Ultra-low-Power, Zero Drift **Operational Amplifiers** for Industrial and Remote Analog Sensors

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ST Developers Conference
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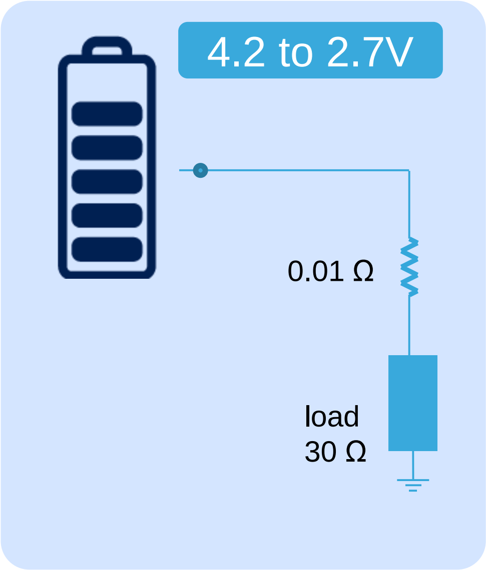
Santa Clara Convention Center - Mission City Ballroom
Santa Clara, CA

Agenda

- Key Op amp parameters for Precision
  - Vio - Input offset Voltage
  - CMRR – Common Mode rejection Ratio
  - Iib – Input bias Current
  - Noise
- Use case Study : Gas Sensor
- Product line: High-performance Op Amps in ST

Why Op Amps and why precision

Battery fuel gauging



0.9 mV ≤ **V1 max** ≤ 1.4 mV

Very small signal

ST Op Amps

Need to amplify

STM32 power supply:
1.65 to 3.6V

12-bit ADC

LSB of the ADC
$= 3.6\ V / 2^{12}$
$= 0.88\ mV$!

Op-Amp parameters

Key Op-Amp parameters for Precision

Input offset voltage (Vio)
Precision/ small signal amplification

Common Mode Rejection Ratio (CMRR)

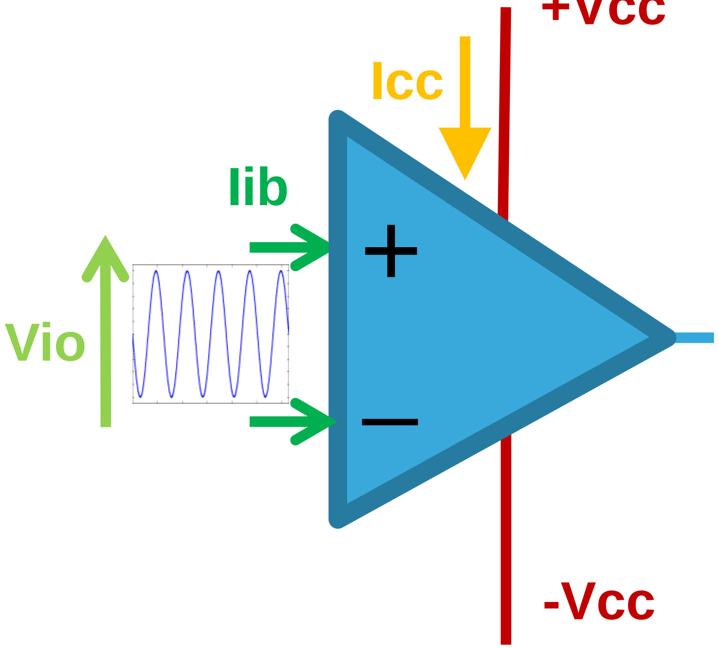
Input bias current (Iib)
High Impedance Sensors
TransImpedance conversion

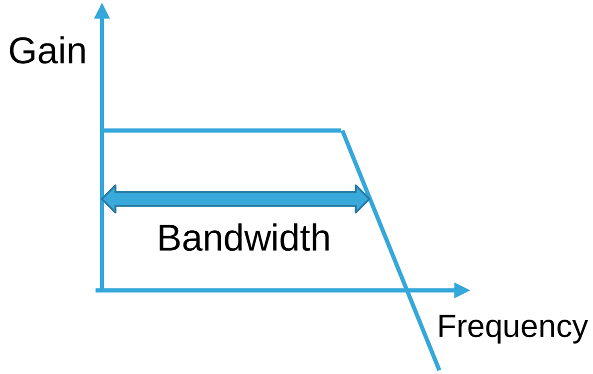
Noise
Output Accuracy in slow applications

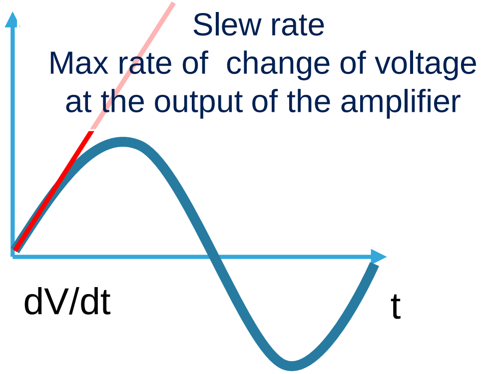
Gain Bandwidth Product (GBP)
Signal frequency

Slew rate (SR)
Response time

Rail to rail input or output
Full scale Signal

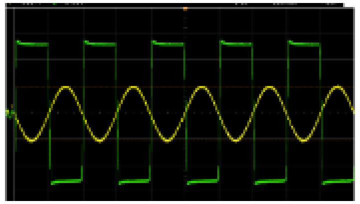






Supply voltage (Vcc)
Application supply range

Supply Current (Icc)
Power consumption /battery life



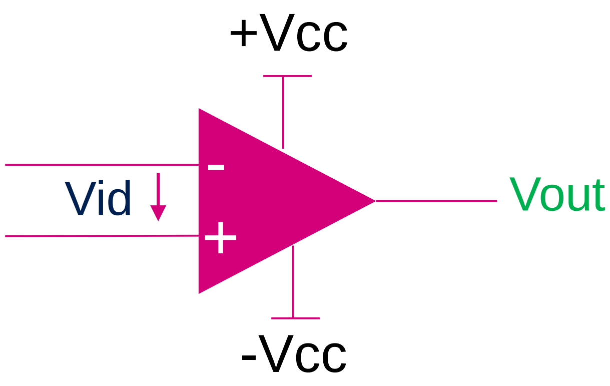
Rail to rail input or output

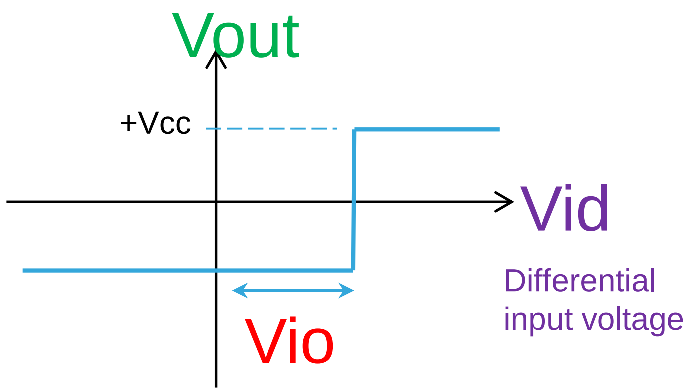
Op Amps: Vio - input offset voltage

Input Offset Voltage

What is this?

- Vio offset





LM324

Symbol	Parameter	Min.	Typ.	Max.	Unit
V_{io}	Input offset voltage [1] T_{amb} = +25° C LM124-LM224 LM324		2	5 7	mV
	$T_{min} \leq T_{amb} \leq T_{max}$ LM124-LM224 LM324			7 9	

TS507

V_{io}	Input offset voltage[2]	V_{icm} = 0 to 3.8 V, T=25 °C TS507C full temperature range TS507I full temperature range		25	100 250 400	µV
		V_{icm} = 0 V to 5 V, T=25 °C TS507C full temperature range TS507I full temperature range			450 550 750	

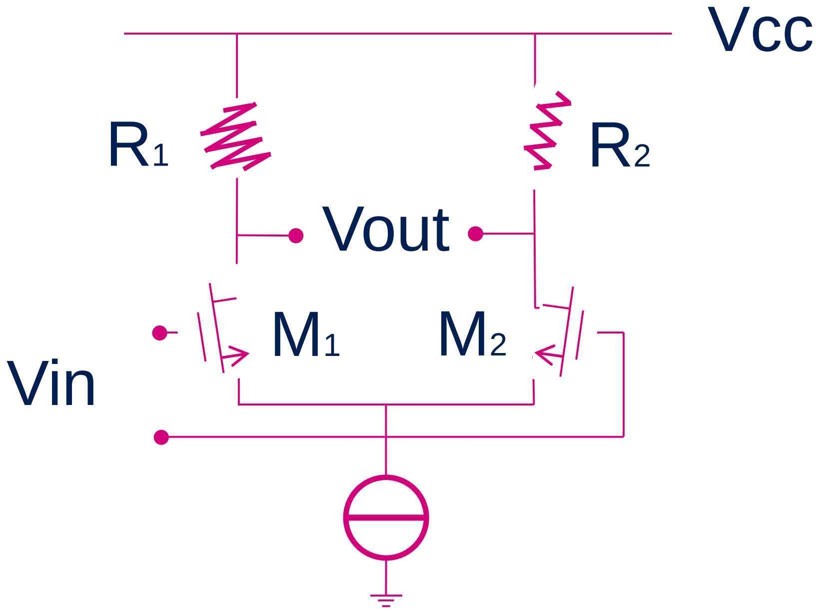
TSZ121 (Very high accuracy)

Symbol	Parameter	Conditions	Min.	Typ.	Max.	Unit
DC performance						
V_{io}	Input offset voltage	T = 25 °C		1	5	µV
		-40 °C < T< 125 °C			8	
$\Delta V_{io}/\Delta T$	Input offset voltage drift[1]	-40 °C < T< 125 °C		10	30	nV/°C

Input Offset Voltage

Where does it comes from?

Differential input



Component mismatch
R1≠R2, M1≠M2 ⇒ **offset**

For CMOS technology

$$\boldsymbol{Vos = \Delta Vth + \frac{VGS-VT}{2}\left(\frac{\Delta R}{R} + \frac{\Delta k\prime}{k\prime} + \frac{\Delta W/L}{W/L}\right)}$$

$\boldsymbol{\Delta Vth}$ linked to the substrate doping.
Second term linked to the MOS size.

