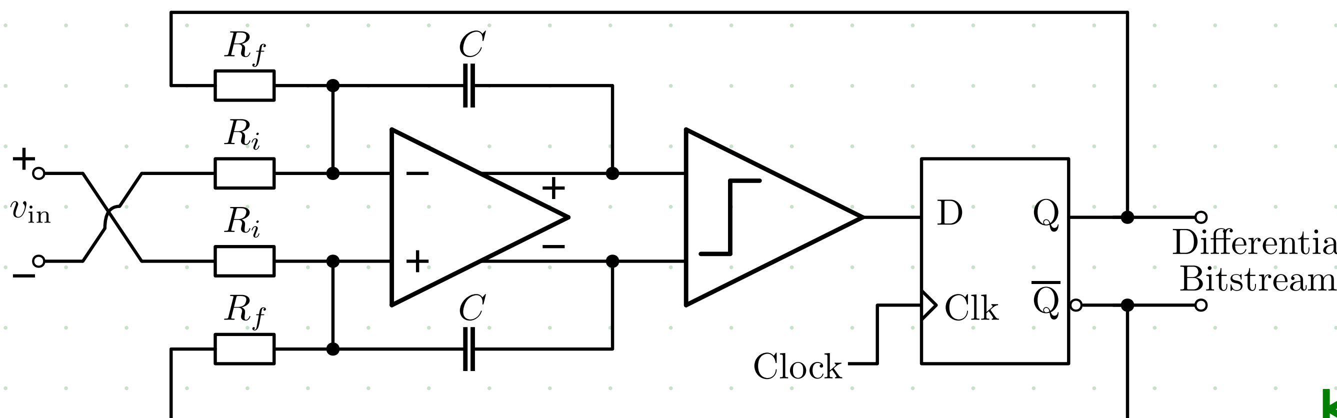
- The detector can be modelled as a charge generator q and a capacitor C_d in parallel.
- Using an integrator in combination with an operational amplifier, the charge generated by an incident can be read out as a voltage.
  - The output of the integrator is proportional to q / C_f and is insensitive to parasitic capacitances
- Fully differential voltage amplifier is used to increase the output swing and to match the output to the maximum input range of the A/D converter.



ΔΣ - Modulator - based A/D Converter

- High signal-to-noise-ratio (SNR) is possible by means of oversampling and noise shaping.
  - Quantization noise power is lower and spread over a much larger oversampling frequency range
  - The noise shaper shifts the quantization noise to higher frequency that can easily be filtered out
- Requires only a few components / building blocks that can be easily integrated on chip





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Design Challenges in Modern CMOS Technology

- Quite high channel-length modulation λ (in the range of 0.1 … 0.5V^{-1})
  - Output resistance is quite low ohmic

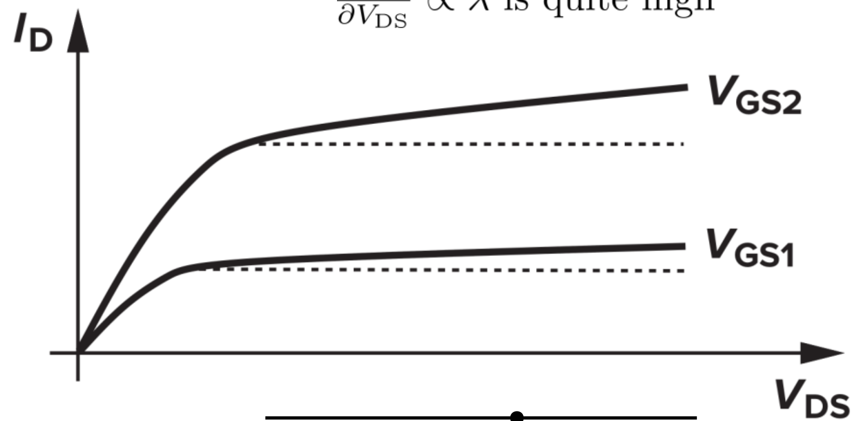
$$r_o = \frac{1}{\lambda I_D} \approx 10k\Omega \ldots 50k\Omega$$

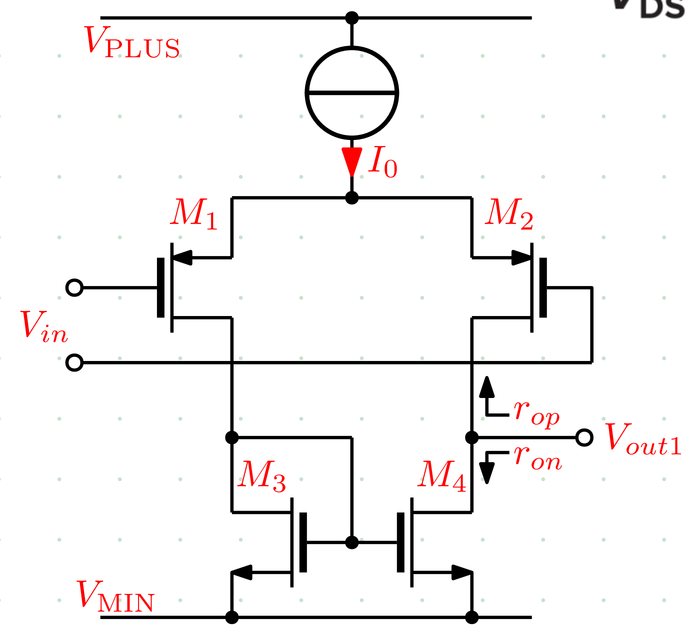
  - Low voltage gain of single-stage amplifier

