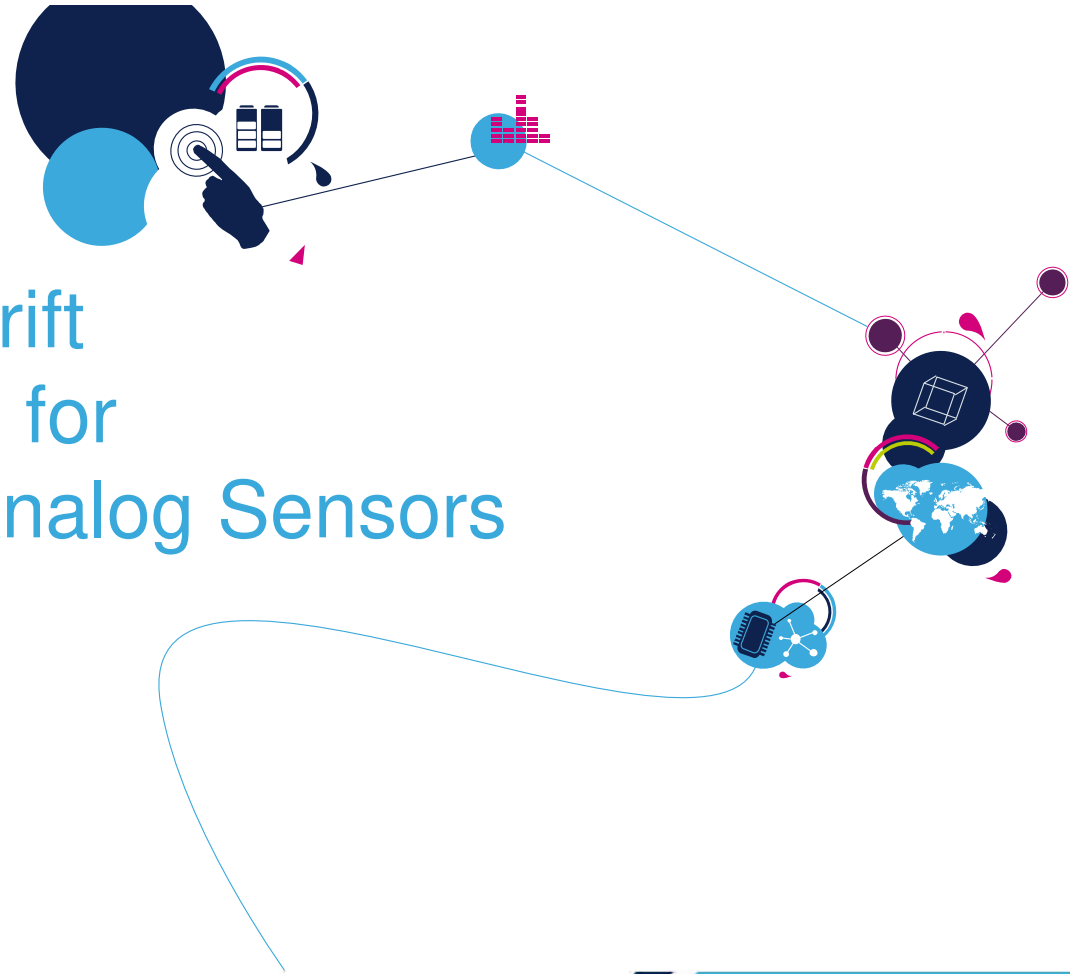


Ultra-low Power, Zero Drift Operational Amplifiers for Industrial and Remote Analog Sensors

Gregory Gosciniak
STMicroelectronics



Technology Tour 2019
Minneapolis, MN | October 24



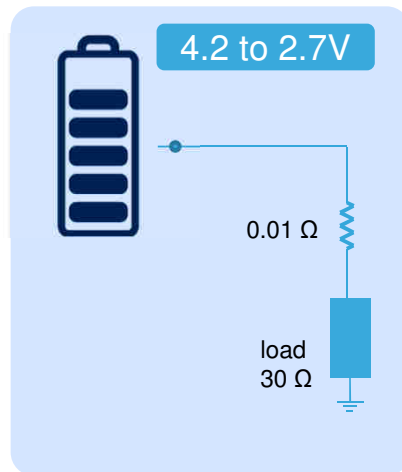
Agenda 2

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

Why Op Amps and why precision

3

Battery fuel gauging



$0.9 \text{ mV} \leq V1 \text{ max} \leq 1.4 \text{ mV}$

Very small signal



Need to amplify

STM32 power supply:
1.65 to 3.6V

12-bit
ADC



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

Input offset voltage (V_{io})

Precision/ small signal amplification

Common Mode Rejection Ratio (CMRR)

Input bias current (I_{ib})

High Impedance Sensors
Transimpedance conversion

Noise

Output Accuracy in slow applications

Gain Bandwidth Product (GBP)

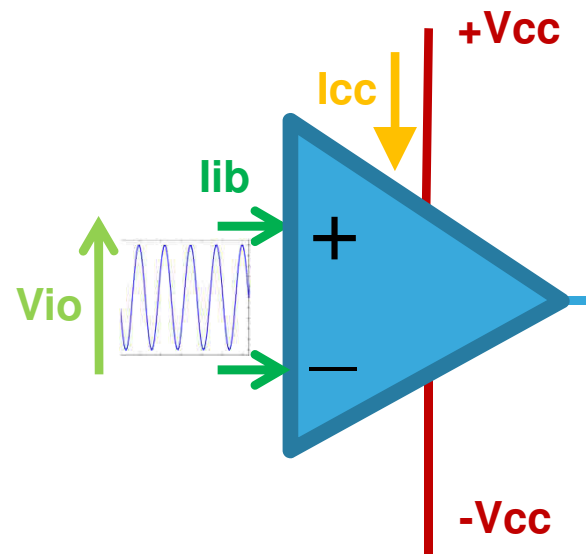
Signal frequency

Slew rate (SR)

Response time

Rail to rail input or output

Full scale Signal



Supply voltage (V_{cc})

