# CURRENT-MODE ELECTRONIC INTERFACES FOR SENSOR APPLICATIONS

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ELECTRONICS FOR SENSORS
&
BIOMEDICAL APPLICATIONS
TECHNOLOGIES & SENSORS
JOINT WORKSHOP
2020

# OUTLINE


01. **SENSORS, A QUICK RECAP**
What is a sensor? How can it be characterized?

02. **ELECTRONIC INTERFACES**
Why using an electronic interface? Discrete vs integrated?

03. **CURRENT MODE APPROACH**
How can we define the concept of current mode operation? What are the main active current mode devices?

04. **THE SECOND GENERATION VOLTAGE CONVEYOR**
The VCII, theory of operation, advantages and disadvantages versus CCIIs and Op-Amps.

05. **VCII BASED INTERFACES FOR SiPMs**
How can we take advantage of a VCII for interfacing a current-emitting device.

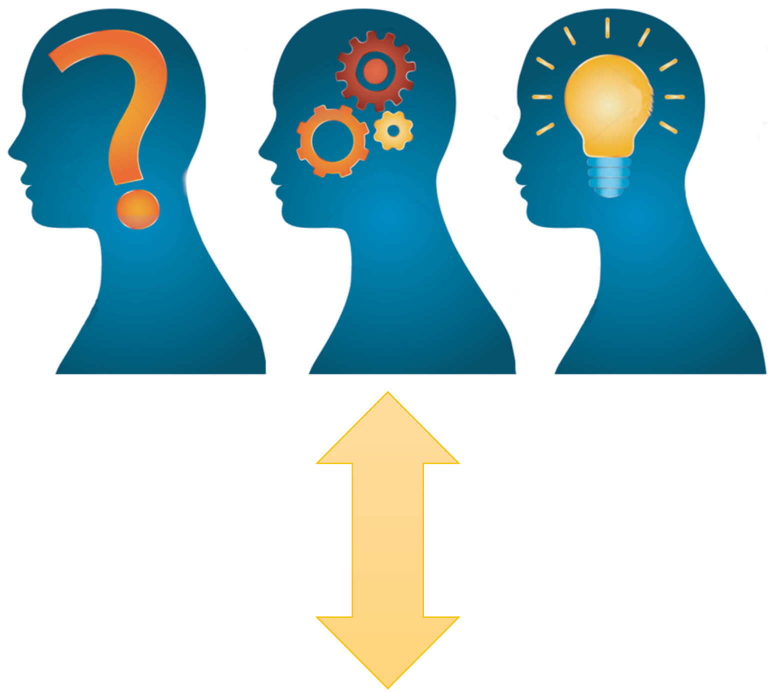
06. **VCII BASIC INTEGRATED TOPOLOGIES**
Some transistor level designs.

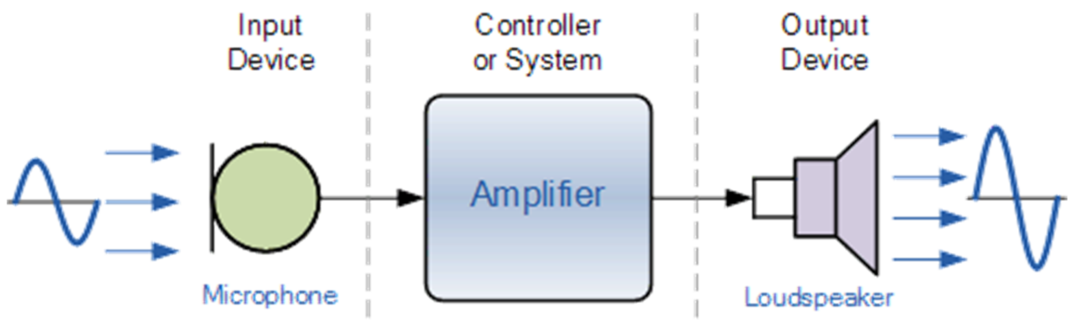
# SENSORS, A QUICK RECAP

# Introduction

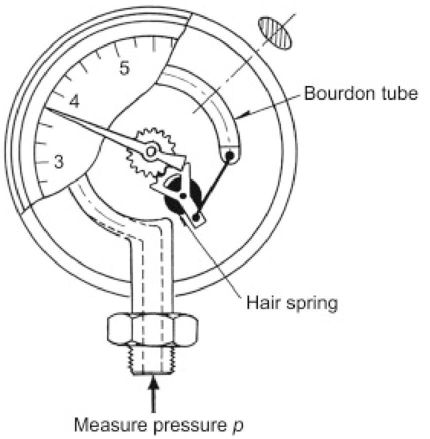
- Interaction between living beings requires SENSING, DECISIONS and ACTIONS.

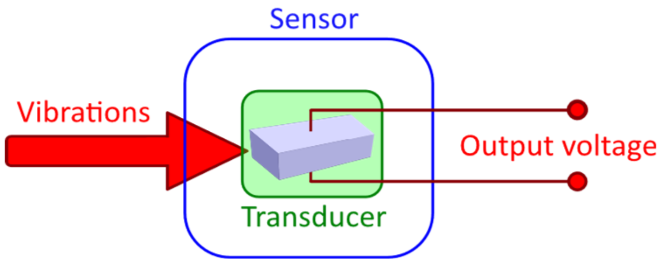
- Natural phenomena are often characterized by physical, chemical or biological events. In order to detect and quantify these events, we need a device or an instrument, to be inserted as first and main element in measurements and control systems. It is the sensing element, in a revelation equipment, which reacts to the phenomenon to be detected.

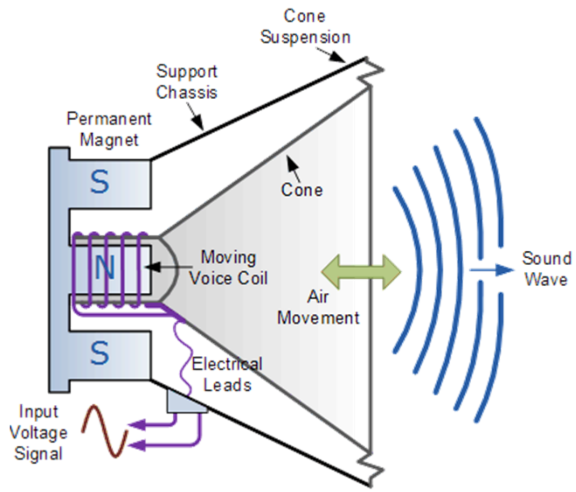




# Some definitions




TRANSDUCERS: convert signals from one energy domain into signals in a different energy domain.

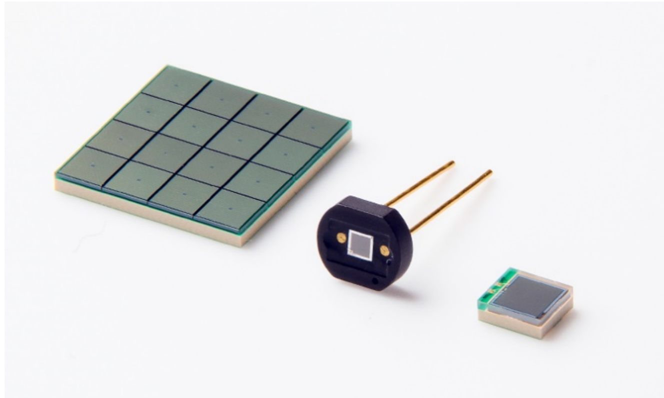
SENSORS: convert signals from an energy domain into ELECTRICAL signals.