$$A_v = g_{mp}\left(r_{op}||r_{on}\right) \approx 5 \ldots 75$$

  - Cascode is indispensable

$$\frac{\partial I_D}{\partial V_{DS}} \propto \lambda \text{ is quite high}$$





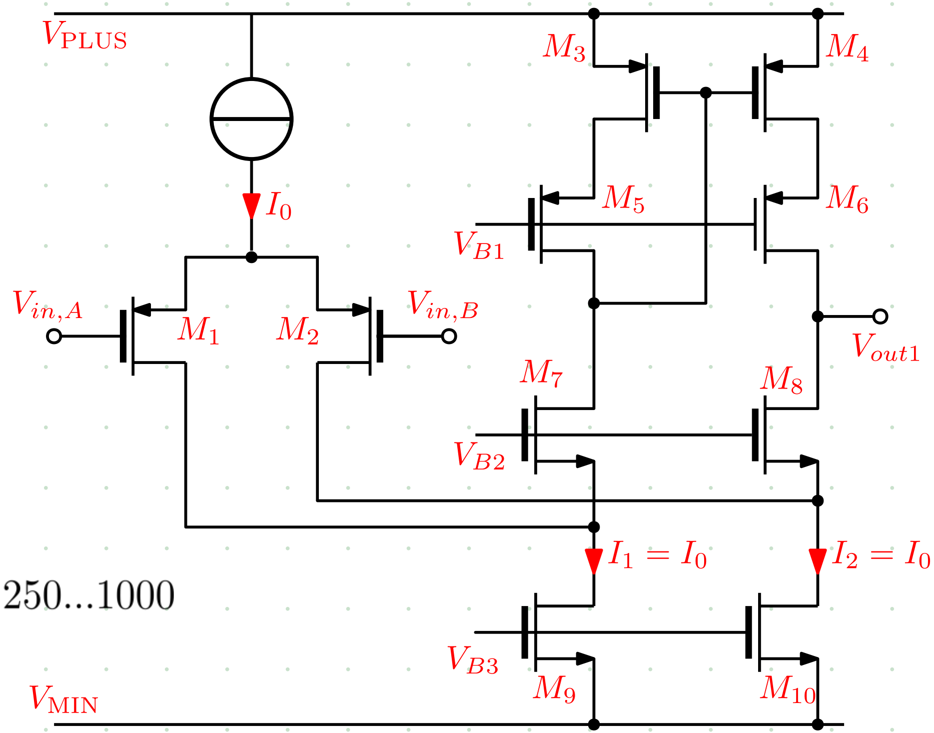
Folded Cascode Differential Amplifier

- Low breakdown voltage of transistors limits the supply voltage
  - Very limited output swing
  - Conventional cascode topology requires large voltage head room
- Low-voltage folded cascode is preferred
  - Output voltage swing

$$V_{\mathrm{PLUS}} - V_{\mathrm{MIN}} - 4\,|V_{\mathrm{OD}}|$$

  - Significant higher voltage gain is possible

$$|A_{v1}| = g_{\mathrm{m2}}\,\{[g_{\mathrm{m8}}\,r_{\mathrm{o8}}\,(r_{\mathrm{o10}}||r_{\mathrm{o2}})]\,||\,[g_{\mathrm{m6}}\,r_{\mathrm{o6}}\,r_{\mathrm{o4}}]\} \approx 250...1000$$



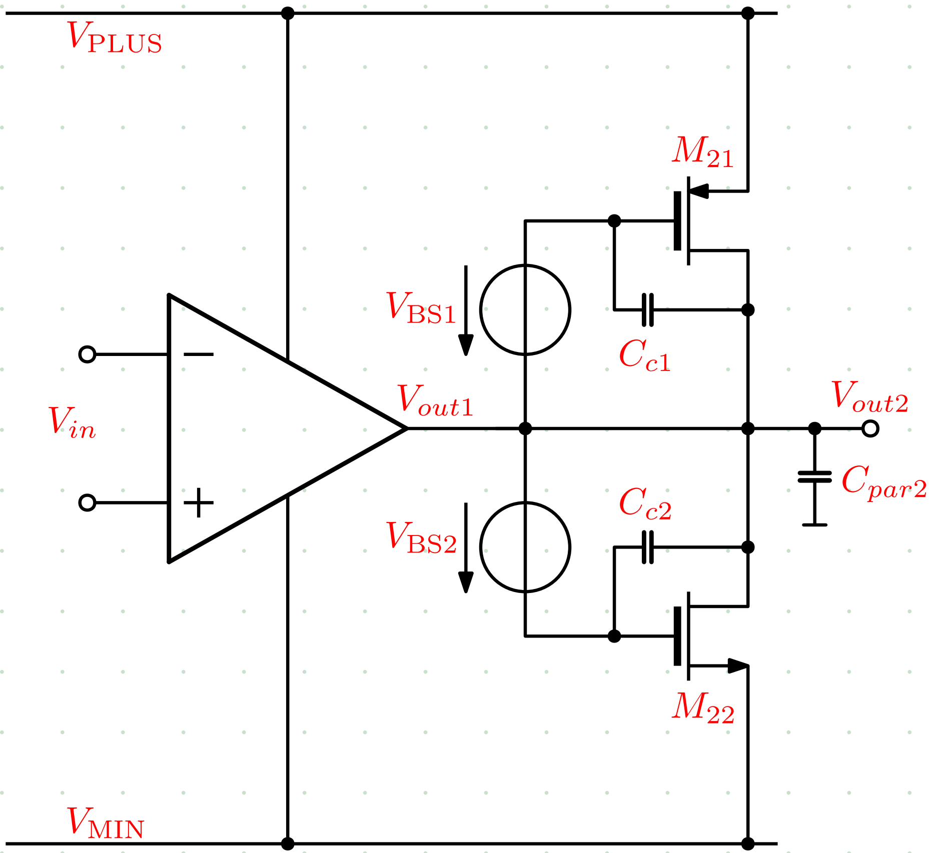
Push-Pull Common-Source Amplifiers as Output Stage