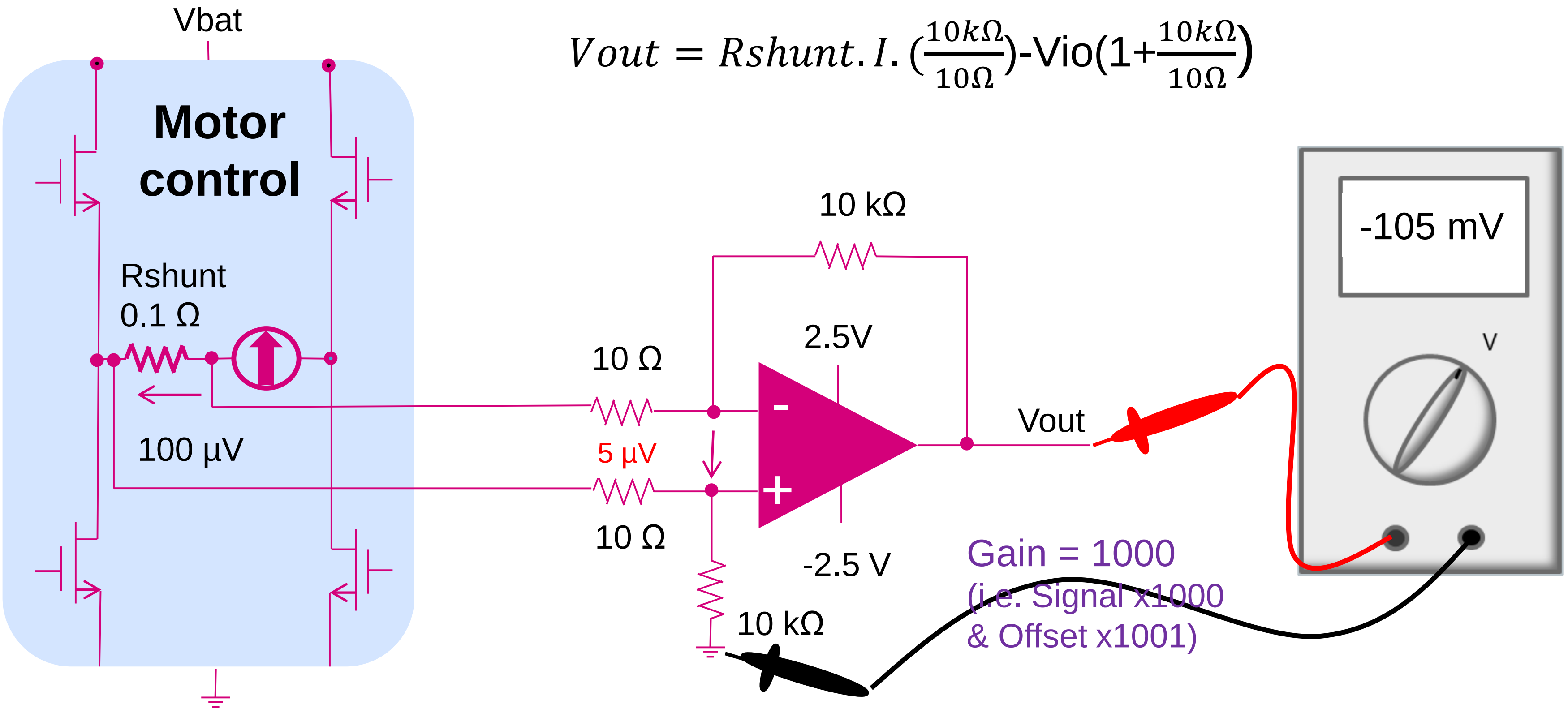
Mismatch is mainly due to:

- Doping variations
- Lithographic errors
- Packaging & local stress

Impact of V_{IO} on a real application

Current sensing for motor control

$$Vout = Rshunt.I.\left(\frac{10k\Omega}{10\Omega}\right) - Vio\left(1+\frac{10k\Omega}{10\Omega}\right)$$



e.g. I = 1 mA in Rshunt

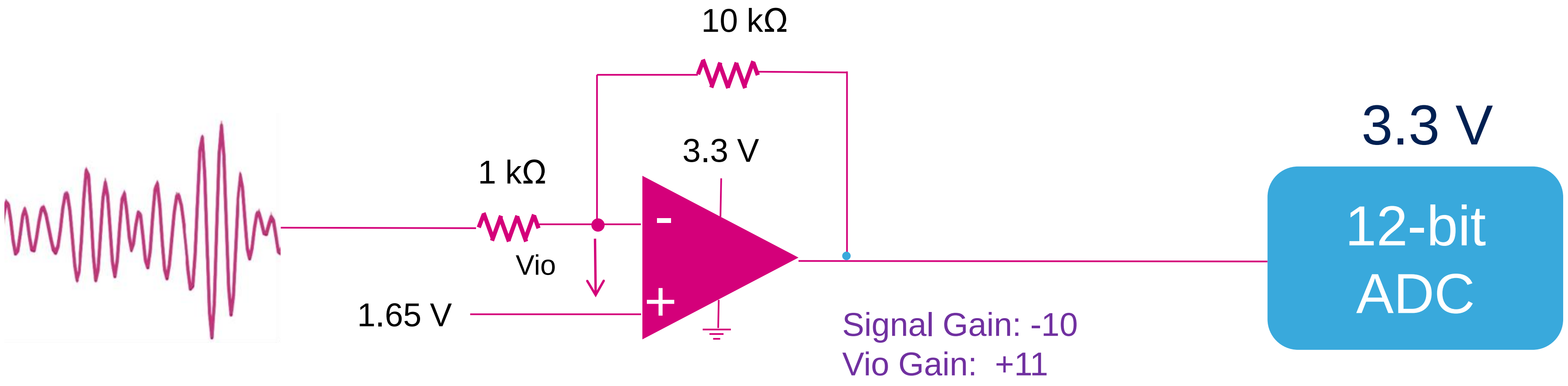
TSZ121
Vio = 5 µV

5% error on speed information
rotation information is correct

Summary of V_{IO} impact
on motor control applications

Opamp	Offset @ 25°C	V_{OUT} for a current I = 1 mA	Comment
Ideal	0 µV	100 mV	Theoretical measurement in a perfect world!
TS507	+100 µV	-100 µV	Speed of the motor is incorrect. Information about the motor rotation is incorrect.
	-100 µV	200 mV	100% error on motor speed. Information about the motor rotation is correct.
TSZ121	+5 µV	95 mV	5% error on the motor speed. Information about the motor rotation is correct.
	-5 µV	-105 mV	5% error on the motor speed. Information about motor rotation is correct.

The real cost of V_{IO}!



The LSB of the ADC is $3.3\ V/2^{12} = 805\ \mu V$
The input signal is amplified by -10, and the V_{IO} by 11

	Maximum V_{IO}	Maximum offset at ADC	Equivalent effective ADC
TSZ121	5 µV	55 µV	~12 bits
TS507	100 µV	1.1 mV	~11 bits
TS512A	500 µV	5.5 mV	~9 bits
TS512	2.5 mV	27.5 mV	~7 bits

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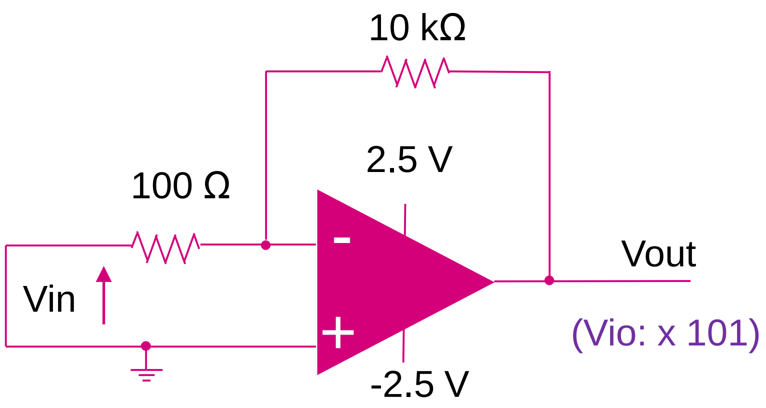
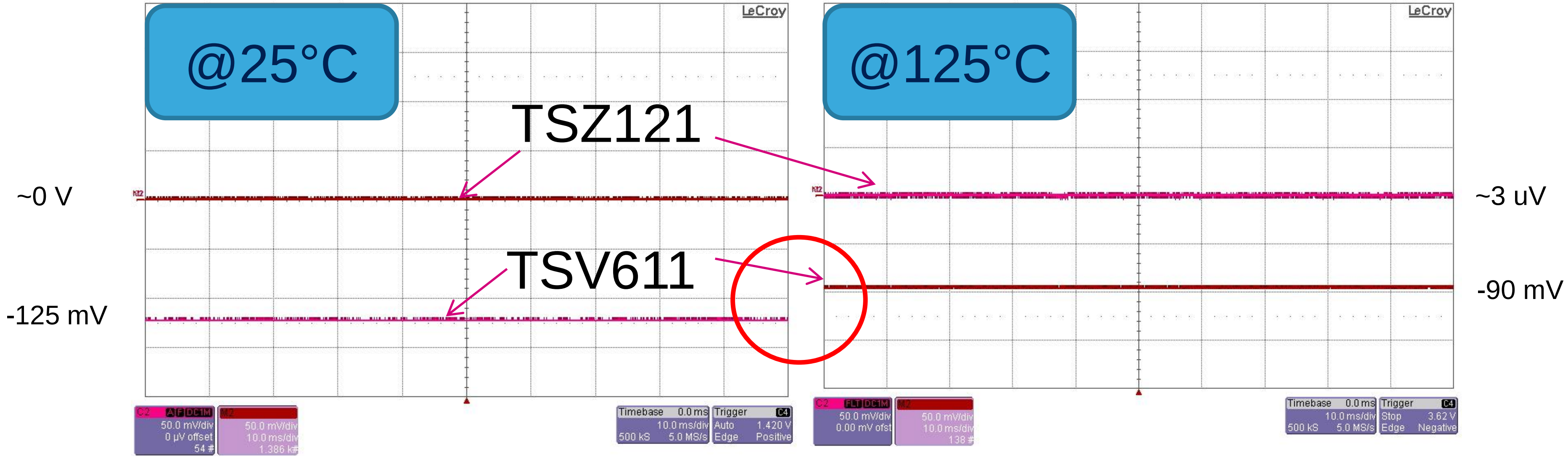
ΔVio/ΔT and calibration



$$Vout = Vin\left(\frac{-10k\Omega}{100\Omega}\right) \pm \mathrm{Vio}\left(1+\frac{10k\Omega}{100\Omega}\right) \quad (1)$$

$$Vout = Vin\left(\frac{-10k\Omega}{100\Omega}\right) \pm \left(\mathrm{Vio} \pm \mathrm{dT}\left(\frac{\Delta Vio}{\Delta T}\right)\right)\left(1+\frac{10k\Omega}{100\Omega}\right) \quad (2)$$