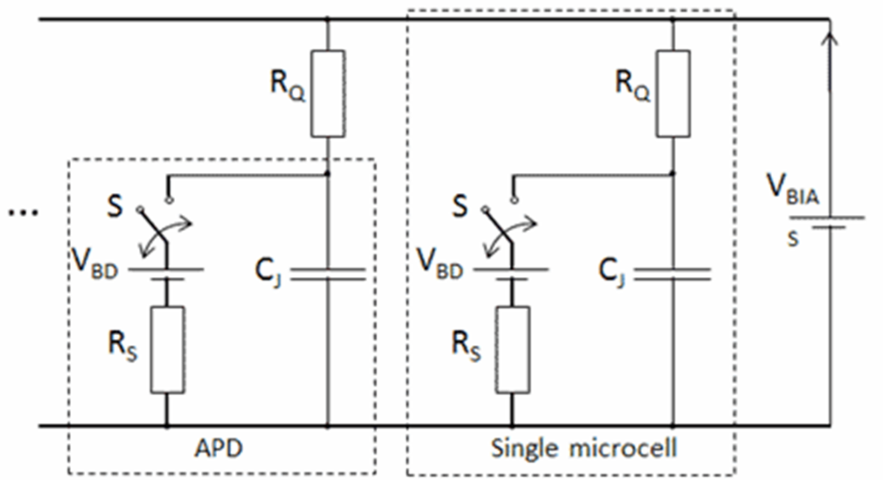
ACTUATORS: convert electrical signals into non-electrical signals.

**SMART SYSTEMS** both bring the measured information from non-electrical domain into electrical and take the actuation decision back, toward the non-electrical domain, making use of sensors and actuators.

# Sensor modelling

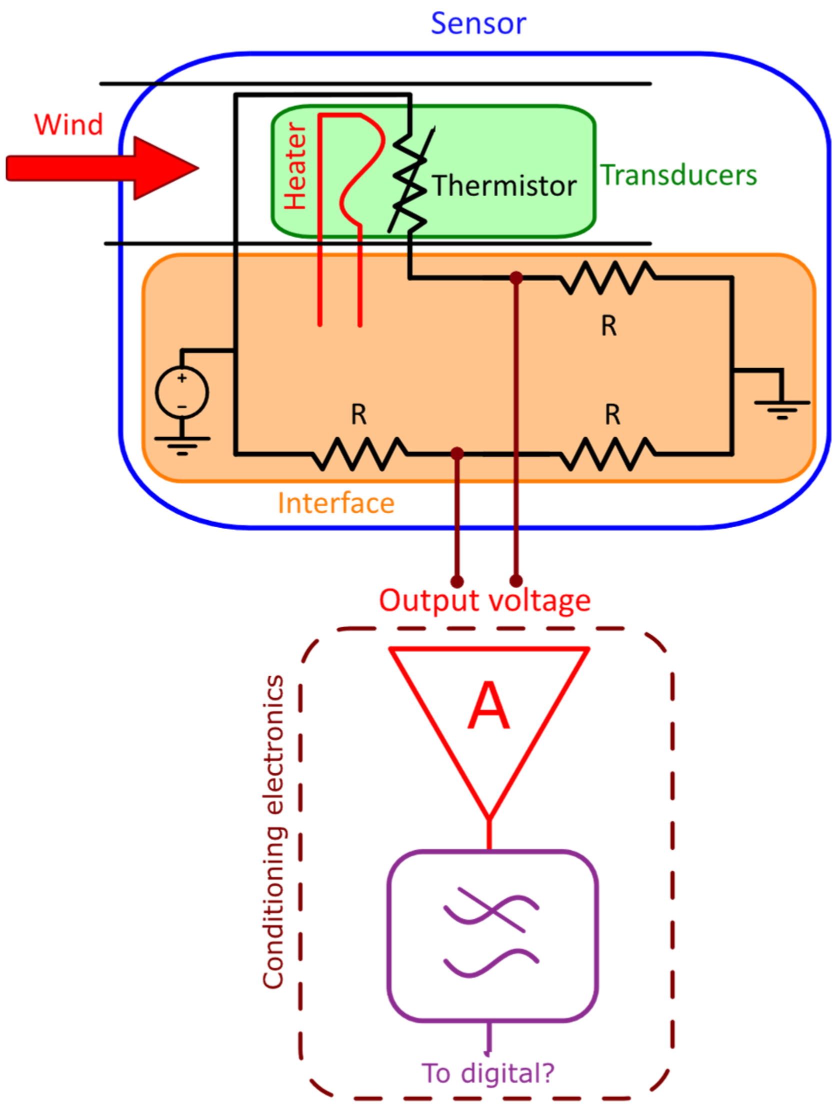
- Generally sensors don’t give directly a readable signal. The majority of the sensors are **PASSIVE** elements, that can be modelled by a **resistor** or a **capacitor**, and vary their parameters according to the change of the biological/chemical/physical measurand variation.
- For this reason, an accurate **modelling** (“analog behavioural model”) of the sensor behaviour must be performed.
- Since a better electrical signal to be quantified is a current or a voltage, the sensor can be **BIASED**. Its output signal often is quite low and must be typically amplified so to have a sufficient reading level.