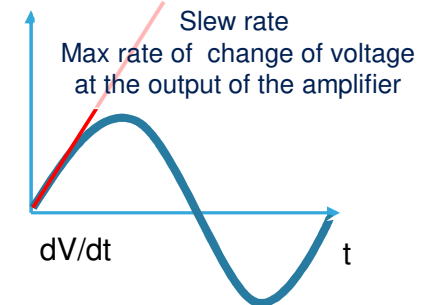
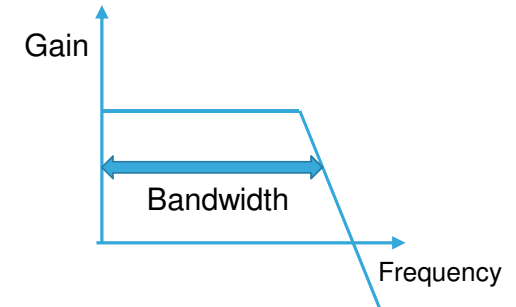
Application supply range

Supply Current (I_{cc})

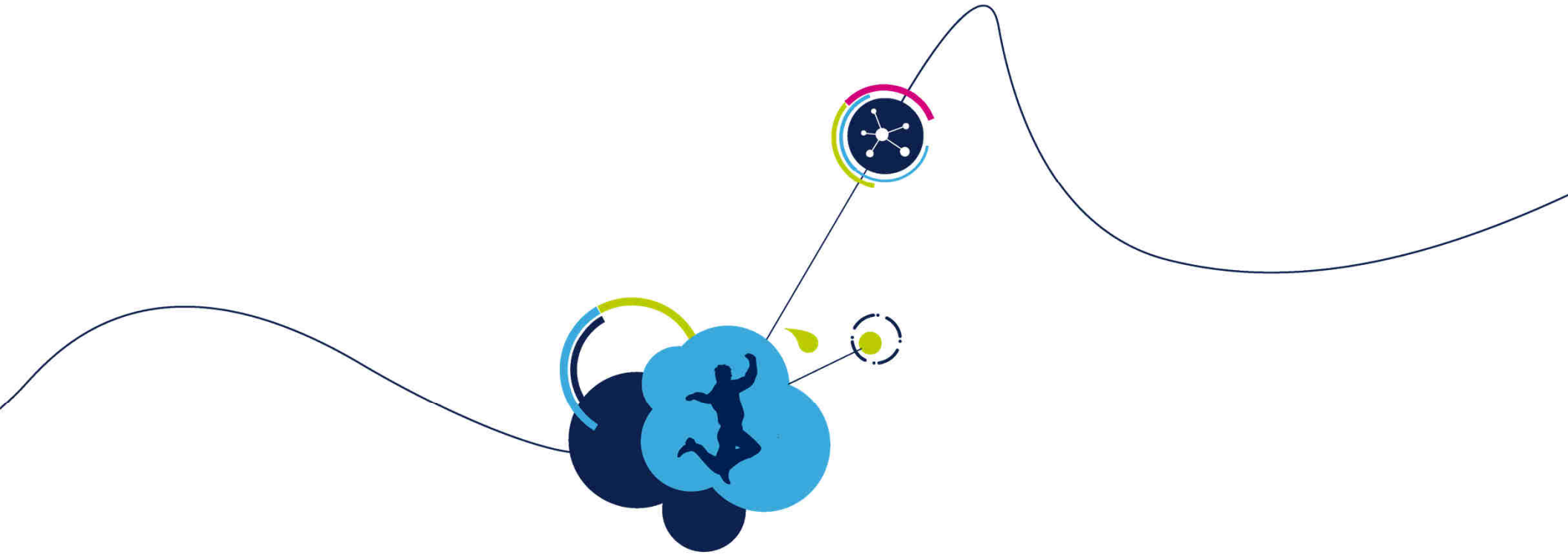
Power consumption /battery life

Op-Amp parameters

4



Rail to rail input or output

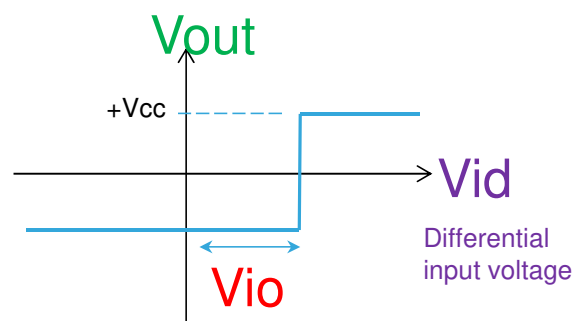
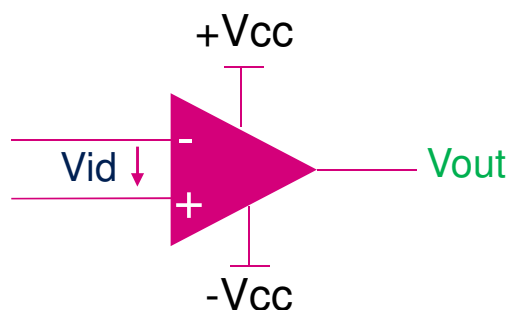


Op Amps: V_{io} - input offset voltage

Input Offset Voltage

What is this?

- Vio offset



LM324

Symbol	Parameter	Min.	Typ.	Max.	Unit
V_{io}	Input offset voltage ⁽¹⁾ $T_{amb} = +25^{\circ}C$ 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 $3.8V$, $T = 25^{\circ}C$ TS507C full temperature range TS507I full temperature range		25	100 250 400	μV
		$V_{icm} = 0V$ to $5V$, $T = 25^{\circ}C$ TS507C full temperature range TS507I full temperature range			450 550 750	

TSZ121 (Very high accuracy)