	Vio @25°C max	Δvio/Δt max
TSZ121	5 µV	30 nV/°C
TSV611	4 mV	10 µV/°C

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Op Amps: CMRR – Common Mode Rejection Ratio

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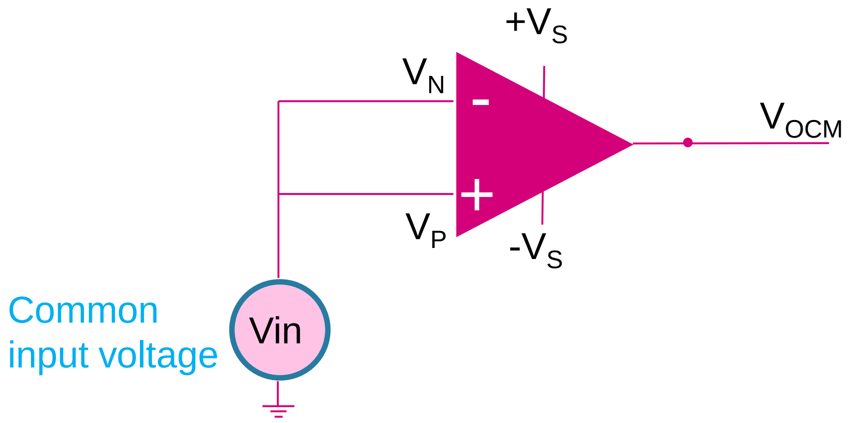
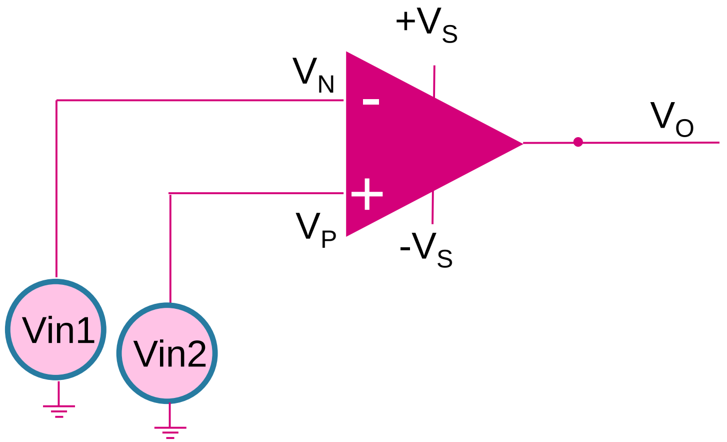
Common Mode Rejection Ratio





$$\text{Common Mode Gain} = \frac{V_{OCM}}{V_P - V_N}$$

$$\text{Differential Gain} = \frac{V_O}{V_P - V_N}$$

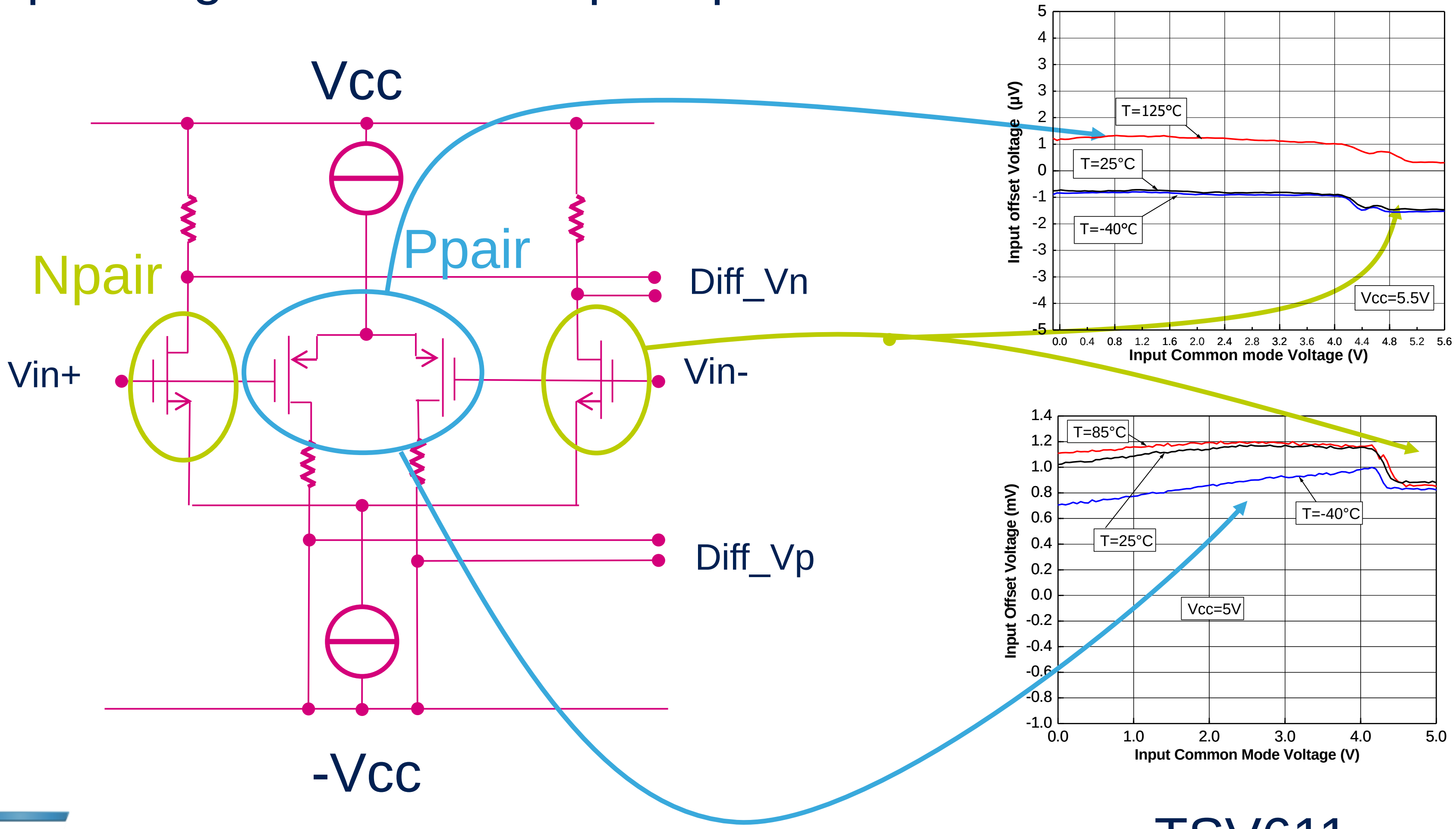
$$\text{Common Mode Rejection Ratio} = \frac{\text{Differential Gain}}{\text{Common Mode Gain}}$$

Essentially CMRR is a measure of the Op-Amp ability to reject the signal which is common to both inputs

Common Mode Rejection Ratio

Input stage of a CMOS op amp

TSZ121



TSV611

- Mismatch between two NMOS or two PMOS is responsible for the Vio.
- No link between the mismatch of the NMOS and the mismatch of the PMOS.
- Each pair will generate its own Vio.

So, depending on the common mode voltage used in the application, the Vio might be different.

Impact of CMRR on battery monitoring

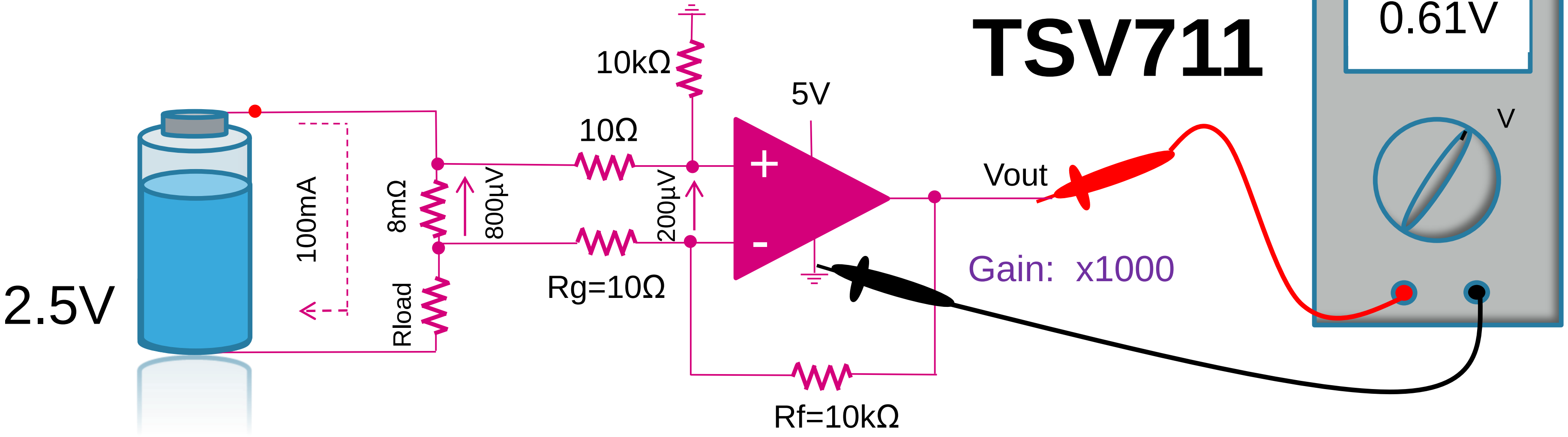
High-side current sensing

$$CMRR_{res} = \frac{1+\frac{Rf}{Rg}}{4\varepsilon}$$

With ε=0.1% precision resistance
and a gain of 1000
The CMRR of the whole schematics is 250250 (108 dB)

$$Vout=0.8-(1+\frac{Rf}{Rg}).Vio \pm \frac{vbat}{CMRRres}(\frac{Rf}{Rg}) \pm \frac{vicm-vcc/2}{CMRRop}(1+\frac{Rf}{Rg})$$

$$Vout = V_{out\_ideal} - k_1.Vio \pm k_2.V_{CMRRresist} \pm k_3.V_{CMMRopamp}$$



TSV711	Impact on Vout	Error %
Vio	0.2V	25%
CMRRres @4.2V (108dB)	16.8mV	2.1%
CMRRop @4.2V (74dB)	340mV	42.5%
CMRRes @2.5V (108dB)	10mV	1.2%
CMRRop @2.5V (74dB)	0mV	0%