# ELECTRONIC INTERFACES

# Sensor and electronic interface

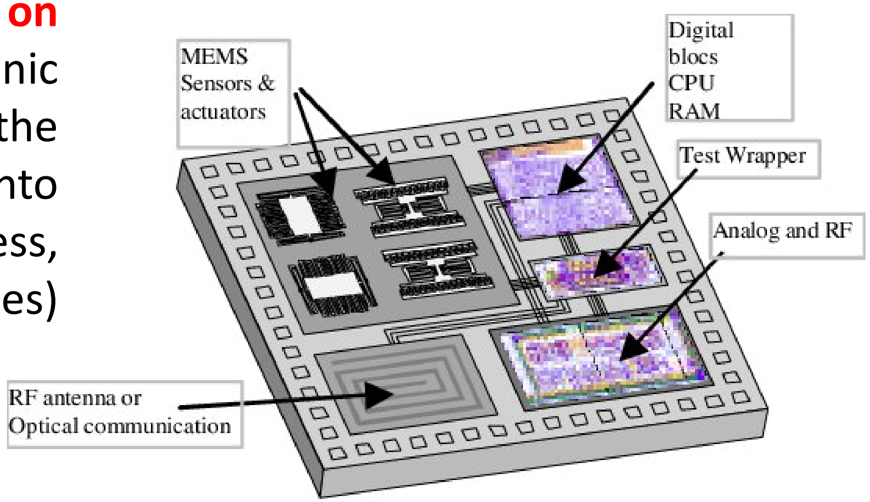


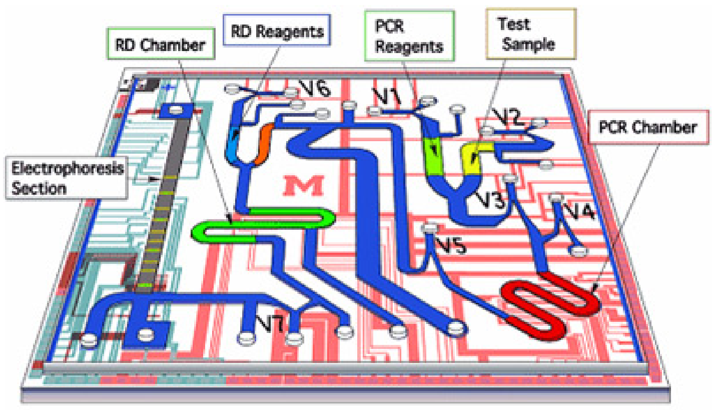

- A suitable sensor interface has to be able also to adapt itself to different kinds of both sensors and measurands, through appropriate electronic circuits, and to improve signal processing by suitable circuit design.

- The first stage of a sensor interface has to be analog, because of the analog nature of the signal coming from sensor.
- An electronic interface has the dual task to operate the final transduction in the case of a sensing element that does not produce a voltage or a current output, and to manipulate (amplify, filter etc…) the signal so to adapt it for the following stages.

# Microsystems and micromodules

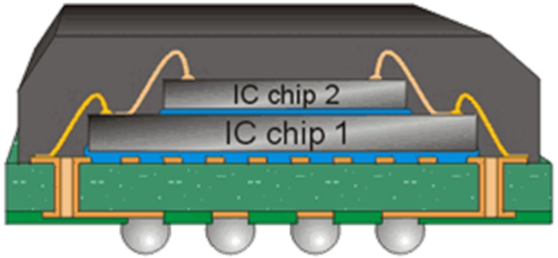
In **microsystems (System on Chip or Lab on Chip)** approach, sensor and electronic interface are integrated on the same chip, the microsensor has to be designed taking into account the material features (layer thickness, doping concentrations and design rules) imposed by the standard IC process used.

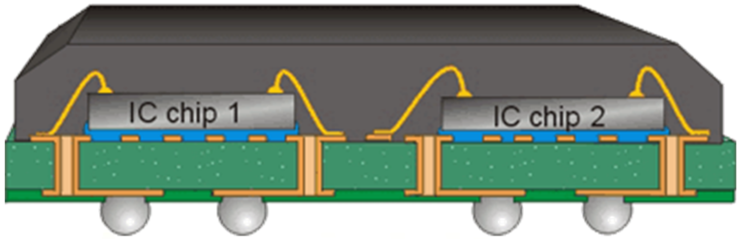


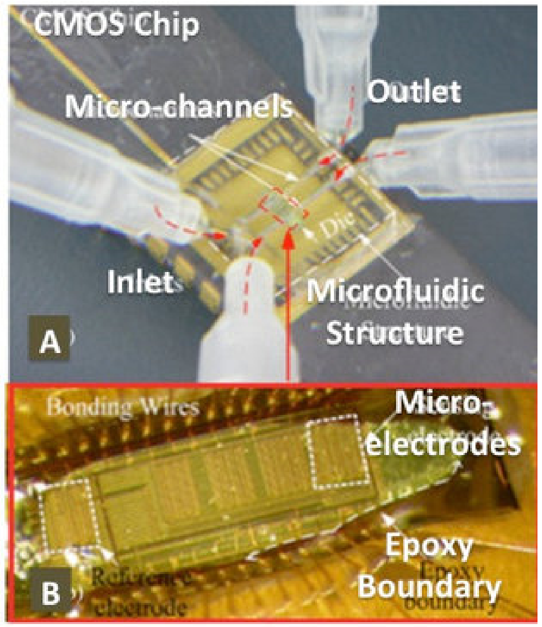




Obviously, this situation reduces the degrees of freedom available for sensor design, thus introducing additional challenges. Moreover, especially when using scaled-down (submicron) technologies, this approach can introduce cost and yield problems, but the advantage is related to minimized and reproducible parasitics.

# Microsystems and micromodules



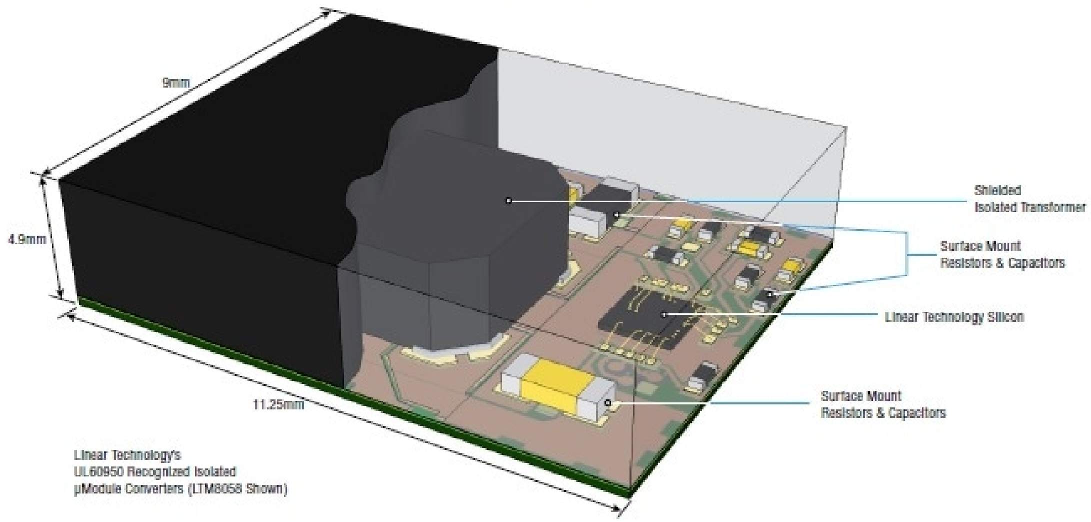




In **micromodule** approach the sensors and the electronic interface circuits are realized on different chips. They are included in the same package or mounted on the same substrate. Interconnections between the sensor and the electronic interface circuit chip can be realized with bonding wires or with other techniques, such as flip-chip or wafer bonding.

With this approach the two chips can be implemented with different technologies, optimized for the sensors and the circuitry, respectively. Typically, expensive submicron technologies are used to realize the electronic interface circuits, while low cost technologies with large feature size and few masks are used for implementing the sensors.
Drawbacks: large parasitics, difficult assembly, no matching.

# Micromodules and discrete approach




A micromodule can be also obtained by joining a chip level sensor with a discrete level active device and passives.

- Larger area occupation
- Larger parasitic components (lower frequency range)
- Higher power consumption

- Better testability and tunability
- Certainty of active device performances (datasheet)
- Improved time to develop

# CURRENT MODE READOUT APPROACH

# Introduction - a definition

*"A voltage-mode (VM) circuit is one whose signal states are completely and unambiguously determined by its node voltages; a current-mode (CM) circuit is one whose signal states are completely and unambiguously defined by its branch currents."*

***B. Gilbert***

# Introduction - CM vs VM

For decades, the dominant signal representation mode has been in voltage form. Today it is much likely the same and it has to do also with practical reasons: voltages can readily be probed by instruments to be displayed and accurately measured without breaking circuit branches. In other words, testing and validating a circuit whose output is in the voltage form can be done in a much easier and accurate way.