- Very high slew rate
- Rail-to-rail output swing
- Lower output resistance

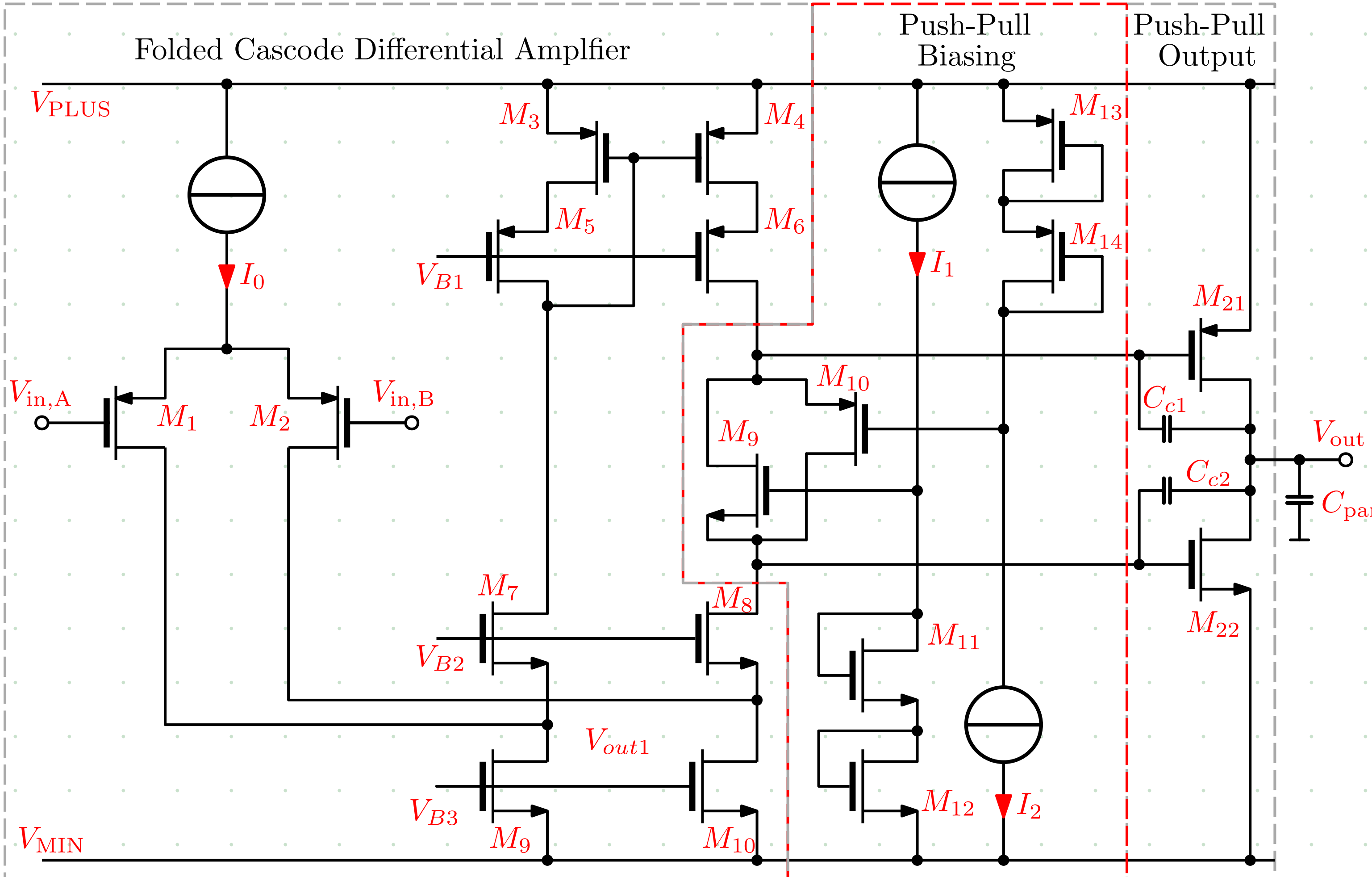
$$r_{\text{out}} = r_{\text{o21}} || r_{\text{o22}}$$

- Increase voltage gain by

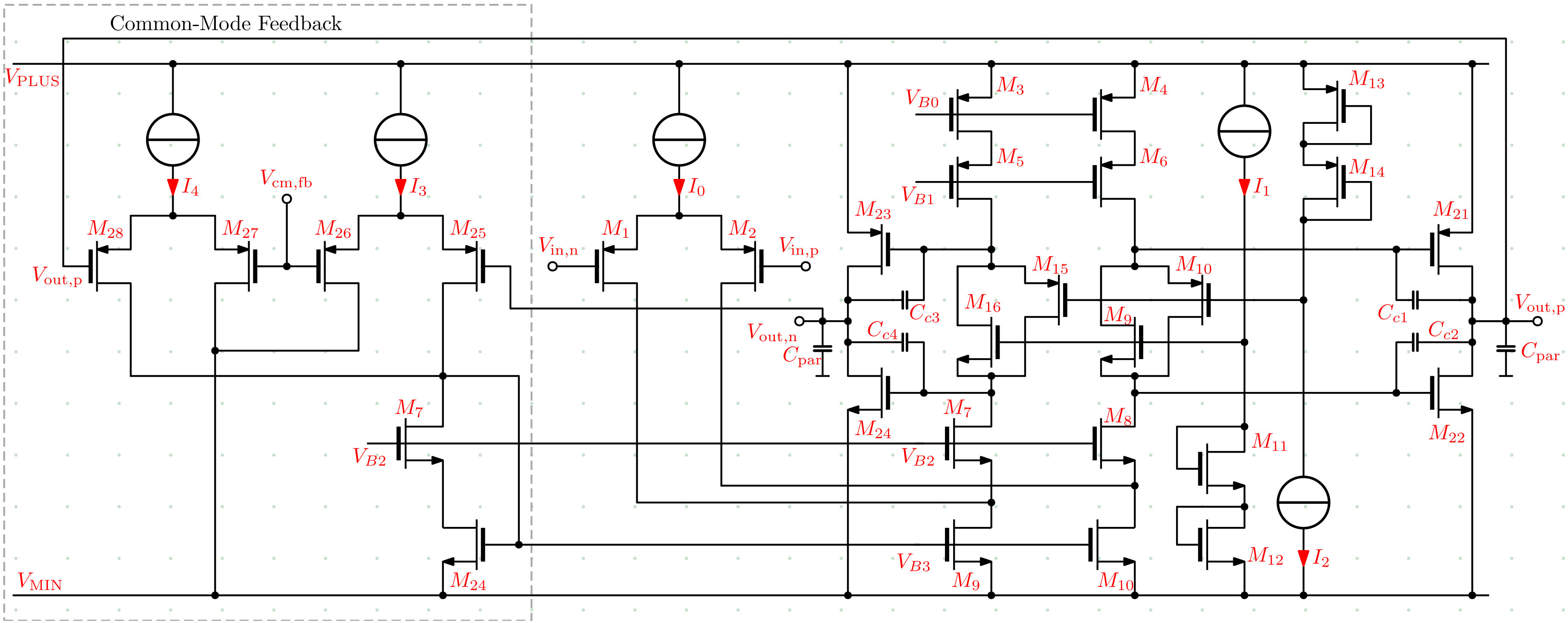
$$|A_{v2}| = (g_{m21} + g_{22})\ (r_{\text{o21}} || r_{\text{o22}}) \approx 10 \ldots 150$$