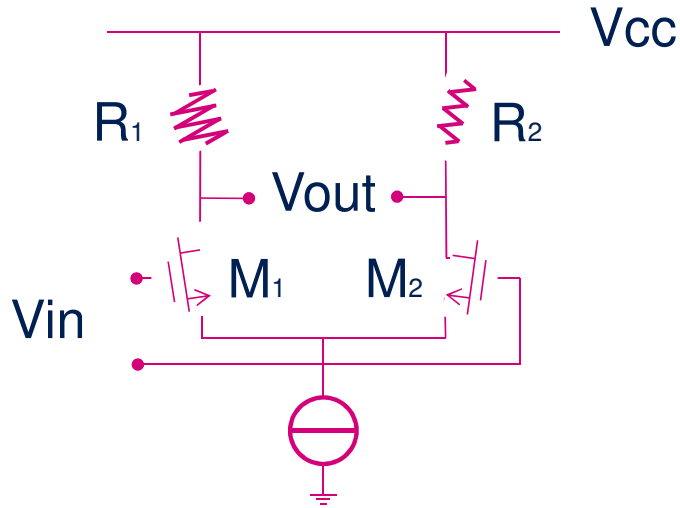
Symbol	Parameter	Conditions	Min.	Typ.	Max.	Unit
DC performance						
V_{io}	Input offset voltage	$T = 25^{\circ}C$		1	5	μV
		$-40^{\circ}C < T < 125^{\circ}C$			8	
$\Delta V_{io}/\Delta T$	Input offset voltage drift ⁽¹⁾	$-40^{\circ}C < T < 125^{\circ}C$		10	30	nV/ $^{\circ}C$

Input Offset Voltage

Where does it comes from?

7

Differential input



Component mismatch
 $R1 \neq R2, M1 \neq M2 \Rightarrow$ **offset**

For CMOS technology

$$V_{os} = \Delta V_{th} + \frac{V_{GS} - V_T}{2} \left(\frac{\Delta R}{R} + \frac{\Delta k'}{k'} + \frac{\Delta W/L}{W/L} \right)$$

ΔV_{th} linked to the substrate doping.
Second term linked to the MOS size.

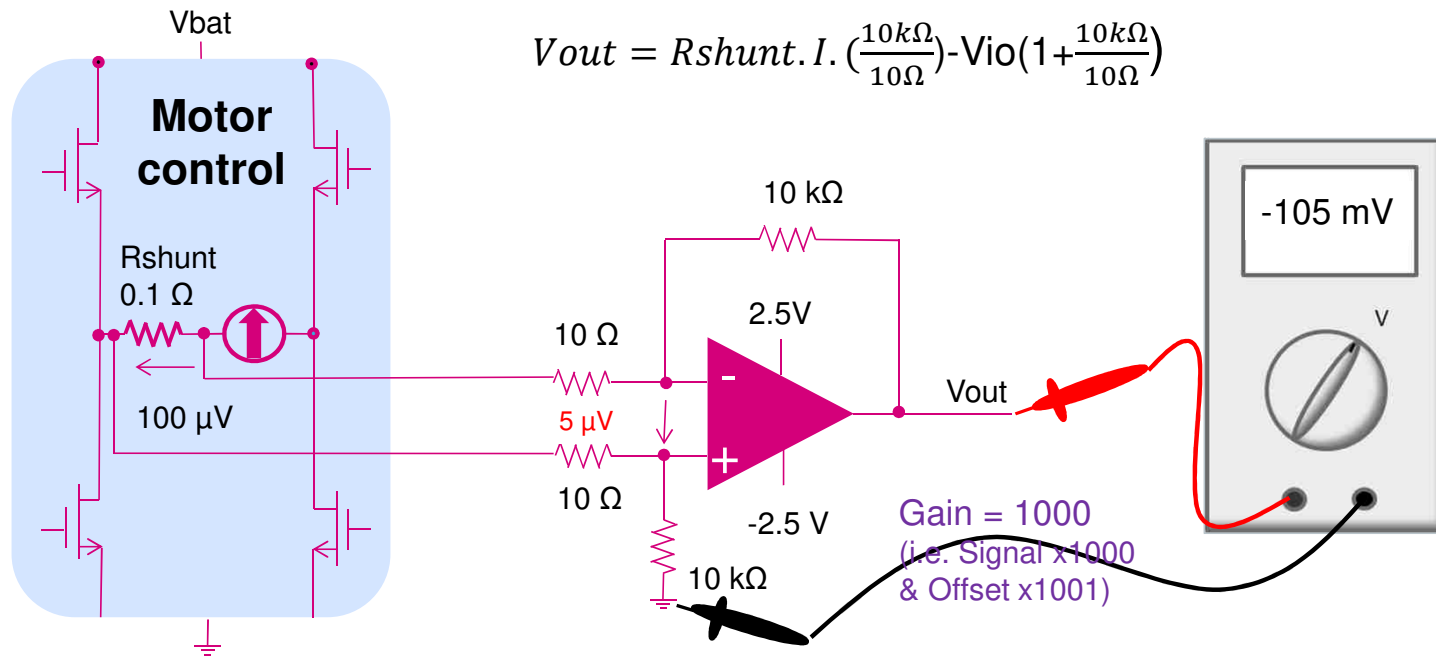
Mismatch is mainly due to:

- Doping variations
- Lithographic errors
- Packaging & local stress

Impact of V_{IO} on a real application

Current sensing for motor control

8



e.g. $I = 1 \text{ mA}$ in Rshunt

TSZ121
 $V_{IO} = 5 \text{ μV}$

5% error on speed information
rotation information is correct

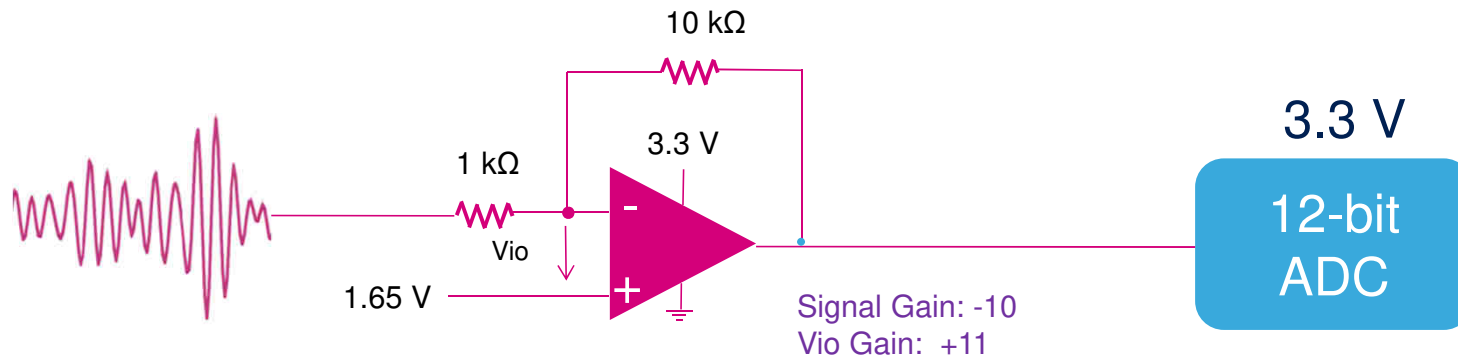
Summary of V_{IO} impact on motor control applications

9

Opamp	Offset @ 25°C	V_{OUT} for a current $I = 1 \text{ mA}$	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} !