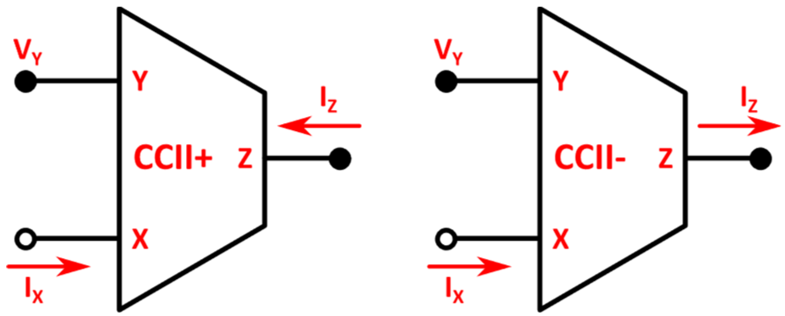
Nonetheless, signaling in the current mode domain has its benefits, especially towards newer and very low pitch integrated technologies:

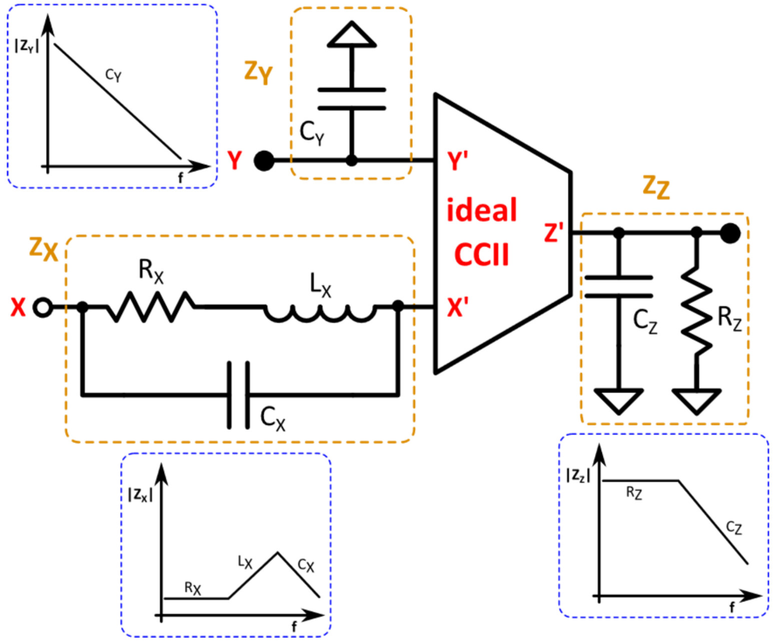
- Higher sensitivity circuits and interfaces with very much reduced supply voltages;
- very simple architectures are synthesizable;
- lower power consumption and higher bandwidths;
- capability to perform signal manipulations such as products, which in a purely VM approach would result extremely difficult.

# CM active devices

## SECOND GENERATION CURRENT CONVEYOR (CCII)

$$\begin{bmatrix} I_Y \\ V_X \\ I_Z \end{bmatrix} = \begin{bmatrix} sC_Y & 0 & 0 \\ \alpha & (R_X + sL_X)//\frac{1}{sC_X} & 0 \\ 0 & \pm\beta & \frac{1}{R_Z//\frac{1}{sC_Z}} \end{bmatrix} \begin{bmatrix} V_Y \\ I_X \\ V_Z \end{bmatrix}$$



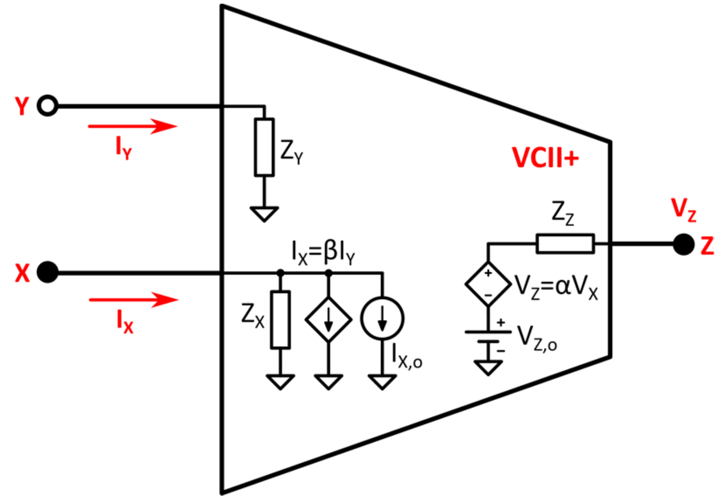

- Well known current mode active device
- Low impedance current input at ***X***
- High impedance voltage input at ***Y***
- High impedance current output at ***Z***
- Unitary α and β parameters. β can be positive or negative.

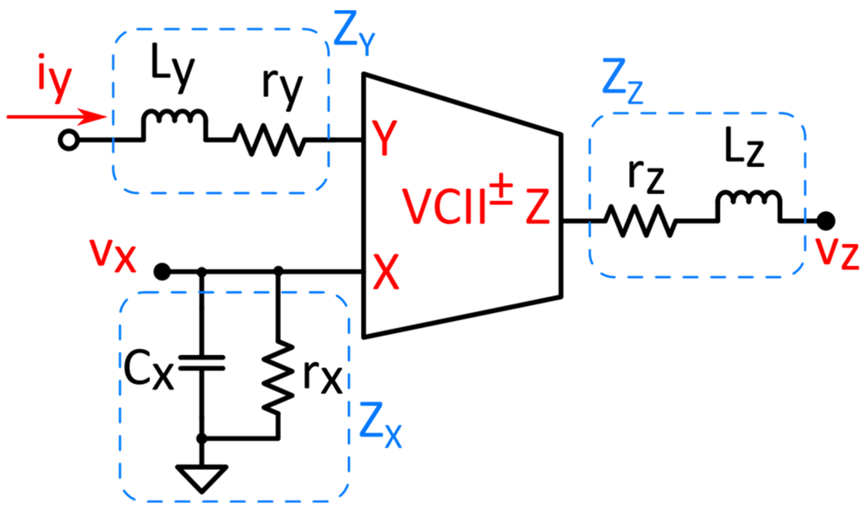
# THE SECOND GENERATION VOLTAGE CONVEYOR (VCII)

# CM active devices

SECOND GENERATION VOLTAGE CONVEYOR (VCII)

$$\begin{bmatrix} I_X \\ V_Y \\ V_Z \end{bmatrix} = \begin{bmatrix} \frac{1}{r_x} + sCx & \pm\beta & 0 \\ 0 & r_y + sL_y & 0 \\ \alpha & 0 & r_z + sL_z \end{bmatrix} \begin{bmatrix} V_X \\ I_Y \\ I_Z \end{bmatrix}$$