High-Gain Operational Amplifier with Single-Ended Rail-to-Rail Output

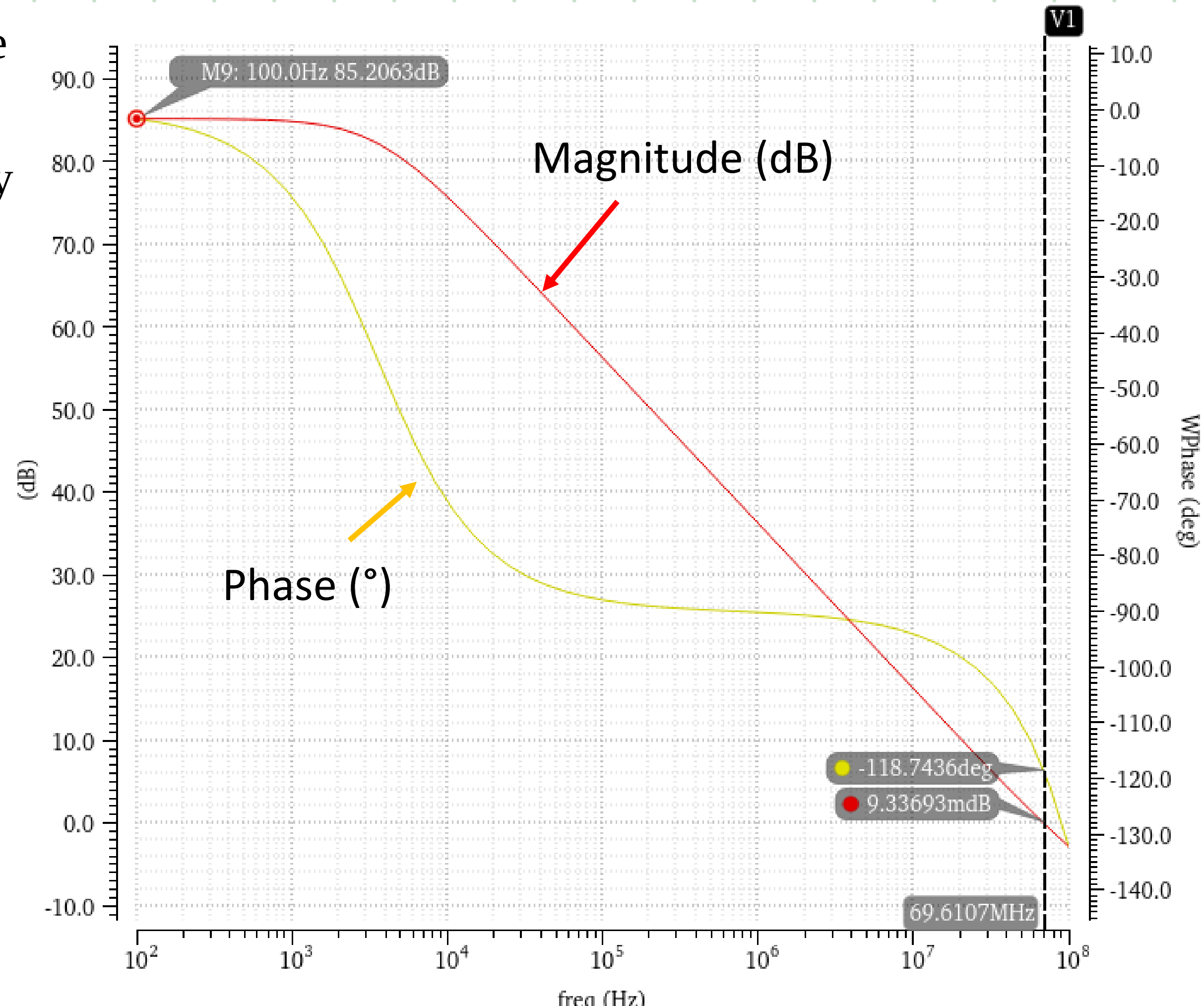


Fully – Differential Operational Amplifier

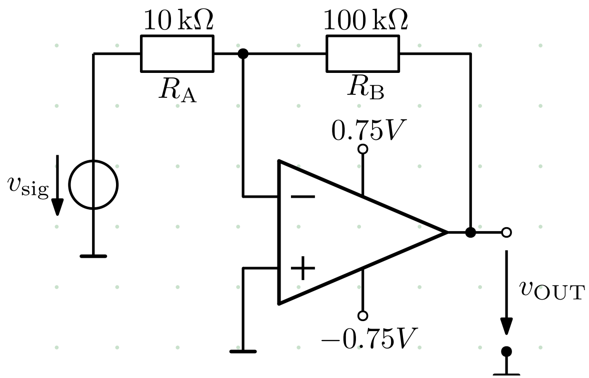


Simulation: Performance, Gain, Bandwidth, Phase Margin

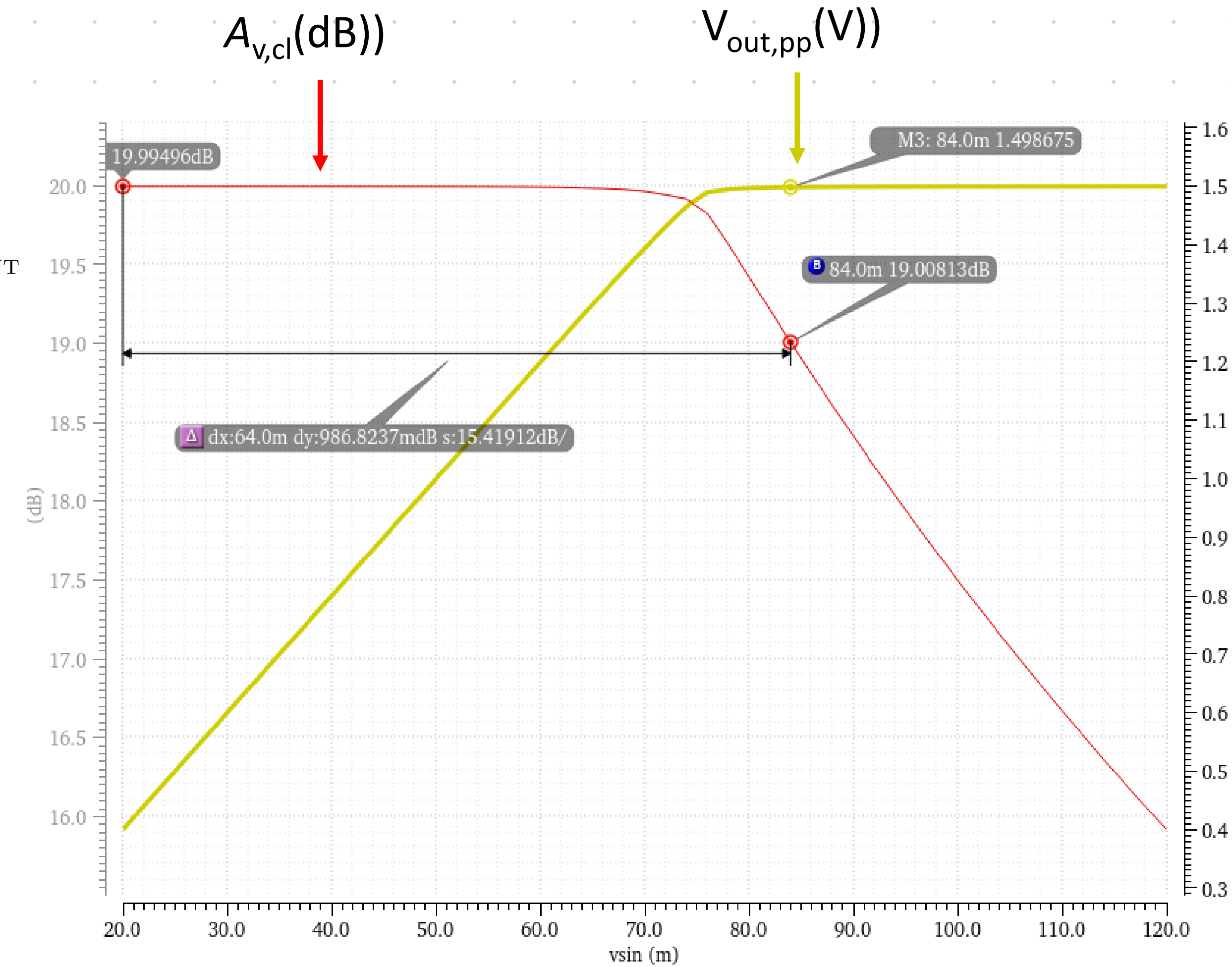
- Maximum Open-Loop Voltage Gain $A_{v,ol} = 85$ dB
- Bandwidth / Transit Frequency $f_T = 70$ MHz
- Phase Margin PM > 60°