10

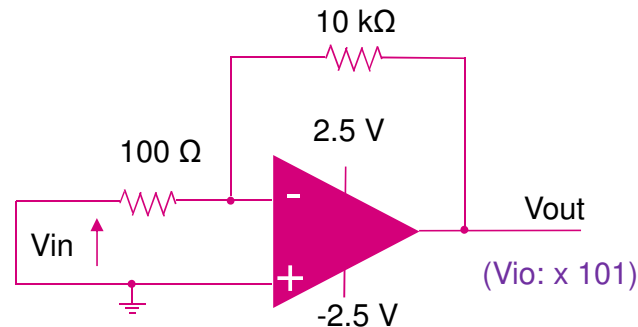


The LSB of the ADC is $3.3 \text{ V}/2^{12} = 805 \mu\text{V}$
 The input signal is amplified by -10, and the V_{IO} by 11

	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

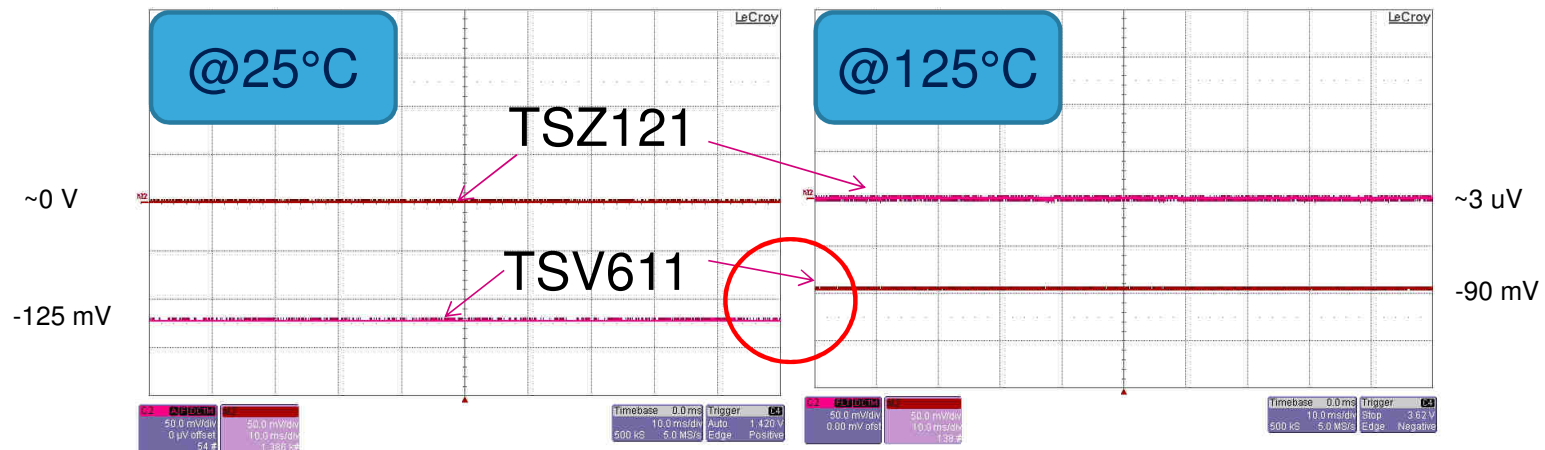
$\Delta V_{io}/\Delta T$ and calibration

11

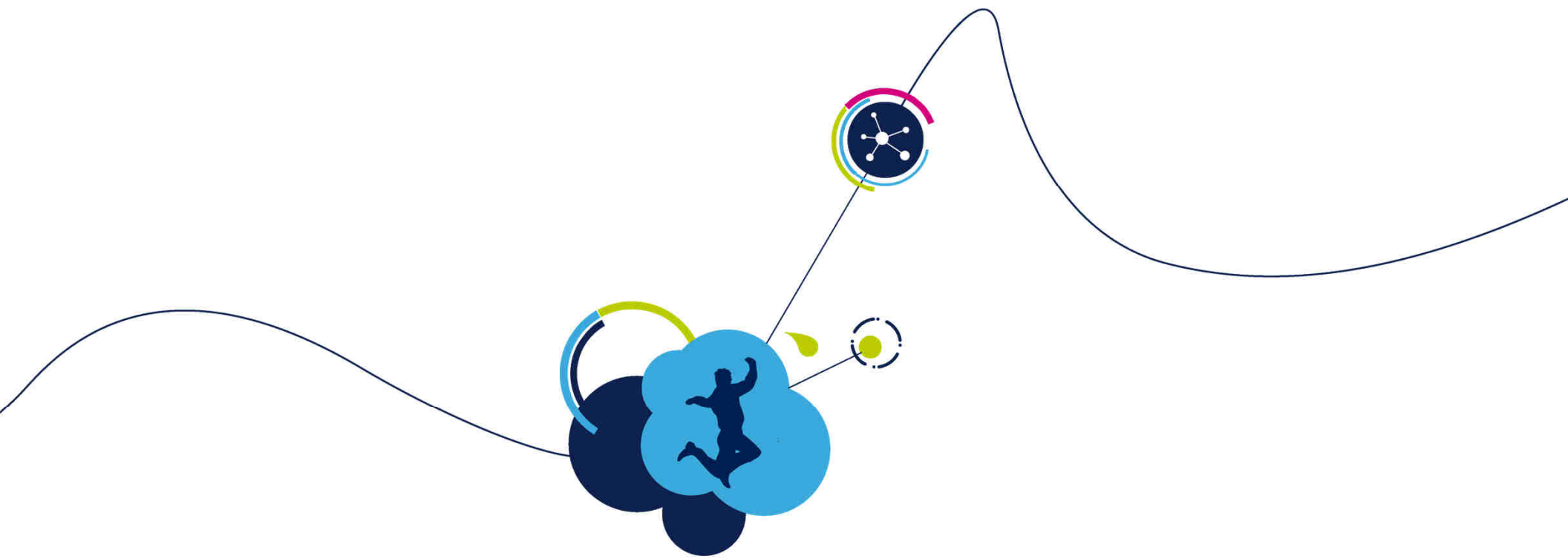


$$V_{out} = V_{in} \left(\frac{-10k\Omega}{100\Omega} \right) \pm V_{io} \left(1 + \frac{10k\Omega}{100\Omega} \right) \quad (1)$$