Example of impact when
Common Mode is varying.
$V_{common\ mode}$ = (V1 + V2) / 2

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Impact of CMRR on a battery monitoring

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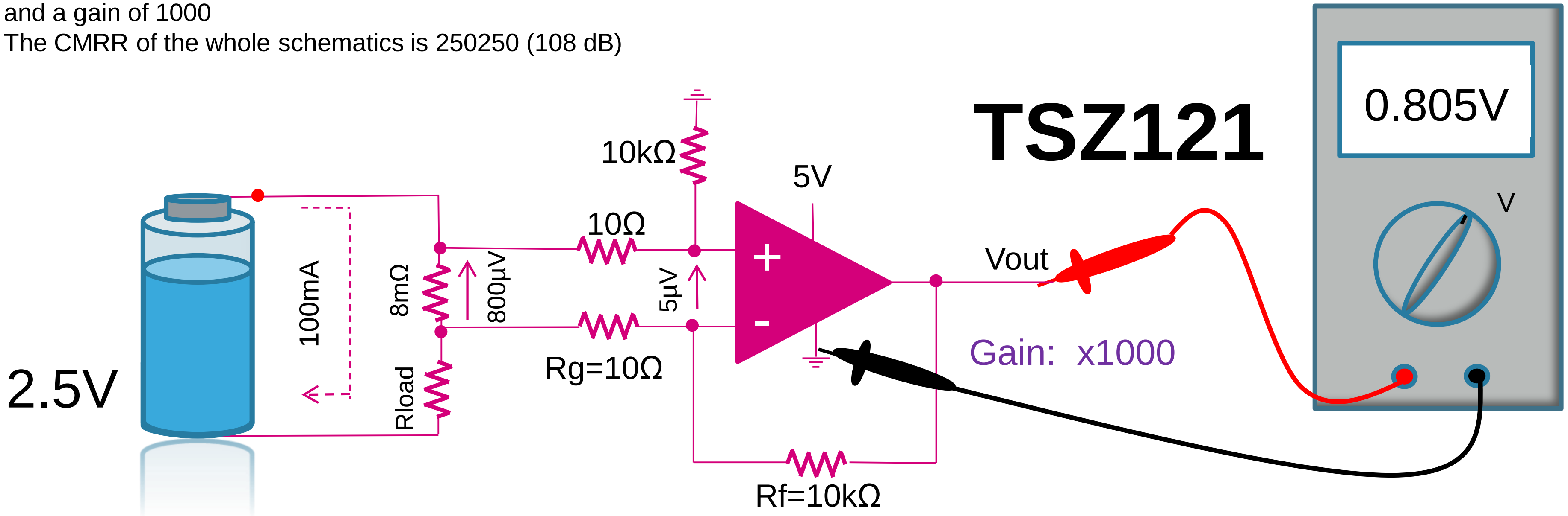

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CMRRop @4.2V (74dB)	340mV	42.5%
CMRRres @2.5V (108dB)	10mV	1.2%
CMRRop @2.5V (74dB)	0mV	0%

TSZ121	Impact on Vout	Error %
Vio	0.005V	0.5%
CMRRres @4.2V (108dB)	16.8mV	2.1%
CMRRop @4.2V (115dB)	3mV	0.4%
CMRRres @2.5V (108dB)	10mV	1.2%
CMRRop @2.5V (115dB)	0mV	0%

V_{IO}, CMRR, PSRR and A_{VD}

(Power supply rejection ration)

PSRR

Input offset

$$Vid = Vio + \frac{\partial Vid}{\partial Vout}\Delta Vout + \frac{\partial Vid}{\partial Vicm}\Delta Vicm + \frac{\partial Vid}{\partial Vcc}\Delta Vcc + \frac{\partial Vid}{\partial T}\Delta T \quad (1)$$

A_{VD}

(differential voltage amplification)

CMRR

(Common Mode rejection ration)

Input offset drift

$$We\ define: Avd = -20\log\left(\left|\frac{\partial Vid}{\partial Vout}\right|\right),\ CMRR = -20\log\left(\left|\frac{\partial Vid}{\partial Vicm}\right|\right),\ SVR = -20\log\left(\left|\frac{\partial Vid}{\partial Vcc}\right|\right)\ and\ DV_{io} = \left|\frac{\partial Vid}{\partial T}\right|$$

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Op Amps: Iib – Input bias current

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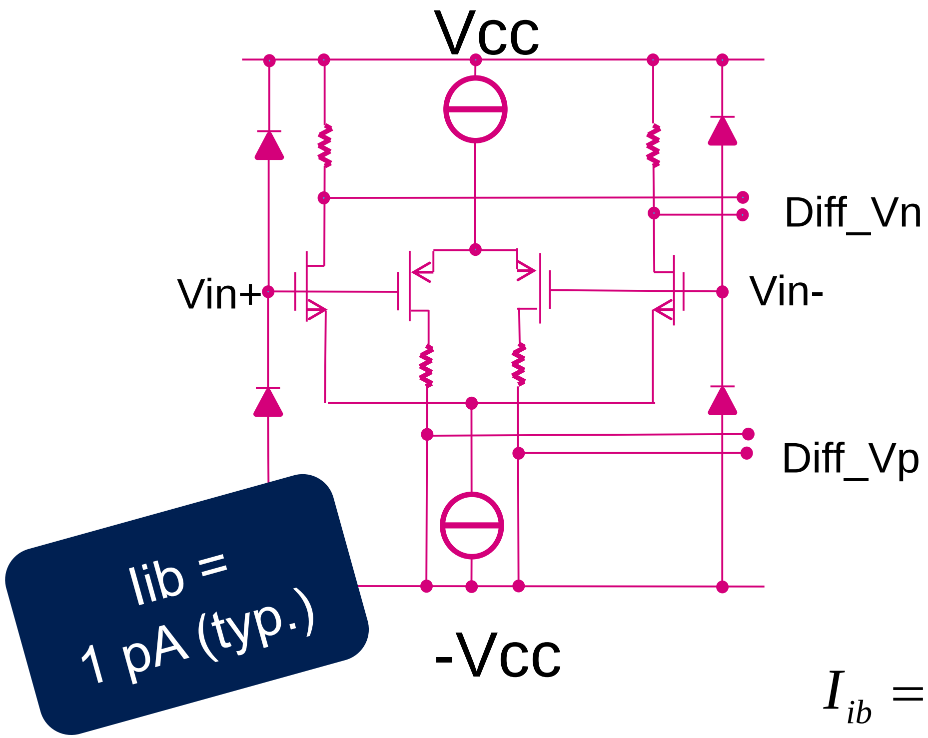
Input bias current