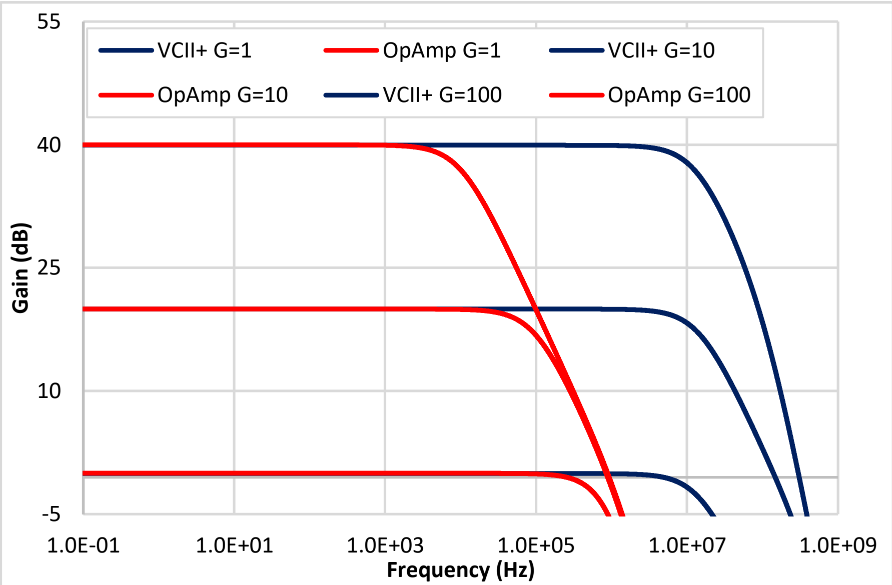




- Relatively new current mode active device
- High impedance voltage input at ***X***
- Low impedance current input at ***Y***
- Low impedance **voltage output** at ***Z***
- Unitary α and β parameters. β can be positive or negative.

# A brief comparison

VCII <-> Op-Amp

The voltage output of a VCII can be a linking point between the voltage mode and the current mode approach.




- Constant BW at different gain levels
- Very easy transistor level topology
- Lower power consumption
- Higher GBW product due to the lack of frequency compensation

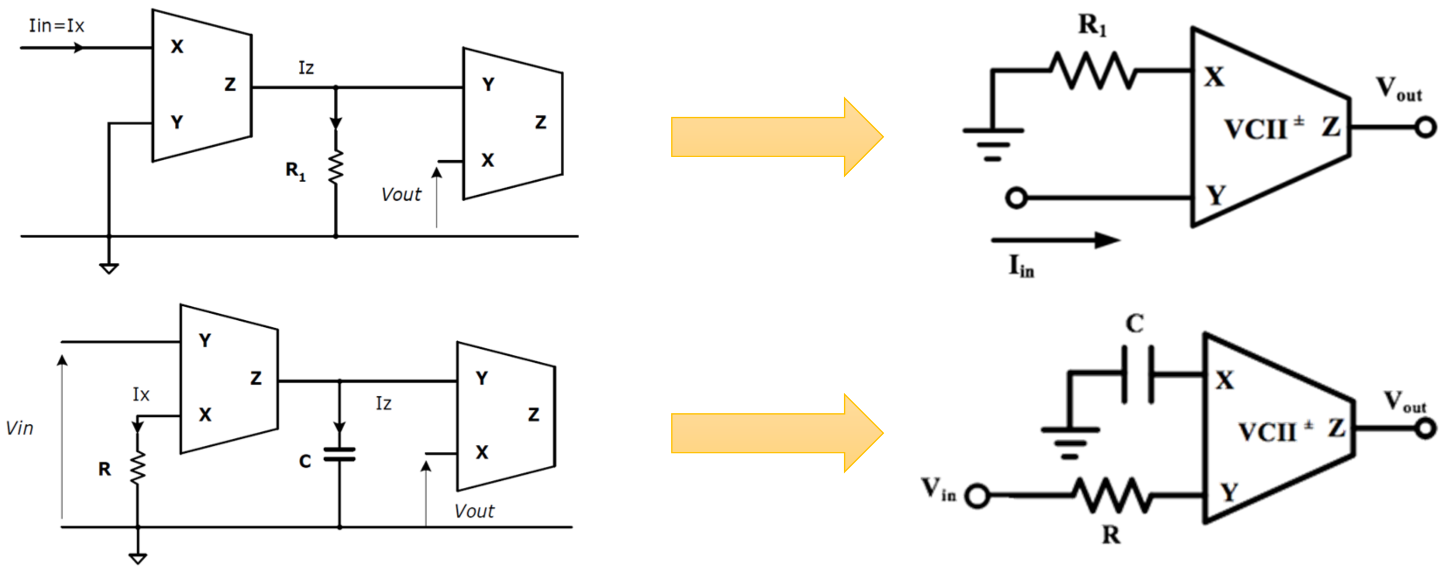
- No easy way to perform a differential measurement
- Impossibility to take advantage of the negative feedback properties

# A brief comparison

VCII <-> CCII

CCII

VCII

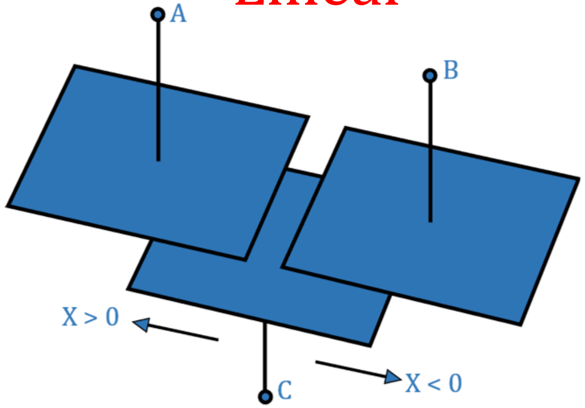



- Low impedance voltage output -> compatible with voltage mode systems
- Same signal processing capabilities with a reduce number of active devices