$$V_{out} = V_{in} \left(\frac{-10k\Omega}{100\Omega} \right) \pm (V_{io} \pm dT \left(\frac{\Delta V_{io}}{\Delta T} \right)) \left(1 + \frac{10k\Omega}{100\Omega} \right) \quad (2)$$



	V_{io} @25°C max	$\Delta v_{io}/\Delta t$ max
TSZ121	5 μ V	30 nV/°C
TSV611	4 mV	10 μ V/°C

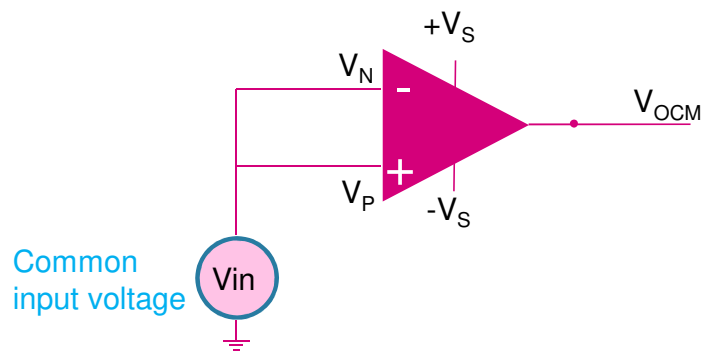


Op Amps: CMRR – Common Mode Rejection Ratio

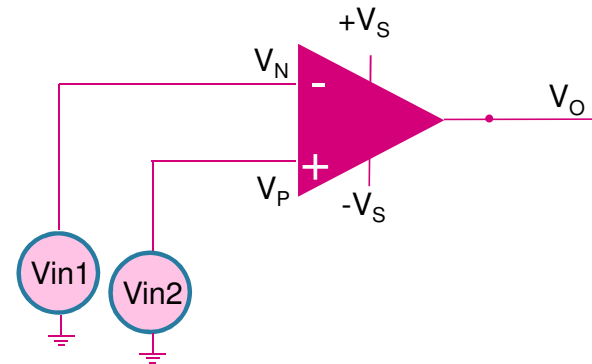
Common Mode Rejection Ratio (CMRR)

Common Mode Rejection Ratio

13



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



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

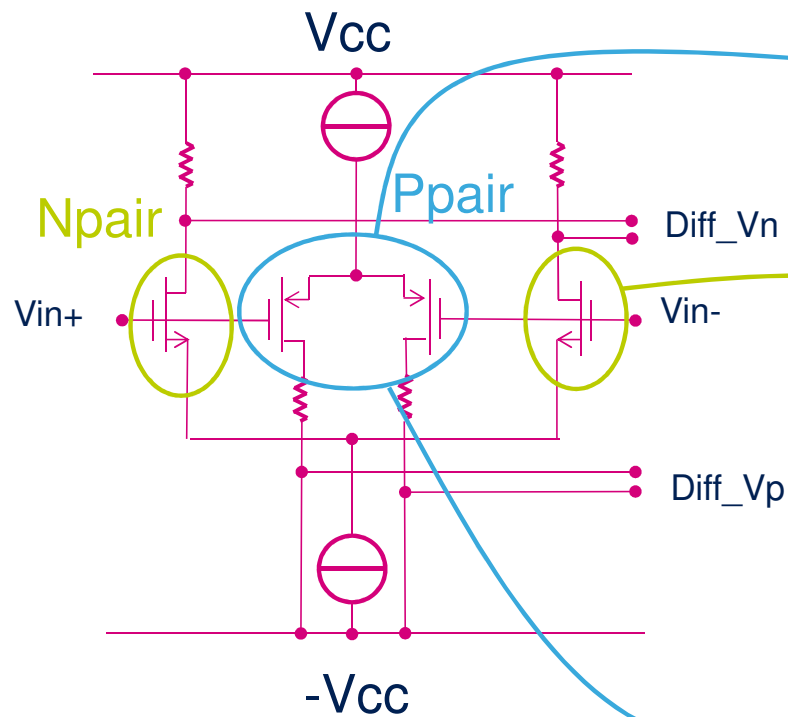
$$\text{Common Mode Rejection Ratio} = \frac{\text{Differential Gain}}{\text{Common Mode Gain}}$$

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

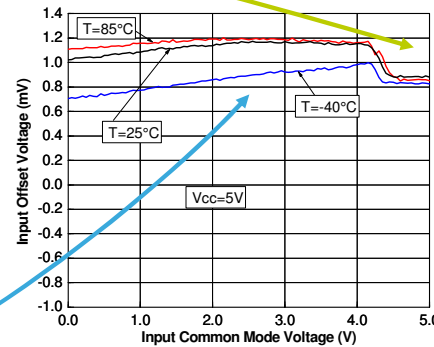
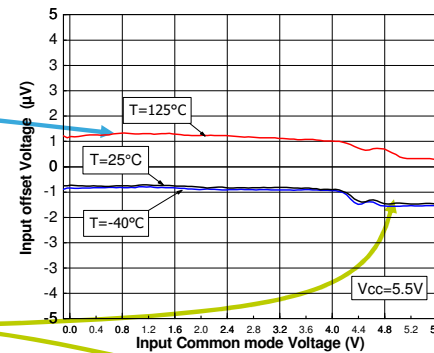
Common Mode Rejection Ratio

14

Input stage of a CMOS op amp



TSZ121



TSV611

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

So, depending on the common mode voltage used in the application, the V_{io} might be different.