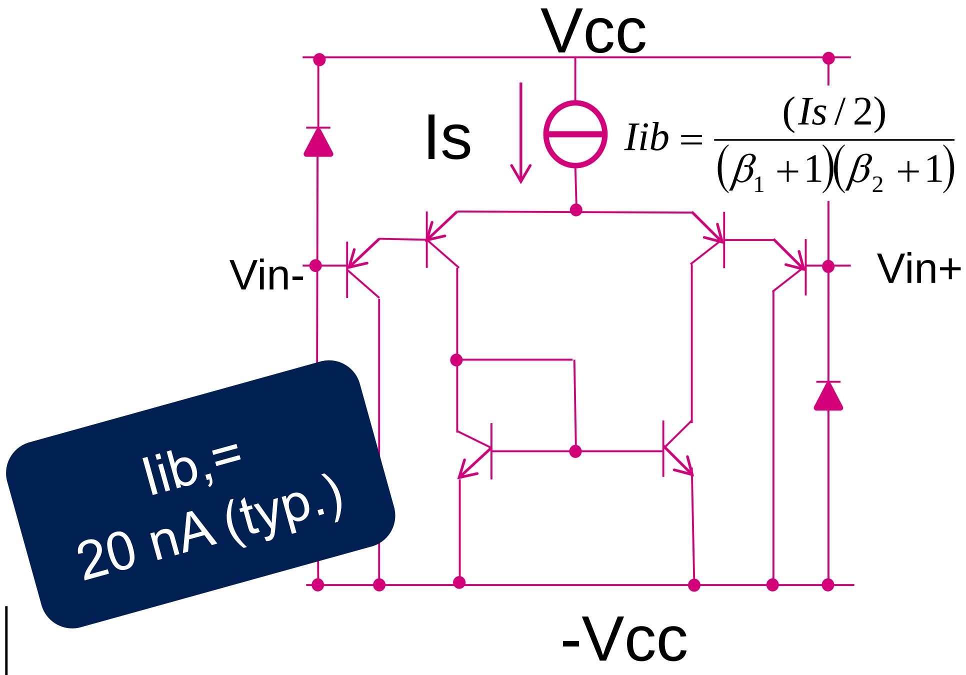
CMOS

No gate current, only diode leakage



BIPOLAR

Current in/out (NPN/PNP) in the base

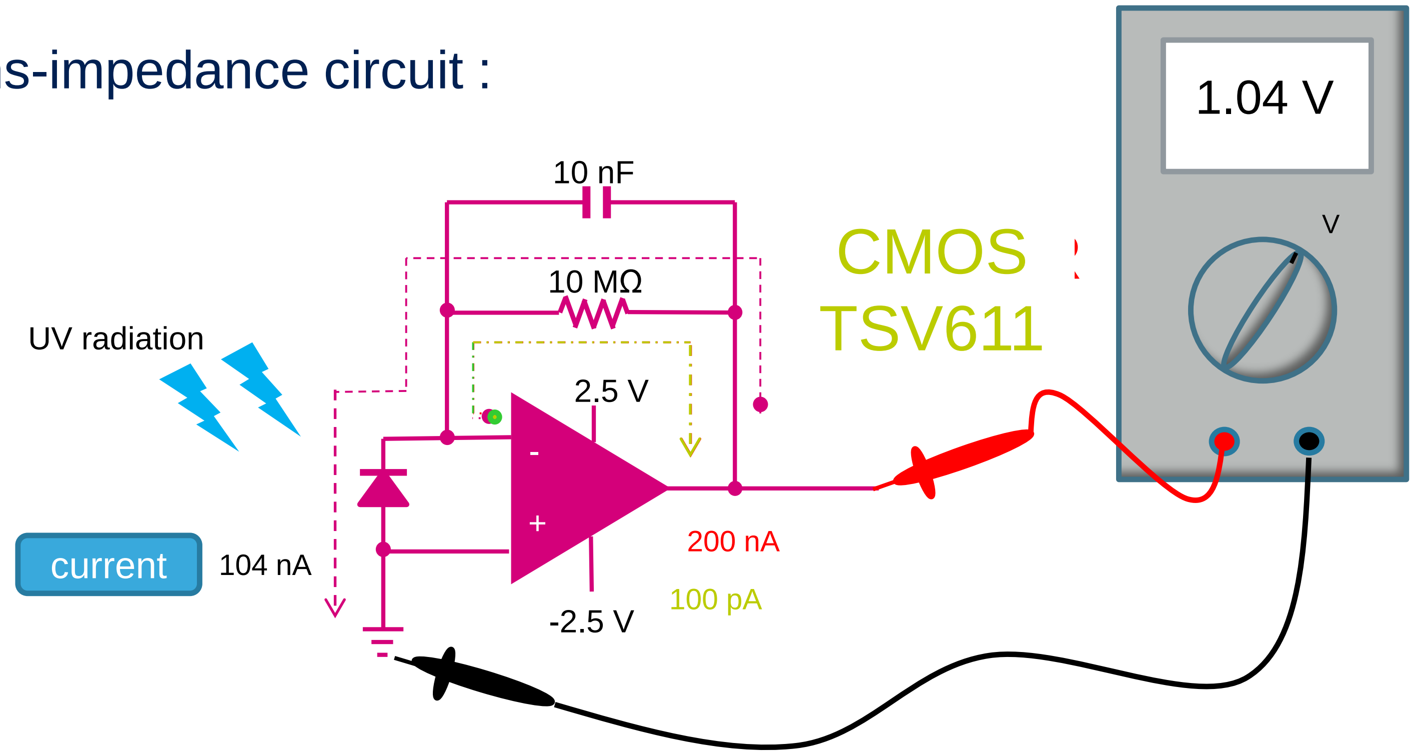


$$I_{ib} = \left| \frac{I_{ibn} + I_{ibp}}{2} \right|$$

- Input currents are also important sources of error, especially for high source impedances (>100kΩ)

UV sensor application

- UV source Index: 4
- Trans-impedance circuit :



UV table translation for the UV sensor and Gain of 10M						
UV1	UV2	UV3	UV4	UV5	UV6	UV7
0.26 V	0.52 V	0.78 V	1.04 V	1.3 V	1.56 V	1.82 V

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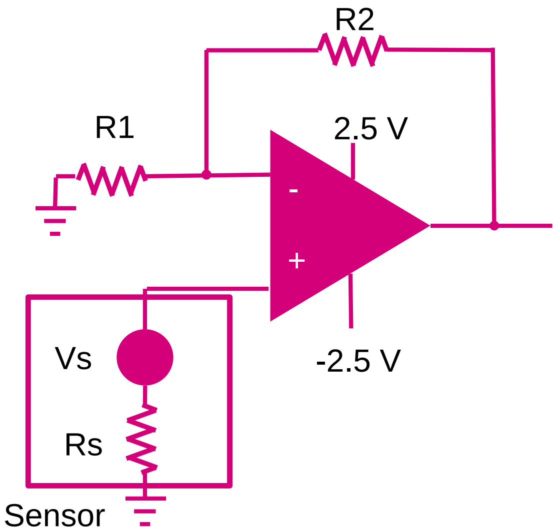
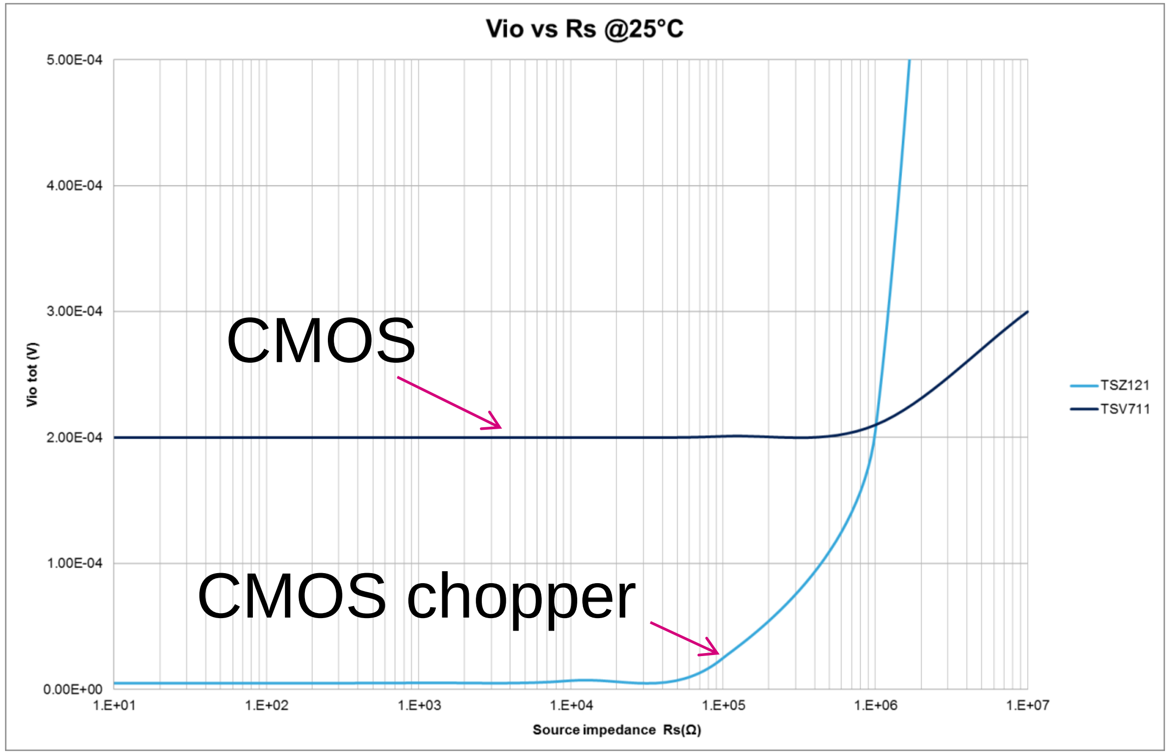
Is the TSZ121 chopper
always a good choice?





$$\text{Vio tot} = Vio + Rs.In \quad (1)$$

$$\text{Rs} > \frac{Vio}{In+} \quad (2)$$

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Op Amps: Noise

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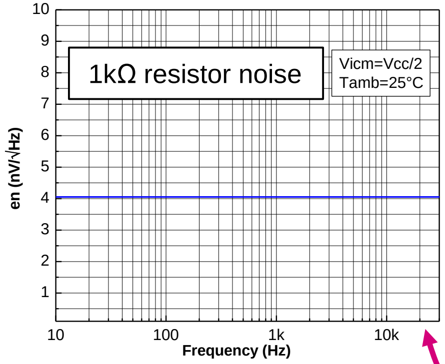
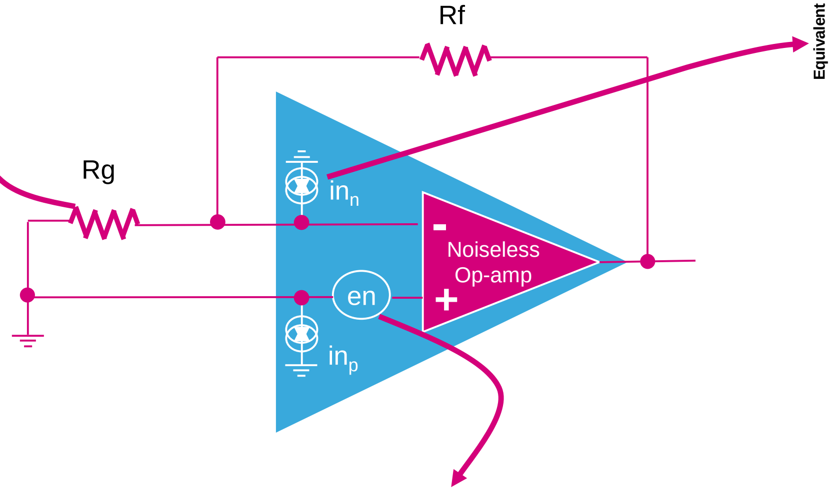
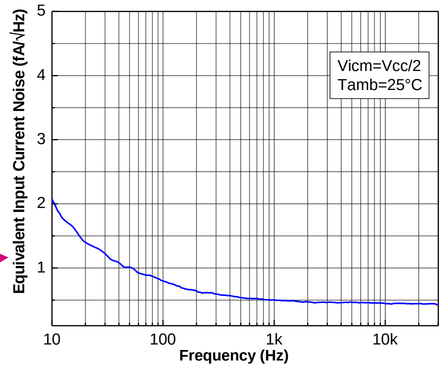
Noise sources of an op amp



There are 5 sources of noise





Resistors Rf & Rg generate a white noise with a spectral density of:

$$e_n = \sqrt{4kTR} \quad VHz^{-\frac{1}{2}}$$

For CMOS input op amps, input noise current Inn is extremely low (0.5fA/√Hz) and generally does not affect design