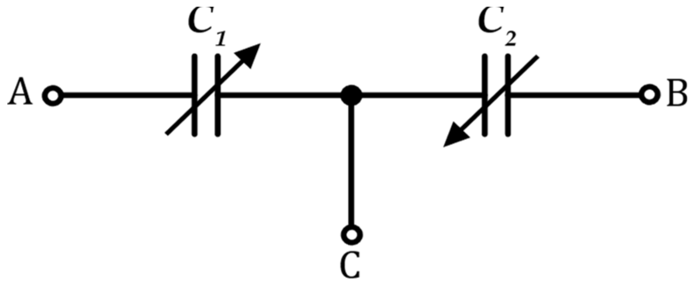
# APPLICATION AS ANALOG INTERFACE

# Differential capacitive sensors

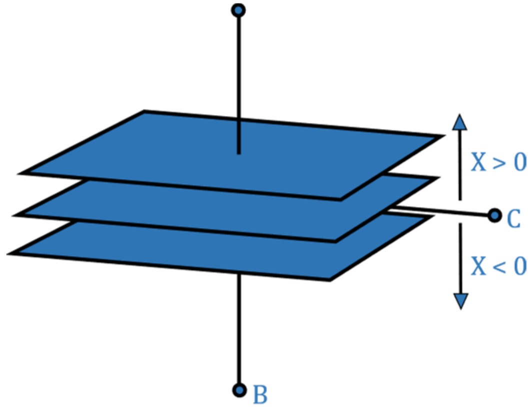
Linear




Equivalent circuit




Hyperbolic




$$C_{1,2} = C_{bl}(1 \pm x)$$

$$(0 < C_{1,2} < 2C_{bl})$$

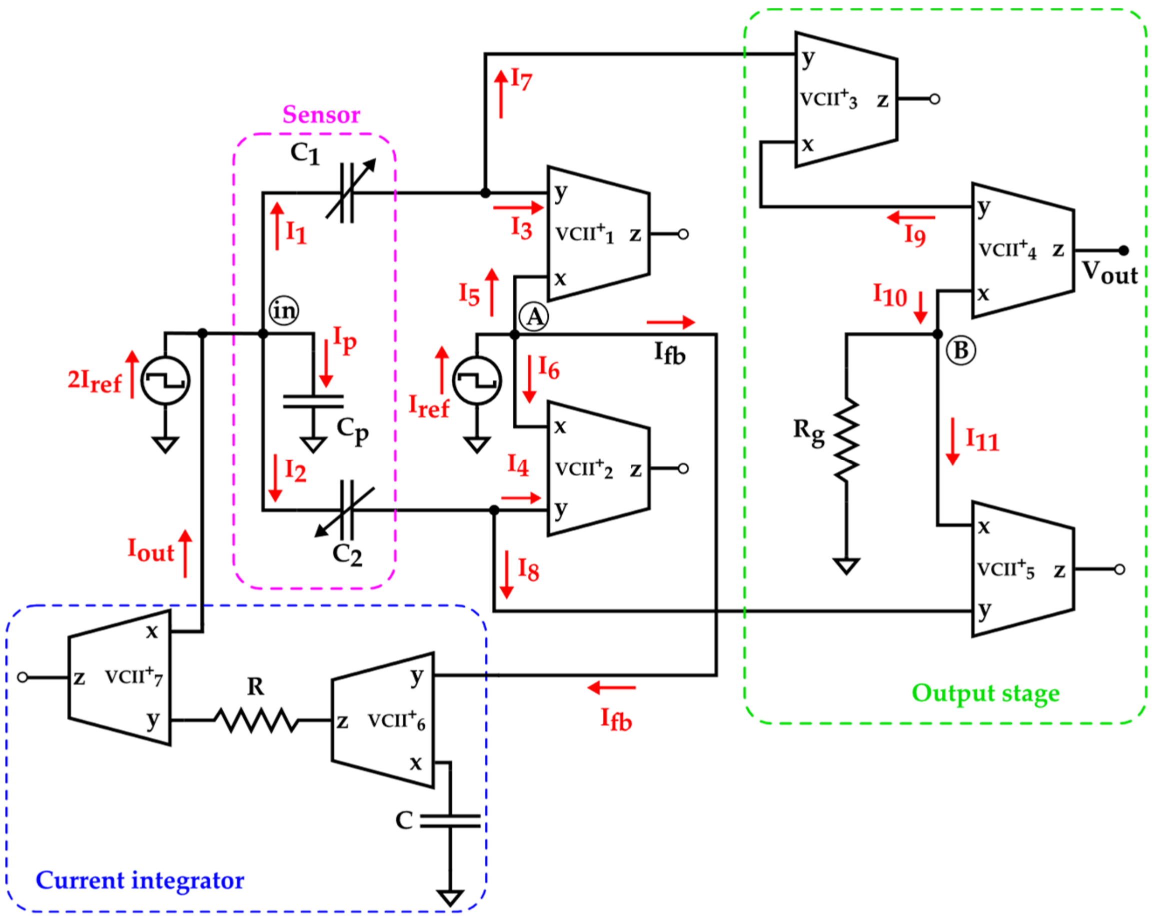
$$X = \frac{C_1 - C_2}{C_1 + C_2}$$

$$C_{1,2} = \frac{C_{bl}}{(1 \mp x)}$$

$$\left(\frac{C_{bl}}{2} < C_{1,2} < \infty\right)$$

- Couple of capacitors sharing a common node (C).
- Variations from a common baseline, in a differential way.

# Differential capacitive sensors

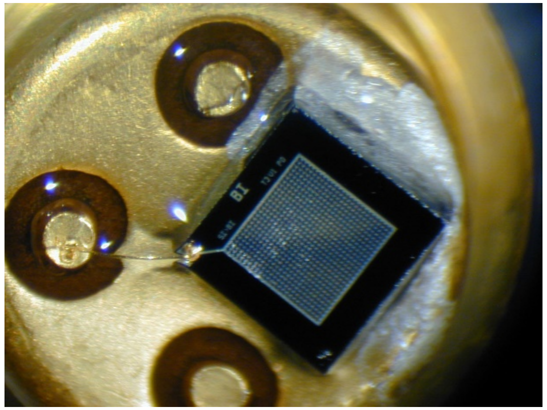



- Output stage performs the difference between currents flowing through the sensor
- Time continuous current feedback to compensate parasitic effects
- Tunable sensitivity either by increasing $I_{ref}$ or $R_g$

$$I_{out} = \alpha_7 \beta_7 \beta_8 \frac{1}{sRC} I_{fb}$$

$$V_{out} \approx \frac{R_g(I_1 - I_2)}{2} = R_g I_{ref} x$$

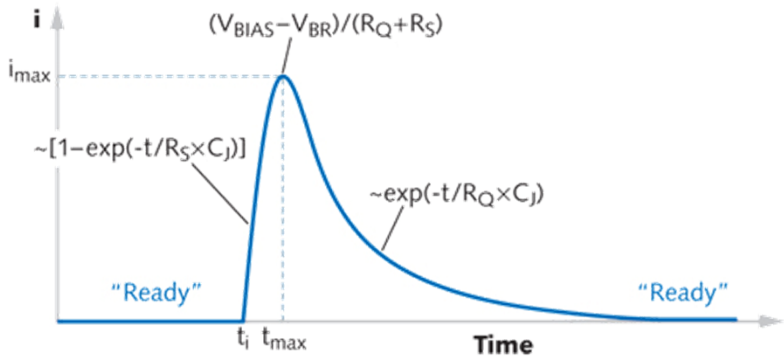
# Silicon photomultipliers (SiPMs)

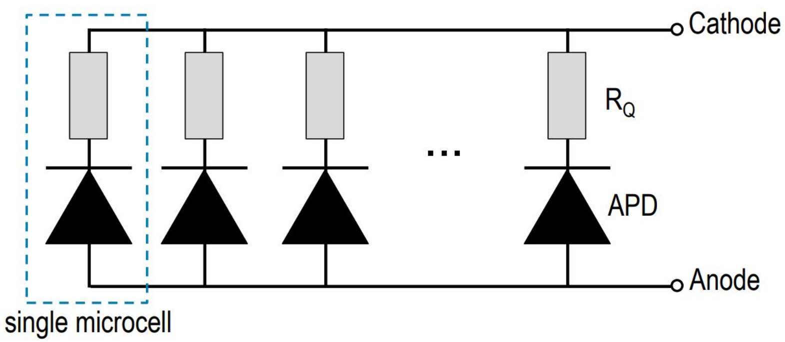


- Photomultipliers are **extremely sensitive detectors of light** (photons).
- The main role is to multiply the current produced by incident light up to 100 million times , in order to detect even individual photons.
- The **Silicon Photomultipliers**, or **SiPMs**, are much smaller than PMTs and can guarantee the same features, or even better performances in some cases.