Impact of CMRR on battery monitoring

High-side current sensing

12

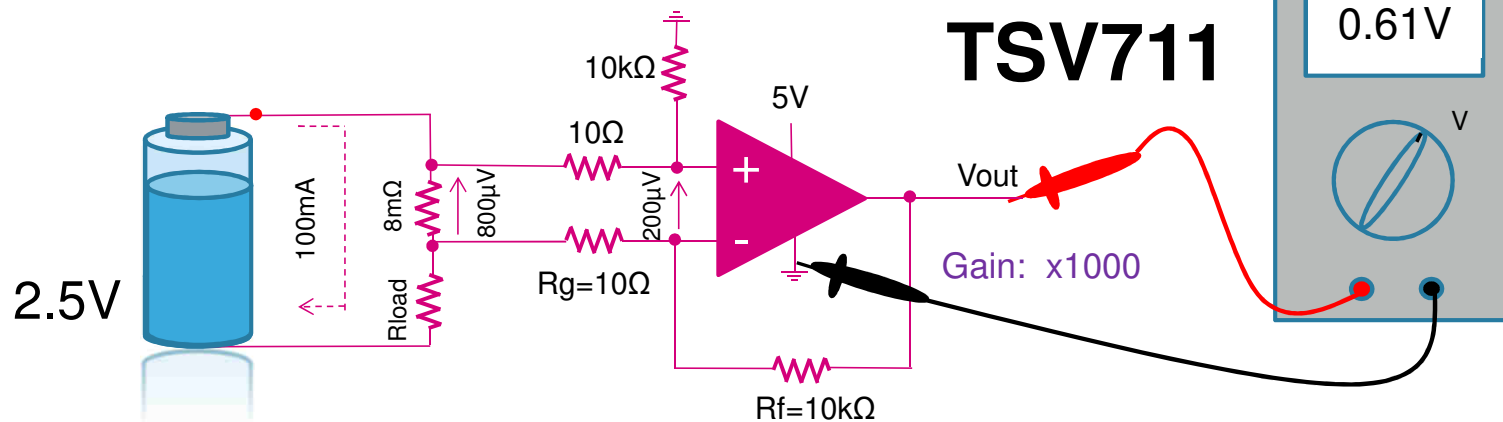
$$CMRR_{res} = \frac{1 + \frac{R_f}{R_g}}{4\epsilon}$$

With $\epsilon=0.1\%$ precision resistance
and a gain of 1000

The CMRR of the whole schematics is 250250 (108 dB)

$$V_{out} = 0.8 - \left(1 + \frac{R_f}{R_g}\right) \cdot V_{io} \pm \frac{v_{bat}}{CMRR_{res}} \left(\frac{R_f}{R_g}\right) \pm \frac{v_{icm} - v_{cc}/2}{CMRR_{op}} \left(1 + \frac{R_f}{R_g}\right)$$

$$V_{out} = V_{out_ideal} - k_1 \cdot V_{io} \pm k_2 \cdot V_{CMRR_{resist}} \pm k_3 \cdot V_{CMRR_{opamp}}$$



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

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

Impact of CMRR on a battery monitoring

High-side current sensing

13

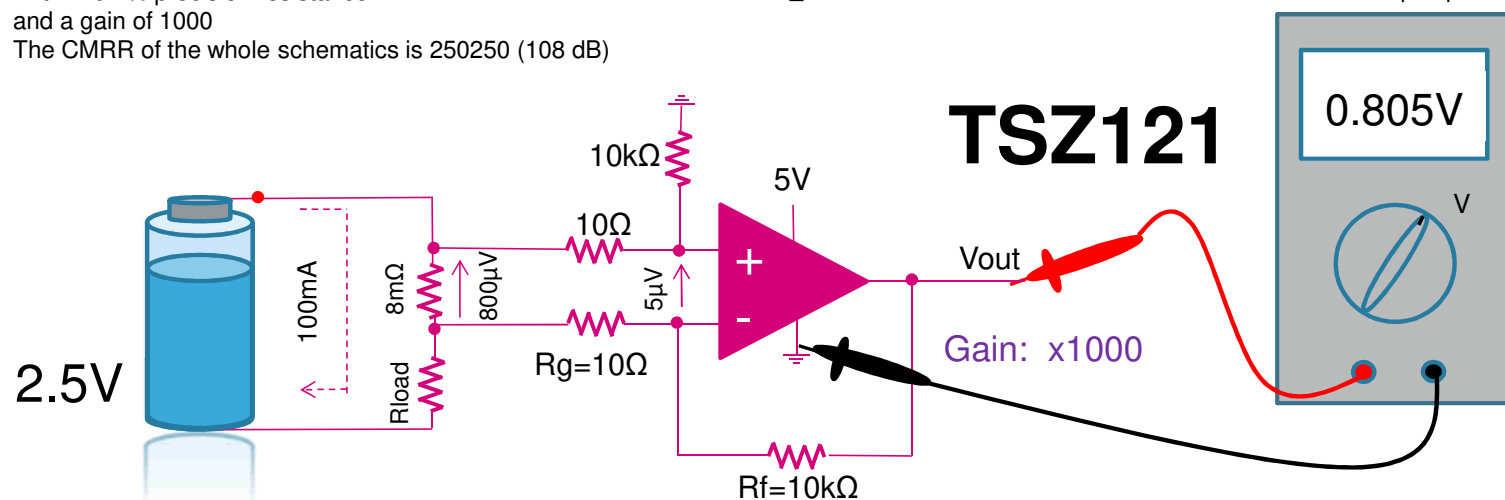
$$CMRR_{res} = \frac{1 + \frac{R_f}{R_g}}{4\epsilon}$$