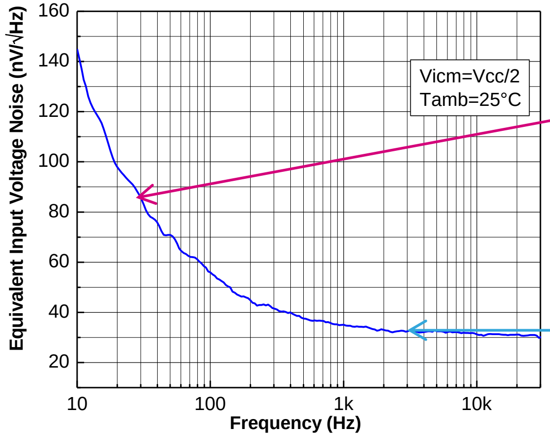
Where

$k = 1.38\,10^{-23} \; JK^{-1}$

(Boltzmann's constant)

$T = T(^{\circ}C) + 273.15$

(Temperature in Kelvin)



$\frac{1}{f}$ noise (flicker noise)

Input noise voltage: $e_{nf}(f) = \sqrt{\frac{enf\,(1Hz)}{f}}$ V/√hz

White noise

en V/√hz

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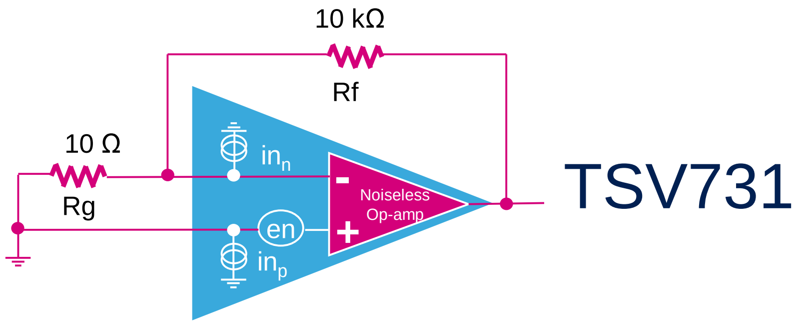
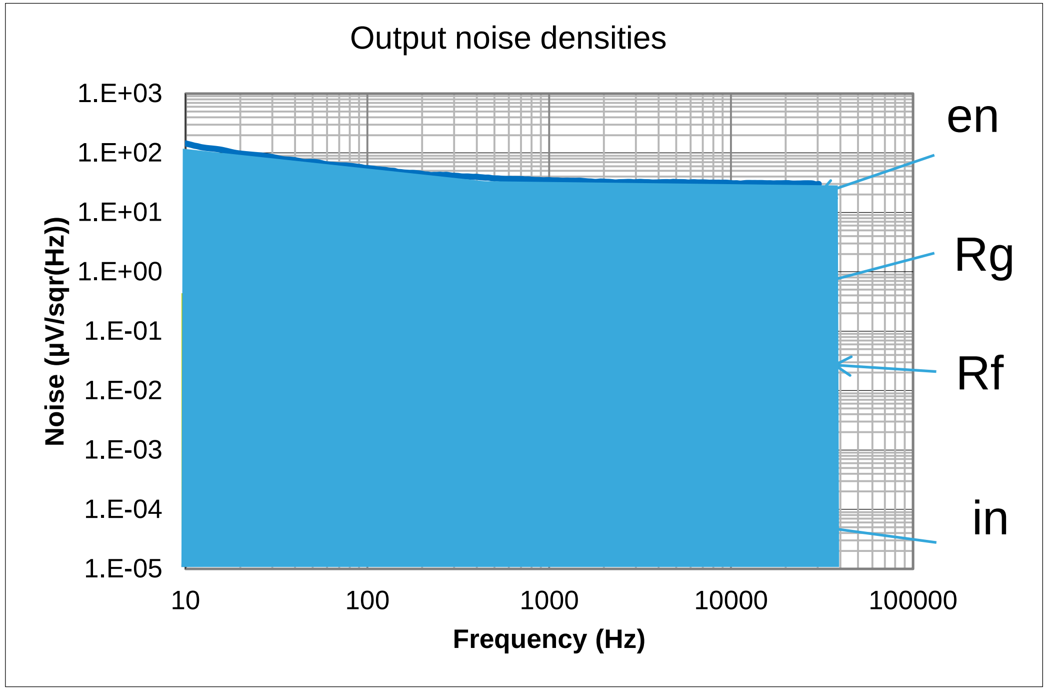
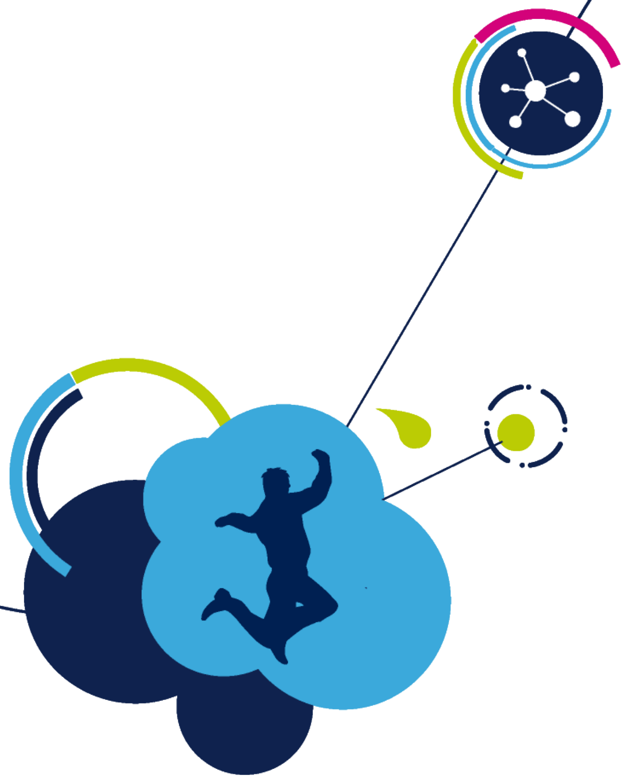
Contribution of each source of noise





Noise voltage contribution to the output BW = 30 kHz		
Noise Source		en V_{RMS}
OPAMP	en	$5.37\ 10^{-3}$
	In	$8.66\ 10^{-9}$
THERMAL	Rf	$2.2\ 10^{-6}$
	Rg	$70.5\ 10^{-6}$

$$VoutRms = \sqrt{en^2 + In^2 + Rf^2 + Rg^2}$$



Use-case study: Gas sensor

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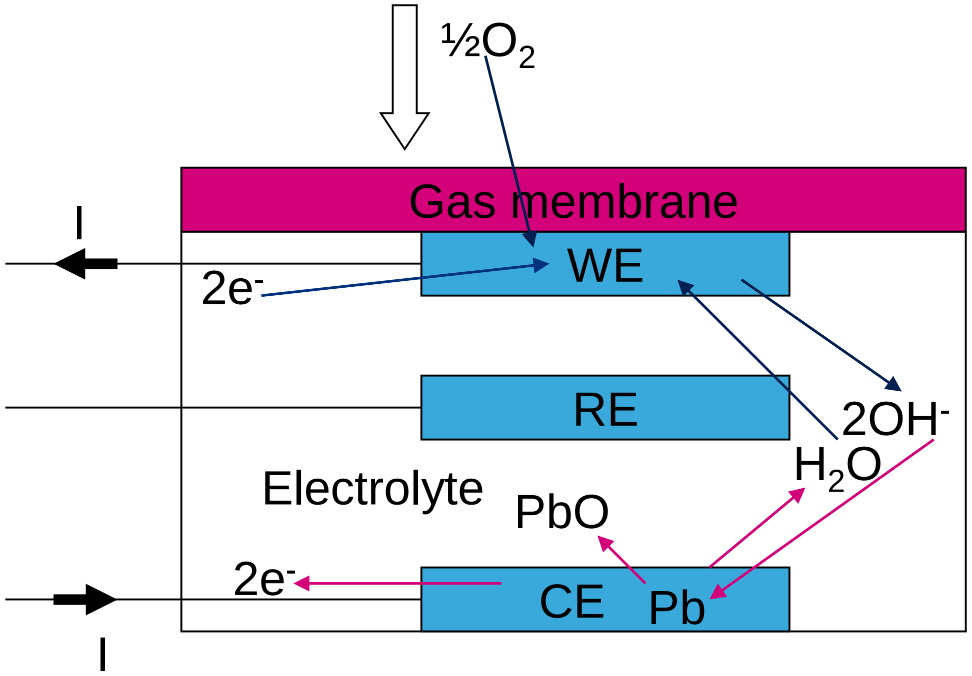
Gas sensors

- Unmonitored gas can rapidly become a danger
- In many industries such as refining, mining, and semiconductor industries, monitoring air quality is mandatory for security reasons.
- Different gas sensor technologies exist.
  - The **electrochemical sensing** technique has the advantage of having a linear output and operating with a low consumption
  - → it operates on batteries for a long period of time
  - Other types of technologies : Metal Oxide Semiconductor, Non Dispersive Infra Red
- Most frequently gases monitored using electrochemical sensors:
  - Oxygen (O2), Carbon Monoxide (CO), Hydrogen Sulfide (H2S) and Nitrogen Dioxide (NO2).

What is an electrochemical sensor

- The sensor generates a current flowing from WE to CE
  - The current generated by the chemical reactions is proportional to the gas concentration.