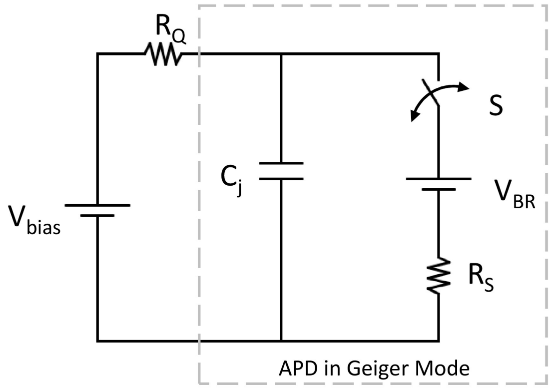
***SiPMs structure***: series combination of an **avalanche photodiode (APD or SPAD)** with a **quenching resistor**.

Biomedical applications: optical sensors (Doppler, pulseoximeter etc…)



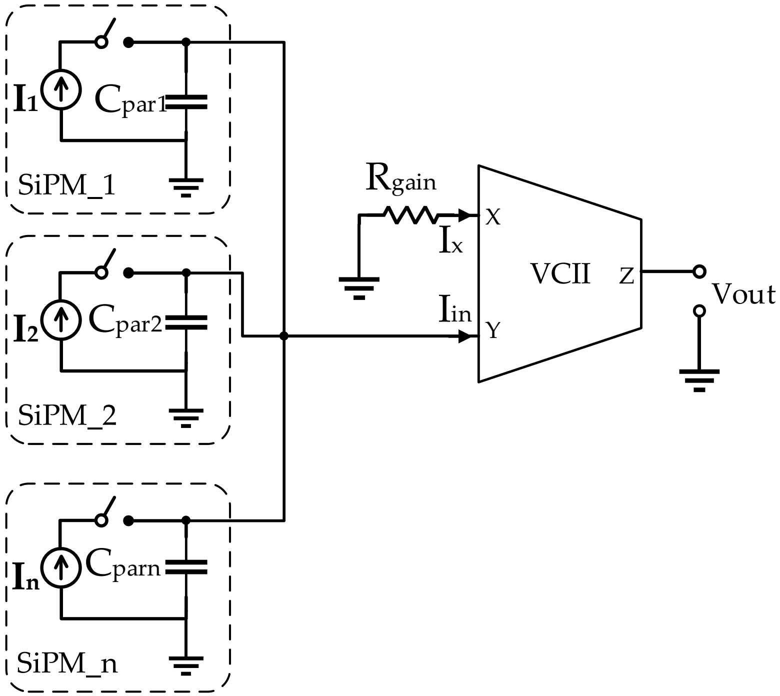



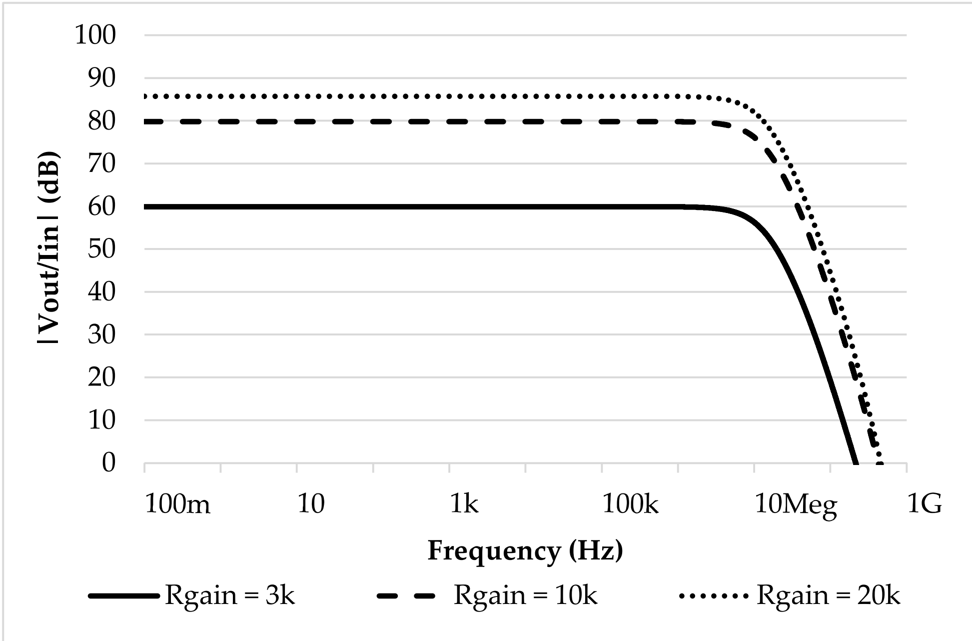

Equivalent circuit model



# The VCII as analog interface

- Due to its characteristics, the VCII can easily work as a TI amplifier.
- It can work for the single SiPM as well as an array of SiPMs without losing the information about how many photons hit the array.
- In the latter case the spatial information is lost.