With $\epsilon=0.1\%$ precision resistance
and a gain of 1000

The CMRR of the whole schematics is 250250 (108 dB)

$$V_{out} = 0.8 - \left(1 + \frac{R_f}{R_g}\right) \cdot V_{io} \pm \frac{v_{bat}}{CMRR_{res}} \left(\frac{R_f}{R_g}\right) \pm \frac{v_{icm} - v_{cc}/2}{CMRR_{op}} \left(1 + \frac{R_f}{R_g}\right)$$

$$V_{out} = V_{out_ideal} - k_1 \cdot V_{io} \pm k_2 \cdot V_{CMRR_{resist}} \pm k_3 \cdot V_{CMRR_{opamp}}$$



TSV711	Impact on Vout	Error %
Vio	0.2V	25%
CMRRres @4.2V (108dB)	16.8mV	2.1%
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}

17

$$V_{id} = V_{io} + \frac{\partial V_{id}}{\partial V_{out}} \Delta V_{out} + \frac{\partial V_{id}}{\partial V_{icm}} \Delta V_{icm} + \frac{\partial V_{id}}{\partial V_{cc}} \Delta V_{cc} + \frac{\partial V_{id}}{\partial T} \Delta T(1)$$

Input offset

(Power supply rejection ration)

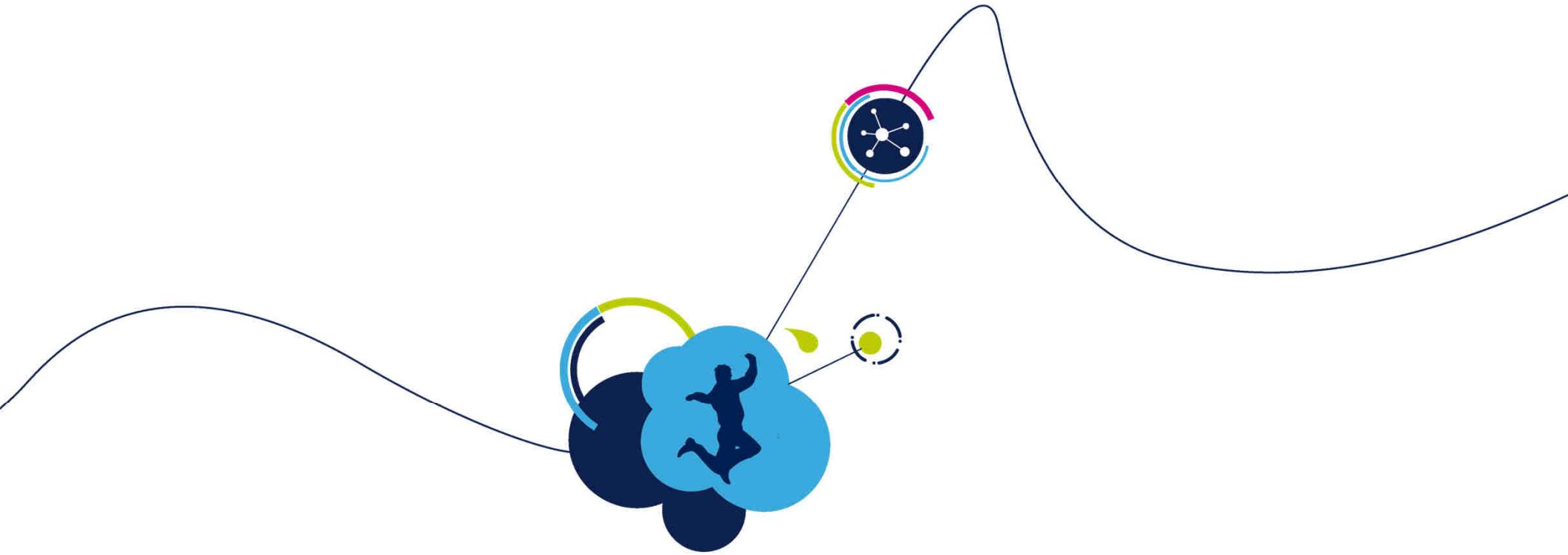
PSRR

A_{VD}
(differential voltage amplification)

CMRR
(Common Mode rejection ration)

Input offset drift

We define : $A_{vd} = -20 \log \left(\left| \frac{\partial V_{id}}{\partial V_{out}} \right| \right)$, $CMRR = -20 \log \left(\left| \frac{\partial V_{id}}{\partial V_{icm}} \right| \right)$, $SVR = -20 \log \left(\left| \frac{\partial V_{id}}{\partial V_{cc}} \right| \right)$ and $DV_{io} = \left| \frac{\partial V_{id}}{\partial T} \right|$