Oxygen sensor

<u>Case of O2 sensor:</u>

Oxidation on Working Electrode (WE)

$CO + H_2O \rightarrow CO_2 + 2H^+ + 2e^-$

Reduction on Counter Electrode (CE)

$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$

Reference Electrode (RE)

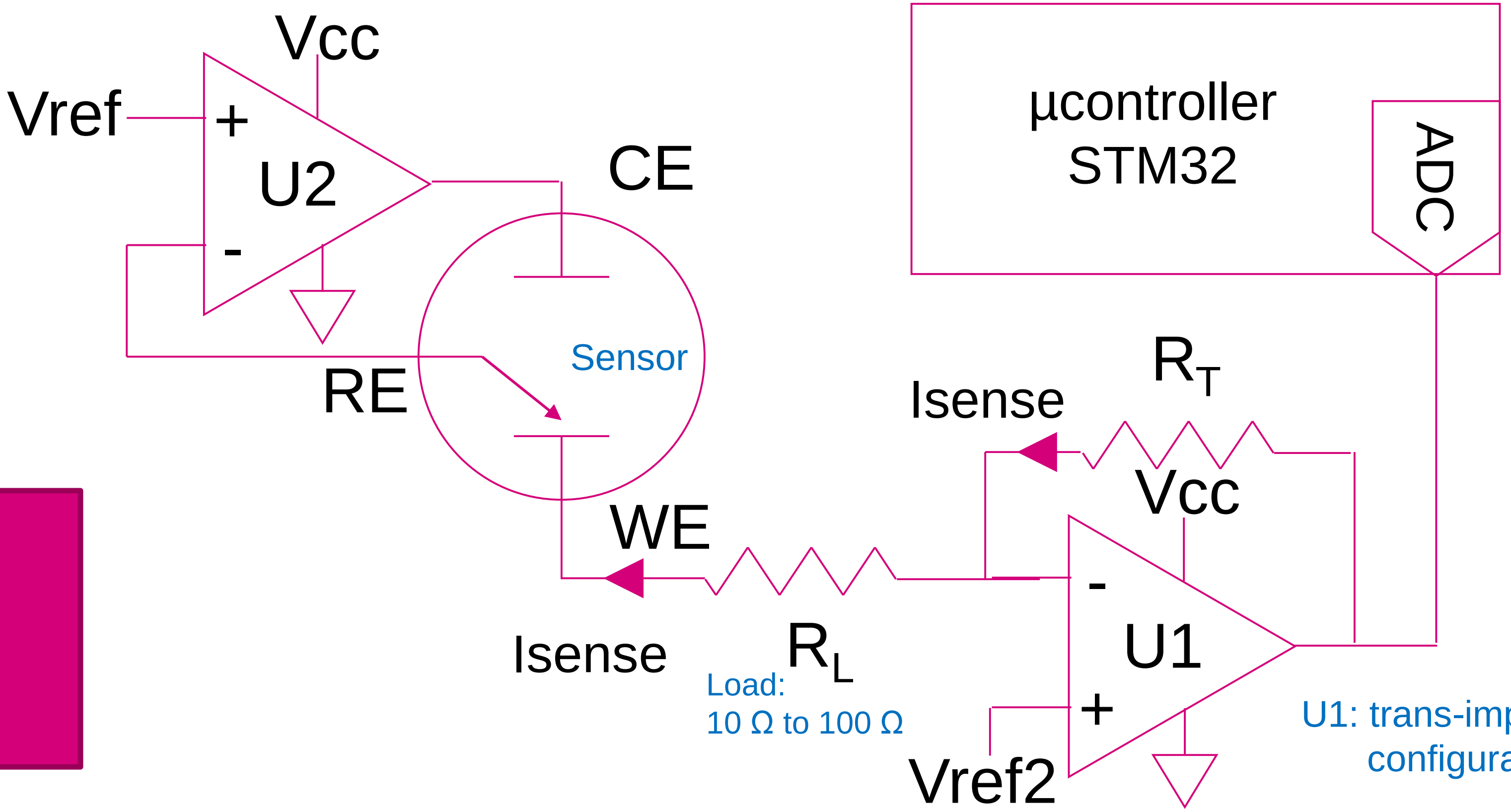
no chemical reaction at the surface,

no current flows.

Electrochemical carbon monoxide sensor and glucometer test strip

3 electrode sensors : Potentiostat

U2: Need to Apply voltage between WE and RE.
No current through RE.



U1: trans-impedance configuration

U1/U2 :

- **TSU112,**
- **TSU102,**
- **TSV712**

Need for ST op-amps !

-Bias the sensor

U2 : RE set to Vref without driving current

-Convert the current into voltage (to drive the ADC)

U1 : Vout= Vref2 + R_T*Isense

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Choosing an Op-amp key parameters

- Small currents means CMOS device
- Rail to rail op-amps preferred especially for low voltages and sensors that require a biasing different than 0V
- Low consumption (battery powered applications)
- Small package

TSZ121/TSZ122/TSZ124
Vio 5uV max

TSU101/TSU102/TSU104
600nA / channel

CMOS
Low Power
Rail to Rail
SC70-5 / DFN8 2x2

TSU111/TSU112/TSU114
900nA / channel, Vio 150uv max

TSV711/TSV712/TSV714
9uA / channel, Vio 200uV max

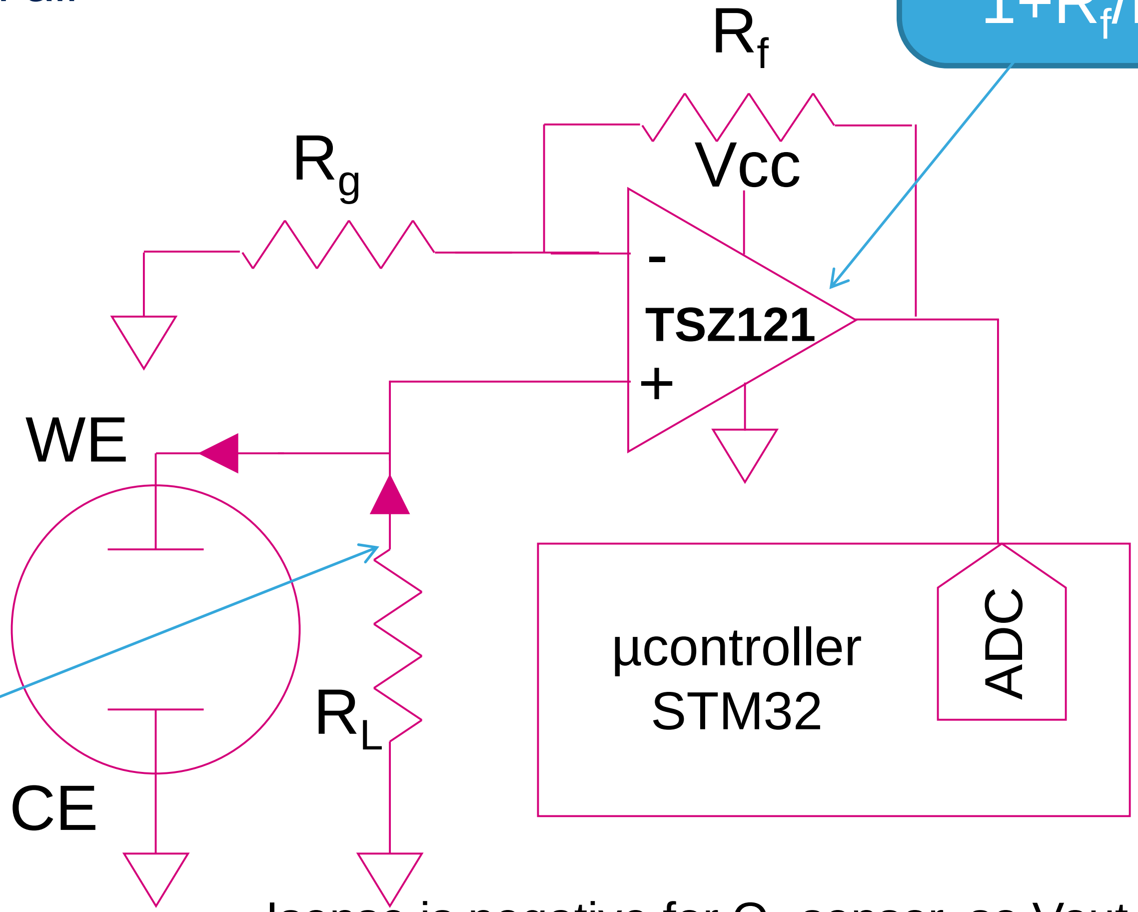
2 electrode sensors : Galvanic configuration

- Alternative config: Voltage drop through Load res. and Amplify
- I to V conversion done by R_L (100Ω)
- Small signal to amplify ~350uA x 100Ω=35mV in air
- Op-amp used in voltage gain need for accuracy

Voltage gain
$1+R_f/R_g$

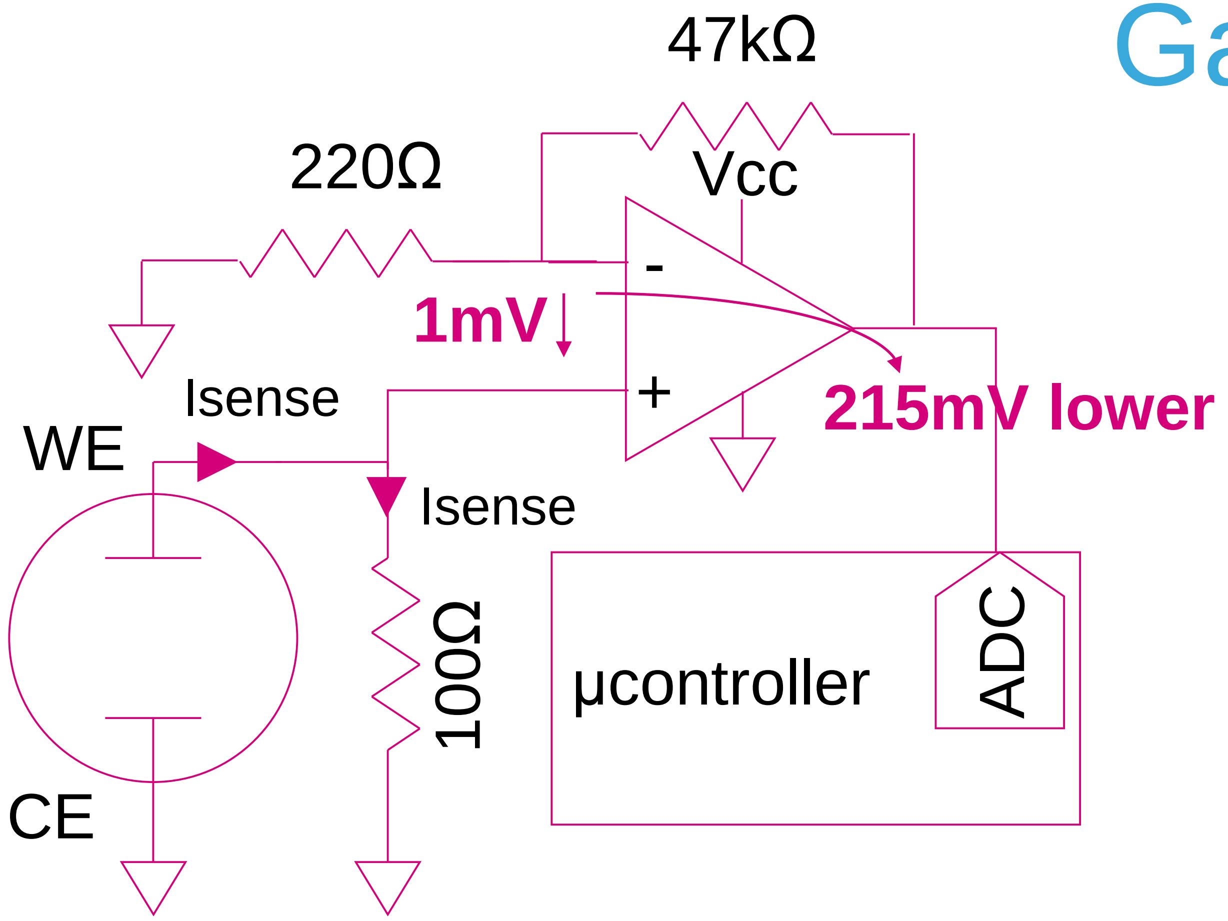
TSZ121
High precision amplifier
5uV max
30nV/°C max
29uA typ