Simulation: Close-Loop Gain of Inverting Amplifier

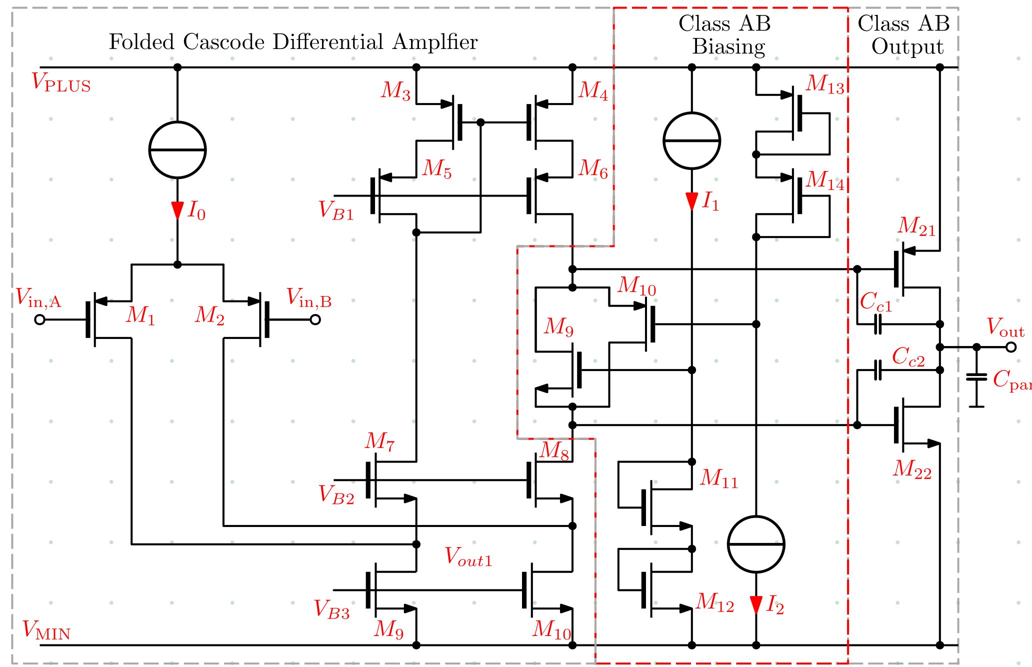


- Very large output swing (rail-to-rail output)
- 1dB output referred peak-to-peak output voltage is 1.5V

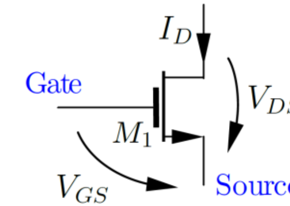


Simulation: Summary

Maximum Open-Loop Gain	85 dB
Transit frequency	70 MHz
Phase Margin	>60°
DC Offset	825 µV
Output Swing	Rail-to-rail
Slew Rate	25.1 V/µs
DIE Area	< 0.25 mm^2
Supply Voltage	1.5V
Current Consumption	1 mA



Design Concepts and Tools



Design of circuits and systems is performed using simple means and rules

- Dimensioning the circuits in accordance to theories by hand-analysis
  - Level-1 spice models/parameters (Schichman-Hodges) for components are necessary

$$I_D = \mu_p C_{ox} \frac{W}{L} \left[(V_{GS} - V_{th}) V_{DS} - \frac{1}{2} {V_{DS}}^2 \right]$$

$$I_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{th})^2 (1 + \lambda V_{\mathrm{DS}})$$

$$V_{th} = V_{th0} + \gamma \left[\sqrt{2\phi_f + V_{SB}} - \sqrt{2\phi_f} \right]$$

- Simulate and optimize the circuits using advanced and precise models (BSIM or PSP)
- Simulation and Layout Tools
  - Cadence Virtuoso with Spectre Simulator
  - ngspice and KiCAD for discrete electronics
- No tool preference, we can work with any open-source tools

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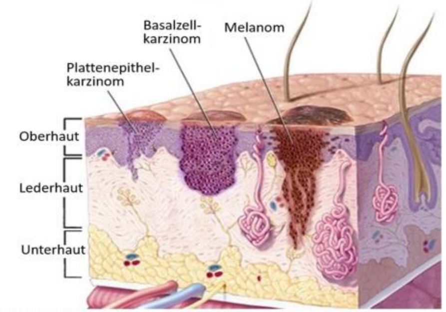
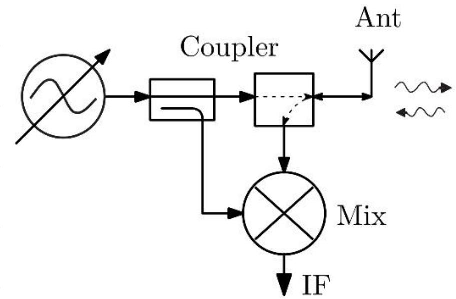
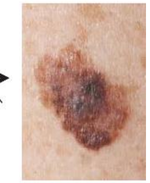
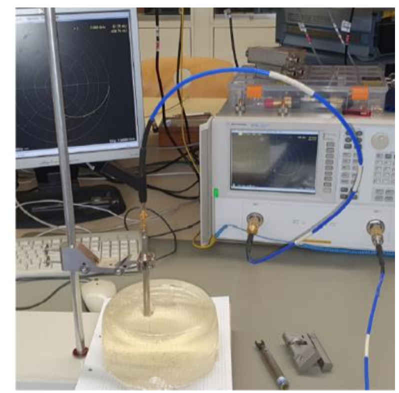
MiDeSCa - Millimeter-Wave Based Detection of Skin Cancer

- MWK-Project with total funding of 165k€
  - Project duration 12/2022 – 05/2024
  - 1 employee with E13
- For early detection of malignant melanoma, detection of the presence of a malignant cell cluster down to a depth of several millimeters below the epidermis is only useful with micro/millimeter waves
- A millimeter wave reflectometer can be used to measure the dielectric properties of the tissue. The amplitude and phase of the reflected wave from the tissue provides information about the complex dielectric properties.
- A compact device consisting of in-house developed integrated millimeter wave transceiver and antenna is expected to make skin cancer detection cost-effective and attractive.