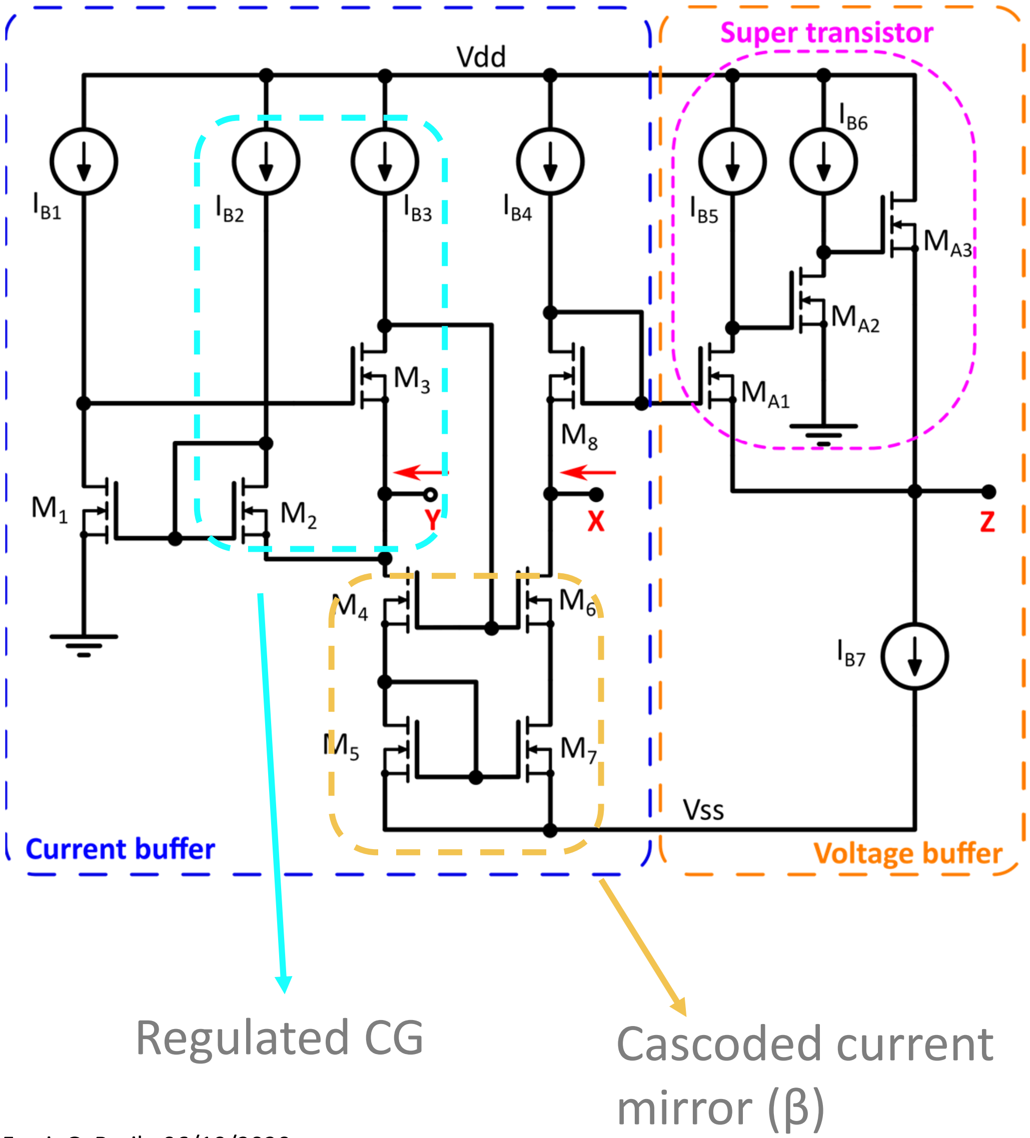




$$V_x = I_x R_{gain} \approx \pm \beta I_{in} R_{gain}$$

$$V_{out} = \alpha V_x \approx \pm \alpha \beta R_{gain} I_{in} \approx R_{gain} I_{in}$$

# VCII TRANSISTOR LEVEL TOPOLOGIES

# Super transistor output stage



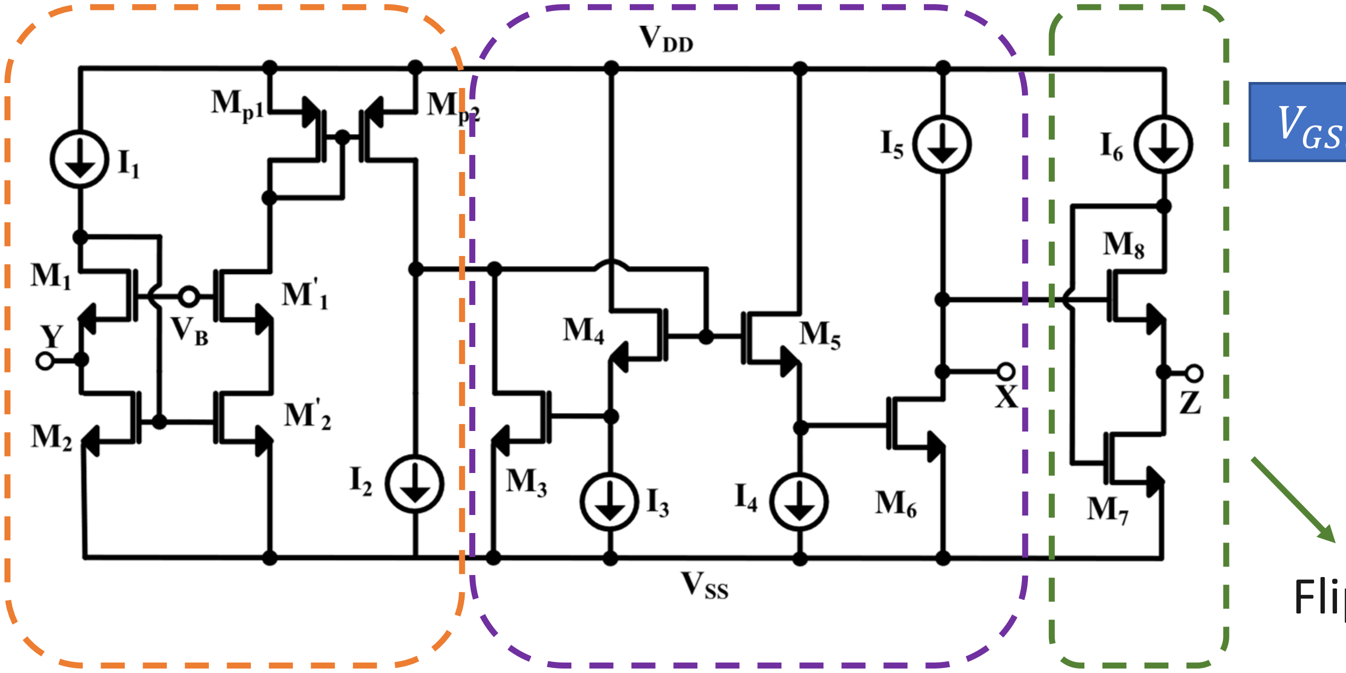

$$r_X = \frac{(ro_7 + ro_6 + gm_6 ro_6 ro_7)(ro_{IB4} + {}^1/_{gm_8})}{(ro_7 + ro_6 + gm_6 ro_6 ro_7 + ro_{IB4} + {}^1/_{gm_8})}$$

$$r_Y = \frac{1}{gm_3 gm_1 (ro_1 \| ro_{I_{B1}})\, gm'_4 (ro_{IB_3} \| ro_3)}$$

$$r_Z = \frac{1}{gm_{A1} gm_{A2} gm_{A3} (ro_{A1} \| ro_{IB5})(ro_{A2} \| ro_{IB6})}$$

| Parameter | Value |
|---|---|
| rx, Cx | 1.2MΩ, ~30fF |
| ry, Ly | 6.7Ω, ~1.5µH |
| rz, Lz | 0.7Ω, ~9µH |
| α (DC value, -3dB BW) | (0.997, 217MHz) |
| β (DC value, -3dB BW) | (0.988, 200MHz) |
| Static Power Consumption | 330µW (101µA) |

# Translinear β-tunable VCII




$$V_{GS3} + V_{GS4} = V_{GS1} + V_{GS2}$$

$$I = I_{D0} e^{\frac{V_{GS} - V_{TH}}{nU_T}}$$

$$I_3 I_4 = I_1 I_2$$

Flipped voltage follower

Translinear Core

Current mirroring

$$G = \frac{I_X}{I_Y} = \frac{I_3}{I_4}$$

- Based on the translinear theory => a PROPER CM device
- Exponential relationship between Id and Vgs needed
- Weak inversion biased transistors -> extremely low power consumption
- Flipped voltage follower output, suitable for weak inversion operations.

# END OF PRESENTATION

# THANK YOU!