I to V conversion
$I*R_L$



Isense is negative for O_2 sensor, so Vout positive

Galvanic sensor - Vio



O_2 sensor specification

Output Signal	0.10 ± 0.02mA in air
Recommended Load Resistor	100Ω

This sensor we have outputs 90.8uA in air*

Voltage to amplify : 9.08mV

In air* output voltage should be 9.08mVx(1+47/0.22)=**1.95V**

(*air means [O2]=20.9%)

	Output voltage	Vio	[02] equivalent
TSZ121	**1.95V**	**5uV max**	**20.9%**
Standard micro-power device	**1.74V**	**1mV**	**18.6%**

The input offset voltage can cause a significant offset (alarm would ring in air for 2nd case device!)

Take away

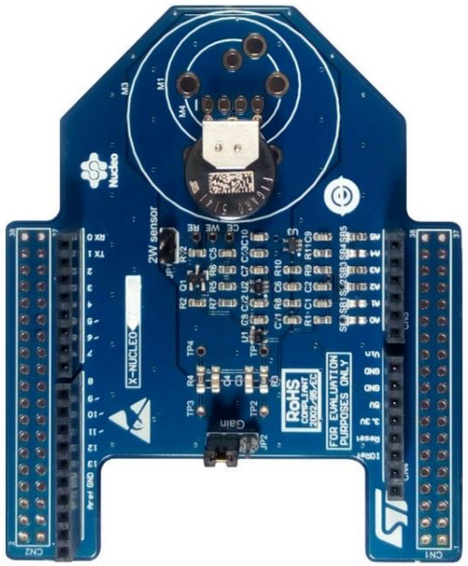
Electrochemical sensors need
High performance Opamps
Different Opamp solutions depending on Sensors & Application constraints.

Products	Features (all specifications given at 3.3 V)
TSU111 **TSU112** **TSU114**	Ultra low consumption: 900 nA typ Low low noise: 3.7 µVpp from 0.1 Hz to 10 Hz Good precision: 150 µV max
TSU101 **TSU102** **TSU104**	Ultra low consumption: 600 nA typ Battery life extension
TSV711 **TSV712** **TSV714**	Good compromise between consumption and precision Icc: 9 µA typ Vio: 200 µV max
TSZ121 **TSZ122** **TSZ124**	Excellent precision: Vio 5 µV max Ultra low noise: 0.8 µVpp from 0.1 Hz to 10 Hz Ideal for galvanic use

Electrochemical gas sensor evaluation pack

2 videos released in February 2018

Order code : **P-NUCLEO-IKA02A1**



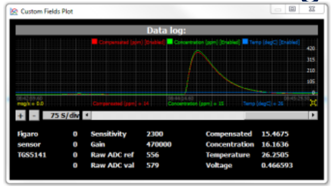
Board

2 x TSU111 nano-power op amps

- Are used for signal conditioning
- Are ideal for electrochemical sensing thanks to high precision and low power consumption

Getting Started

- STM32 Nucleo pack for electrochemical toxic gas sensing



Wireless CO detector demo

- Based on **TSU111** Op Amps and **S2-LP** sub-1GHz RF transceiver and Figaro TGS5141 CO sensor

ST High-Performance Op-Amp Product Line

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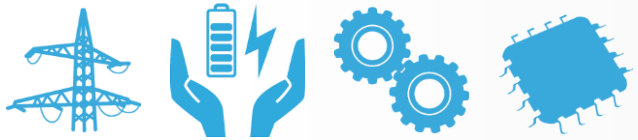
General Purpose Analog

The best choice for longevity, robustness and power efficiency



- 40 years experience in analog
- 5 Billion units manufactured per year (100 units/s)
- 5,400 commercial parts
- Worldwide Customer Base
- Large Technology portfolio From Analog to Mixed Signal
- High reliability products 0.05ppm for Automotive Grade, 1ppm for Standard Grade

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From Standard to High Performance

1980 → **2019**

Icc (LM358)
1.2mA max @25°C

power savings

*supply current enhanced by *1400*

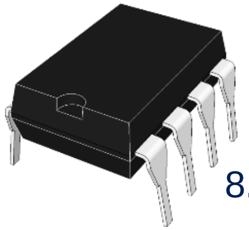
Icc (TSU101)
850nA max @25°C

Vio (LM358)
7mV max @25°C

accuracy

*input offset enhanced by *1400*

Vio (TSZ121)
5µV max @25°C

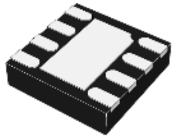


DIP8
8.8mm*6.4mm*4mm

space saving

*volume enhanced by *100*

DFN8
2mm*2mm*0.55mm



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High-Performance Op-Amps

	Nano Power	Micro Power	Low Power	Zero Drift (chopper)	Precision	Energy effective	Fast (High speed)
5 V	TSU	TSV6 🚗	TSV8 🚗	TSZ 🚗	TSV7	TSV5 🚗	TSV9 🚗
16 V		TSX6 🚗			TSX7 🚗	TSX5 🚗	TSX9 🚗
36 V		TSB6 🚗			TSB7 🚗	TSB5 🚗	TSB9 *

🚗 AECQ-100   * In development

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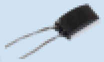
Analog sensors for smart building

Analog Sensor	Circuit topology	Low power	High Accuracy	Wide band	App note
UV sensor Ambient light 	Transimpedance amplifier	TSU101		TSV631	AN4451
Smoke detector 	Transimpedance amplifier	TSV6292		TSV522	
CO detector 	Potentiostat, Transimpedance ampl. or I to V converter	TSU102	TSZ122	TSV732	AN4348
PIR detector 	AC coupled filters with window comparator	TSU104			AN4368
Temperature sensing (RTD) 	Current source + non-inverting amplifier or Instrumentation amplifier	TSV714	TSZ124		

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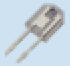
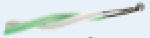
Analog sensors for automotive

Analog Sensor	Circuit topology	Low power	High Accuracy	Wide band	App note
Rain detector Light sensor (Photodiode) 	Transimpedance amplifier	TSV631 IYLT		TSV522 IYST	AN4451
Temperature sensing (Thermocouple) 	Instrumentation amplifier (small signal)	TSX712 IYST	TSZ124 IYPT		
Steering angle (resolver) 	Resolver	TSX564 IYPT		TSX922 IYDT	
NO_x / NH_3 sensor 	Potentiostat, Transimpedance ampl. or I to V converter			TSV912 HYDT	
O2 Sensor 	Potentiostat, Transimpedance ampl. or I to V converter	TSV522 IYST		TSV912 HYDT	

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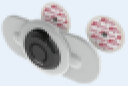
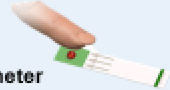
Analog sensors for wearables and health

Analog Sensor	Circuit topology	Low power	High Accuracy	Wide band	App note
Gesture recognition (EMG - electromyography) 	Instrumentation amplifier (small signal)		TSZ124		
Heart rate (2point ECG) 	Instrumentation amplifier (small signal)		TSZ124		
Heart rate + O_2 Pulse oximetry 	Transimpedance amplifier	TSU102			AN4451
Glucose meter 	Reference + 2x transimpedance	TSV612	TSV712		
Blood pressure (piezo resistive) 	Instrumentation amplifier (Wheatstone bridge)	TSV714	TSZ124		

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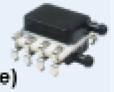
Analog sensors for Industry 4.0

Analog Sensor	Circuit topology	Low power	High Accuracy	Wide band	App note
4-20mA current loop 	Current driver + differential amplifier	TSB611	TSX711	TSB572	
Contactless temperature (Thermopile) 	(Buffer + Instrumentation amplifier + adder) or inverting amplifier	TSZ124			
Transmissive / reflective sensors 	Transimpedance amplifier	TSU101		TSV911	AN4451
Pressure (piezo resistive) 	Instrumentation amplifier (Wheatstone bridge)	TSV714	TSZ124	TSX712	
Force / pressure (strain gauge) 	Instrumentation amplifier (Wheatstone bridge)	TSV714	TSZ124	TSX712	

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TSZ121 versus OPA333

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Texas Instruments

Cross-reference proposed by ST Op amp mobile application

Parameters in green are better or equivalent

OPA333

Part name	Vendor	Vcc min (V)	Vcc max (V)	Icc typ (µA)	Vio max (mV)	GBW (MHz)	R2R
OPA333	TI	1.8	5.5	7	0.01	0.35	Oui
TSZ121	ST	1.8	5.5	31	0.005	0.4	Oui
TSV711	ST	1.5	5.5	10	0.2	0.12	Oui
TSV731	ST	1.5	5.5	60	0.2	0.9	Oui

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Thank You

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