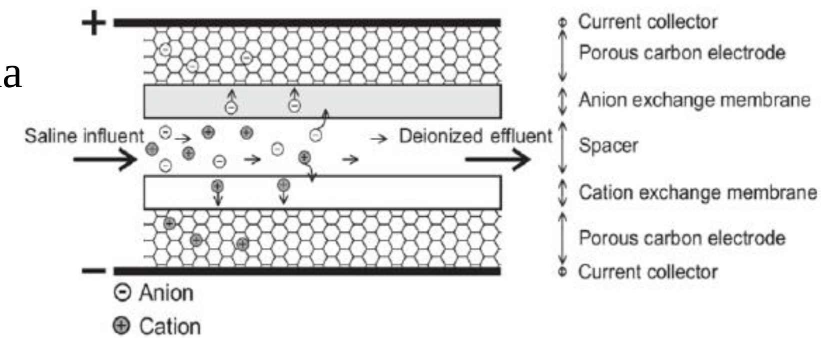


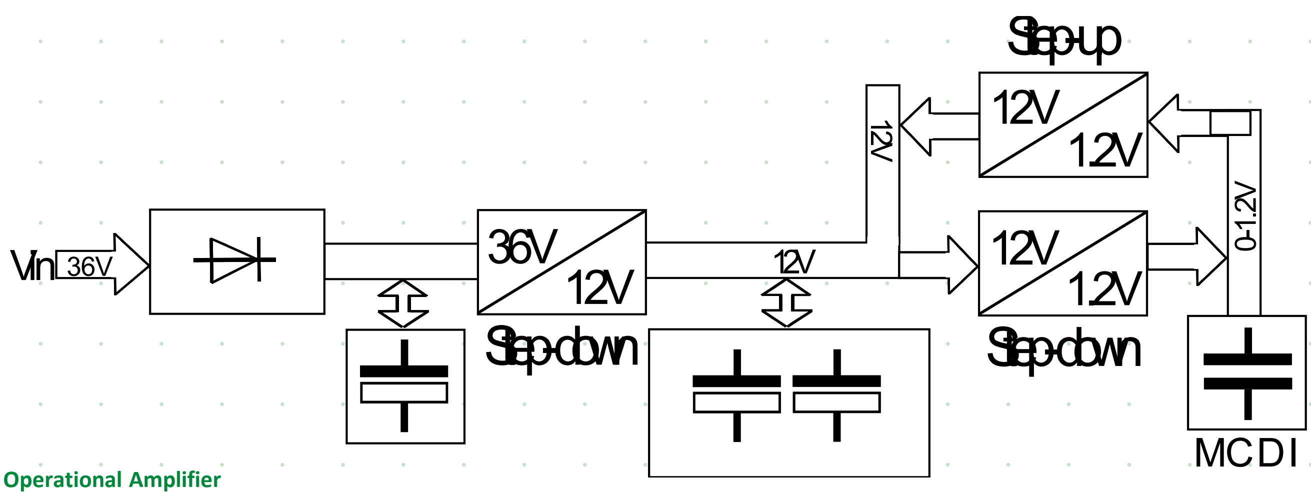




smARt-mcdi : modular, energy self-sufficient solution for drinking water production using PV-powered capacitive deionization

- ZIM-Project with total funding of 196k€
  - Project duration 10/2022 – 03/2024
  - 2 Partners in Germany und 1 Partner in Argentinia
  - 1-employee with E10
- Energy-efficient desalination with "Membrane Capacitive Deionisation" (*MCDI*)-Technology
- Energy self-sufficient system with solar modules and highly efficient DC/DC converters with very high efficiency





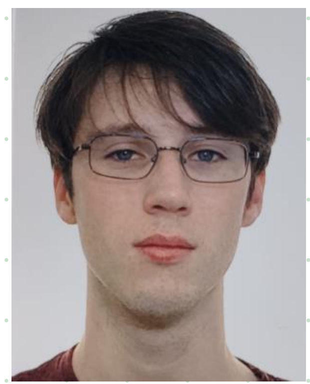
Team

Prof. Dr. Herman Jalli Ng
Projekt Leader
IC Design
Analog Electronics
Lehre

Dr. Denis Jaisson
Project: MiDeSCa
Skin Cancer Detector
RF/EM Simulation
Near field sensors

Marvin Stängle
Project: SmartMCDI
DC/DC Converter
Power Electronics
Board Design

Jan Ippich
IC Design
Operational Amplifier
Charge Amplifier



Janis Bernhauer
Electronics
Board Design
Tutorial

Yannik Mersch
Analog Simulation
Open Source Tool

Natalie Jung
DC Current
Tutorial

Summary

- Modern CMOS technology nodes pose many design challenges for analog circuits
- Using novel circuit techniques such as low-voltage folded cascode and fully differential topology, a high dynamic range can still be achieved for analog system in the modern CMOS technology nodes
- Frontend electronics for radiation detector consisting of charge preamplifier in combination with fully differential variable gain amplifier and ΔΣ-modulator based A/D converter is very suitable to be implemented in IHP 130nm BiCMOS technology
- The design is still in a very early stage and no final spec exists yet.
- For hand analysis of circuits, simple level-1 models are still necessary
- Implementation of the chip doesn‘t really require modern tools from Cadence and Mentor Graphics, simple open-source tools are good enough

Thanks for the Attention

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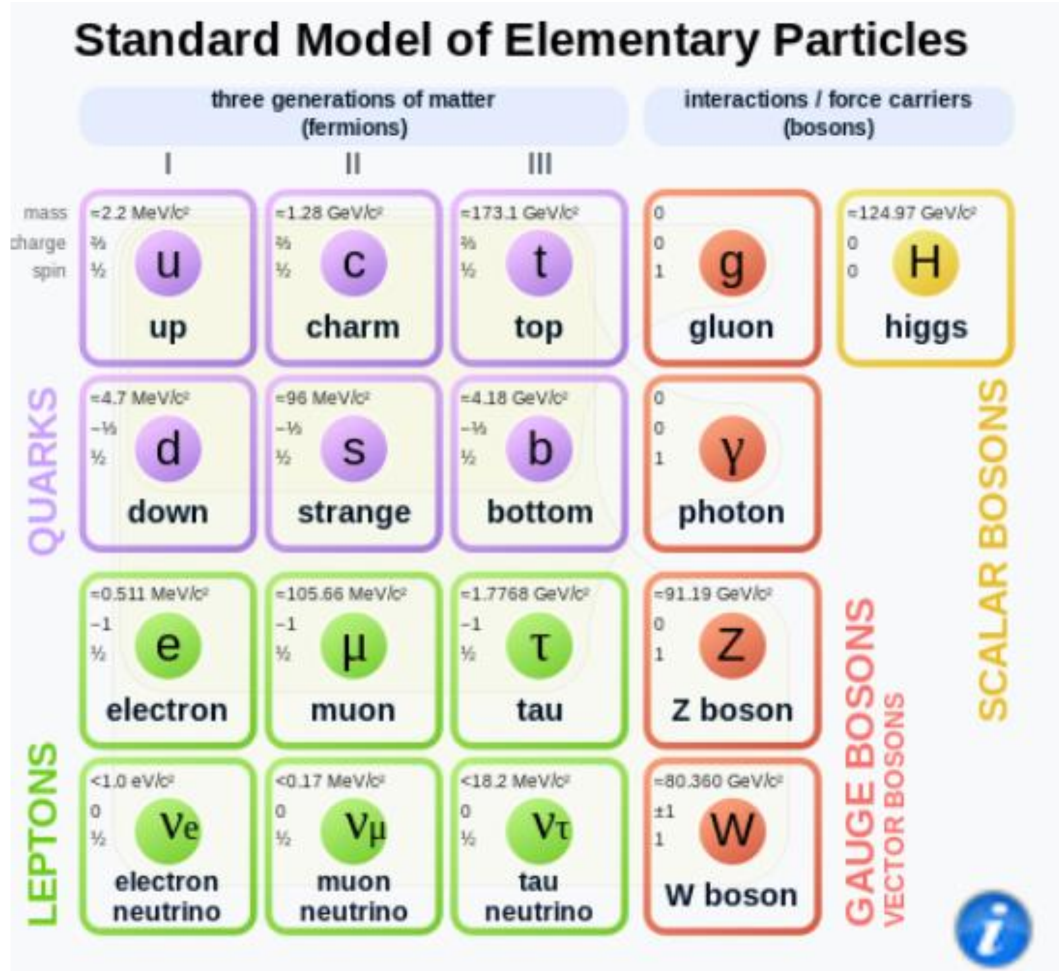
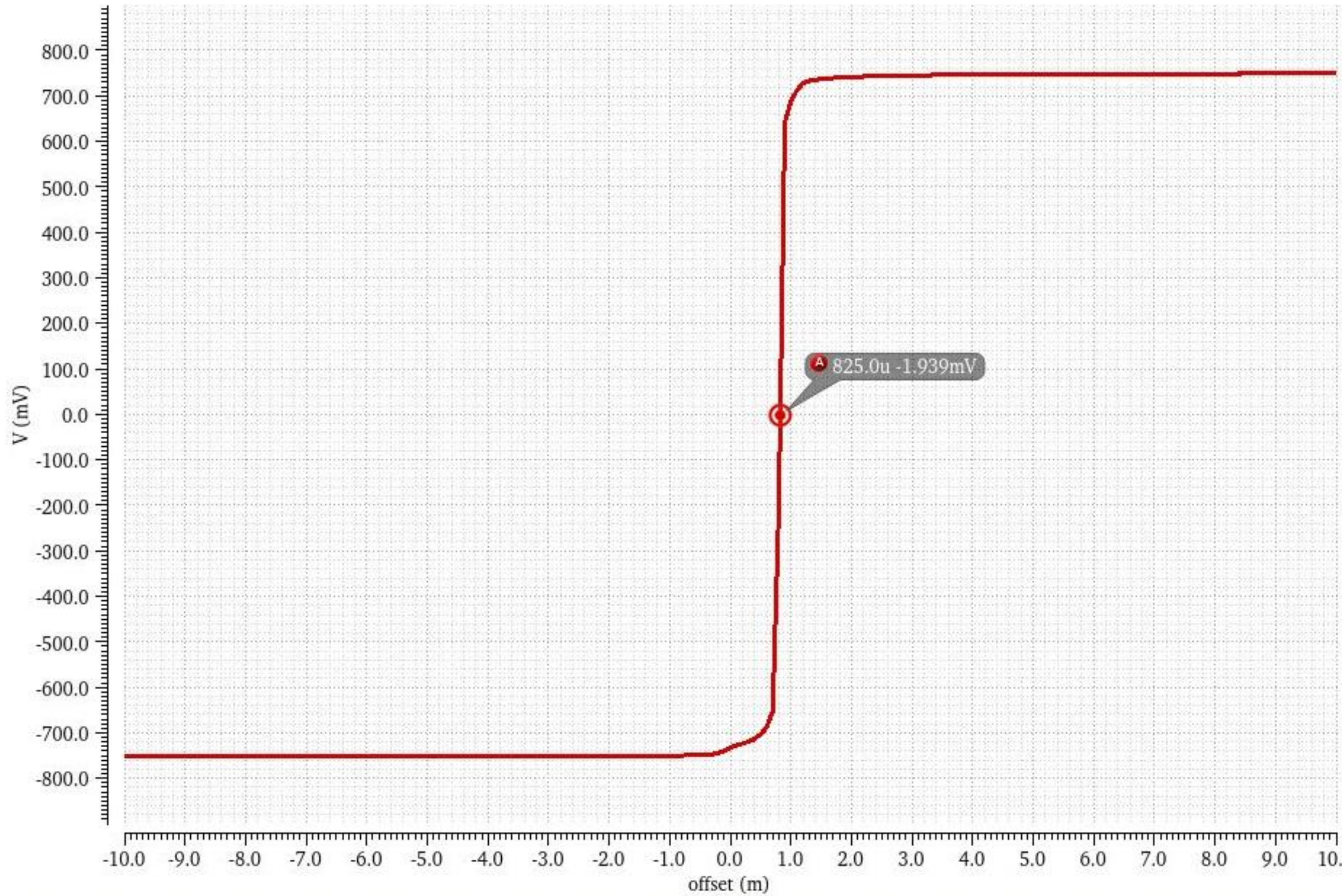
Elementary Particle Pysics



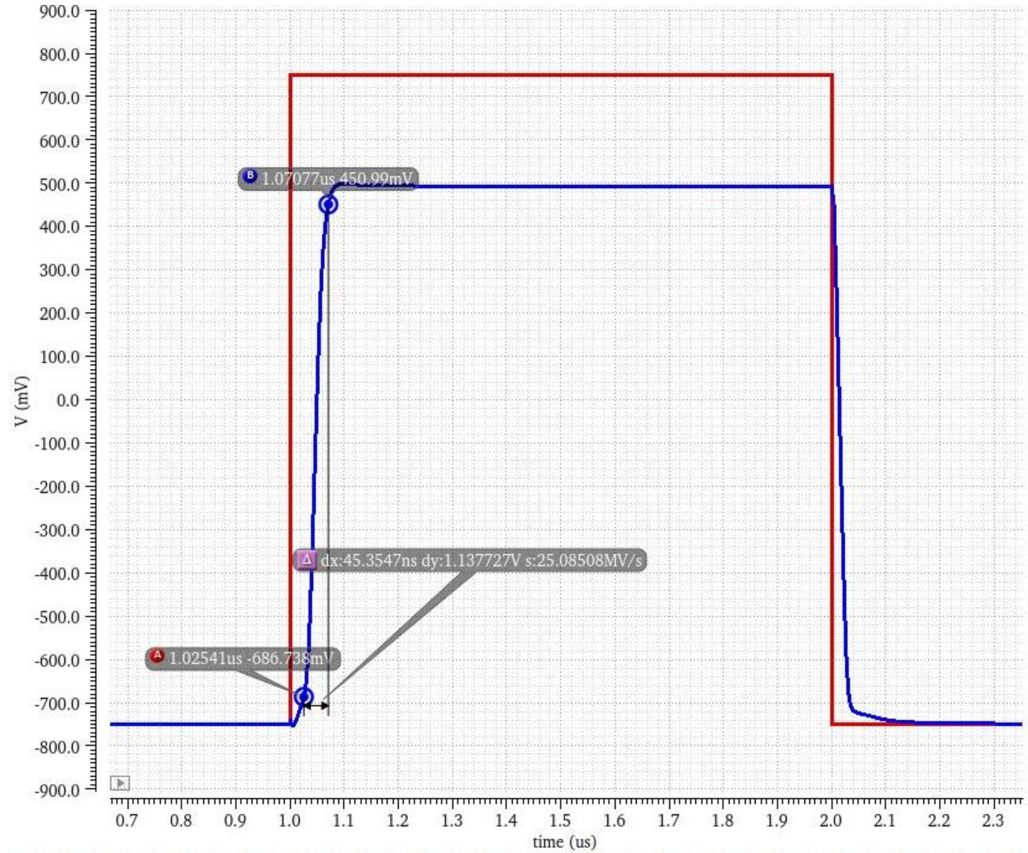
Single Ended OP - Simulation: Offset Voltage

- DC-Offset = 825 µV

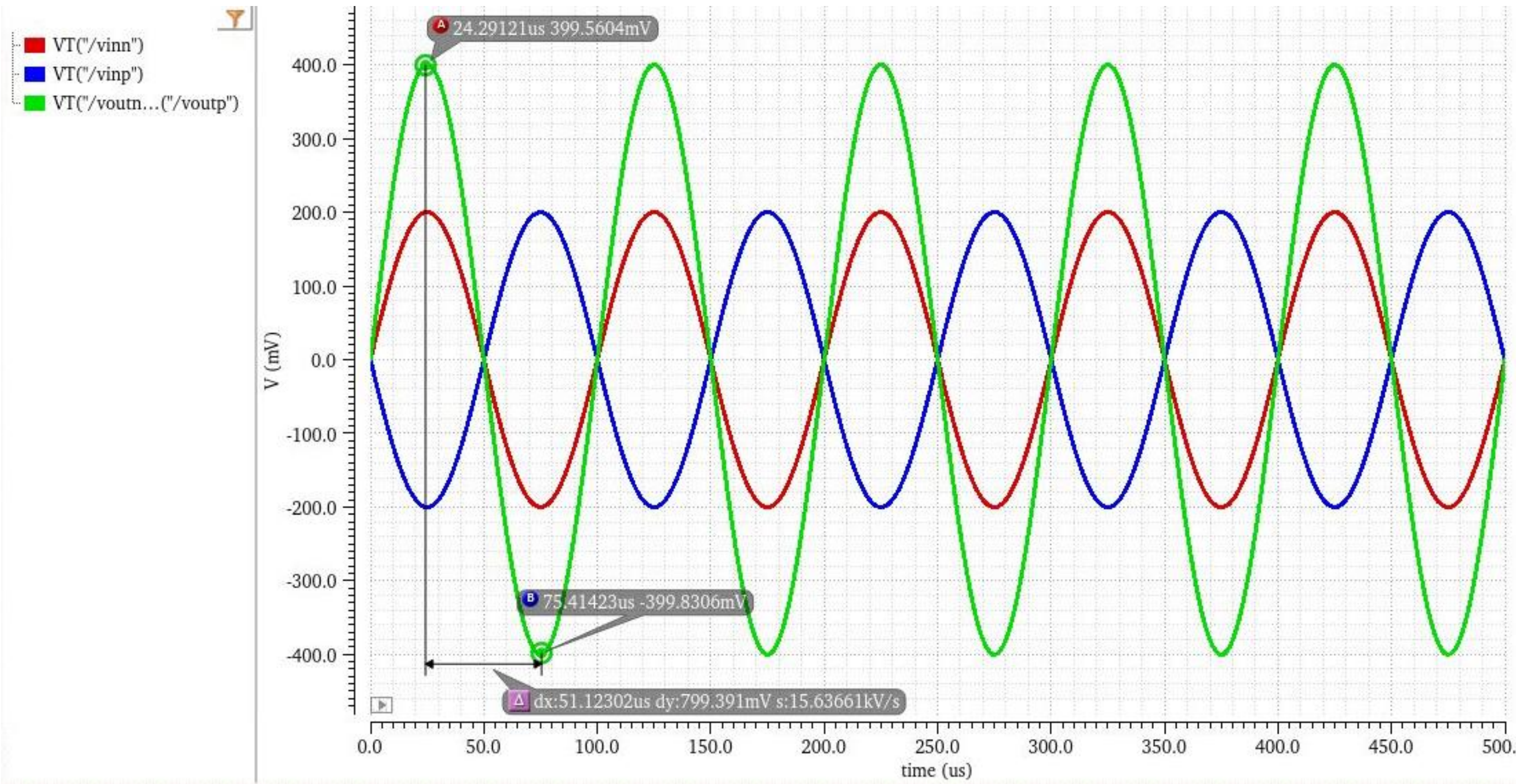


Single Ended OP - Simulation: Slew rate

- $Slew\ Rate = \frac{450.99\ mV - (-686.738\ mV)}{1.07077\ \mu s - 1.02542\ \mu s}$
- $Slew\ Rate = 25.1\ \frac{V}{\mu s}$



Fully Differential OP - Simulation



Charge Amplifier - Simulation