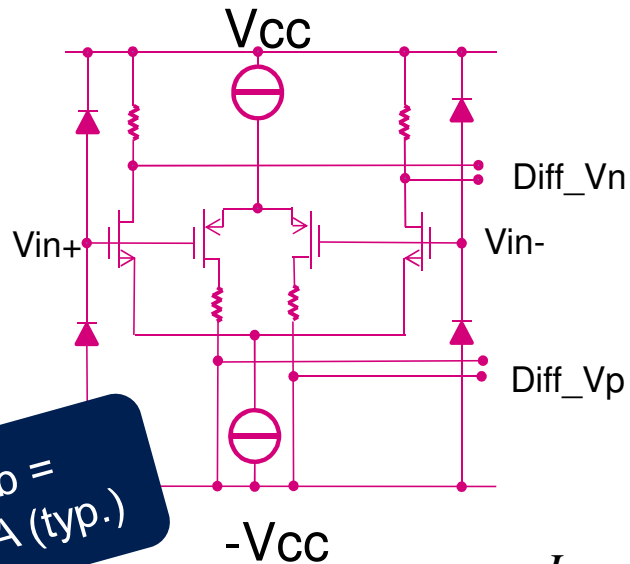
Op Amps: lib – Input bias current

Input bias current

19

CMOS

No gate current, only diode leakage

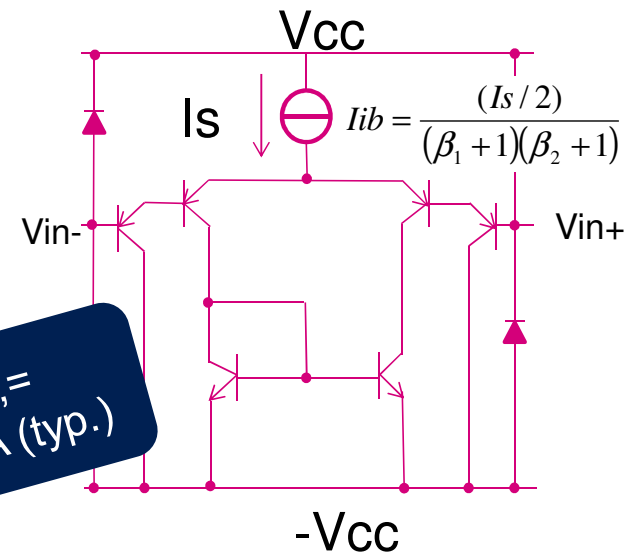


$I_{lib} = 1 \text{ pA (typ.)}$

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

BIPOLAR

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



$I_{lib} = 20 \text{ nA (typ.)}$

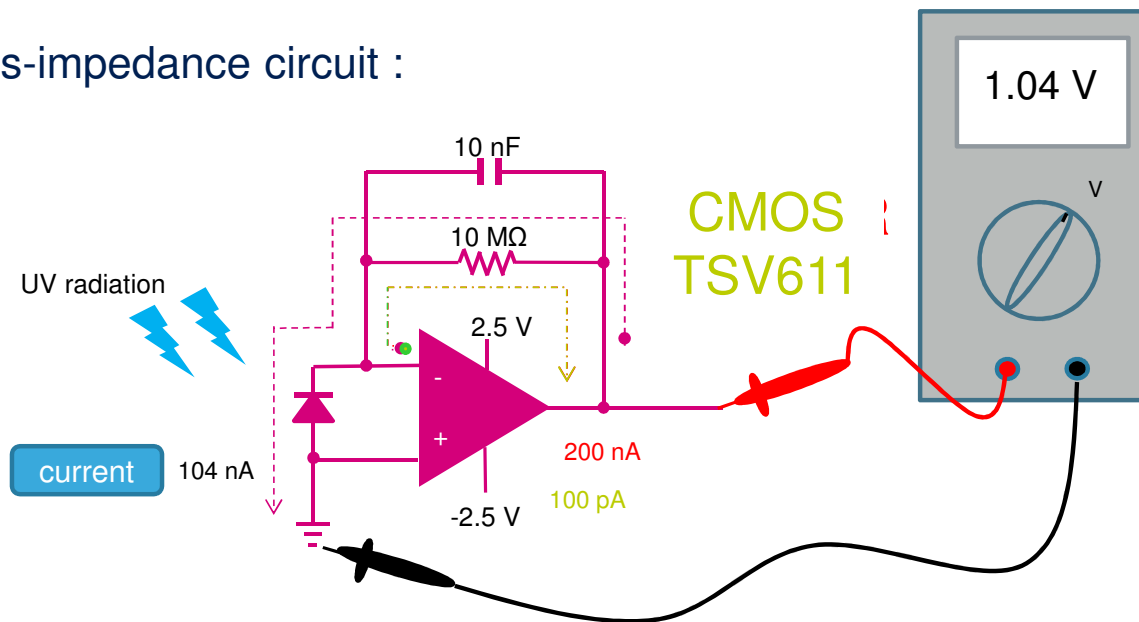
$$I_{lib} = \frac{(I_s / 2)}{(\beta_1 + 1)(\beta_2 + 1)}$$

- Input currents are also important sources of error, especially for high source impedances ($>100\text{k}\Omega$)

UV sensor application

20

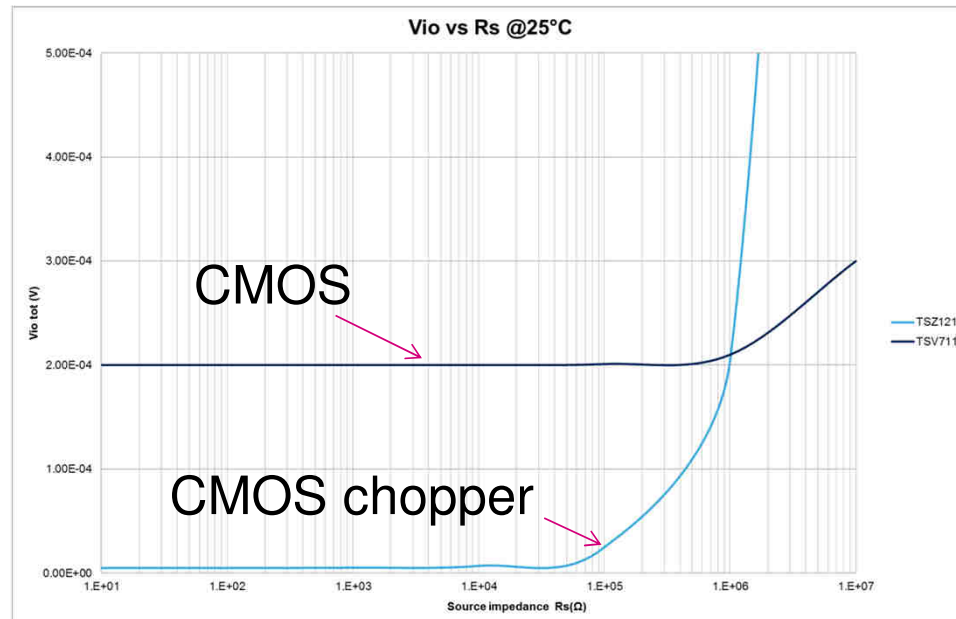
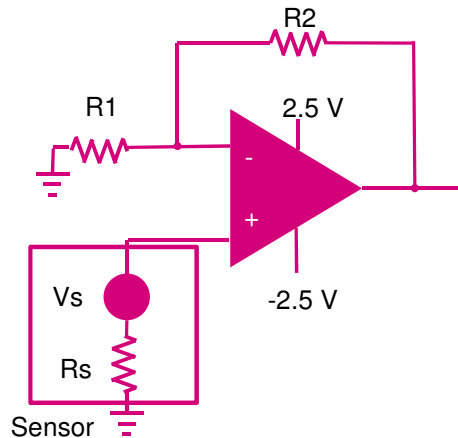
- UV source Index: 4
- Trans-impedance circuit :



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

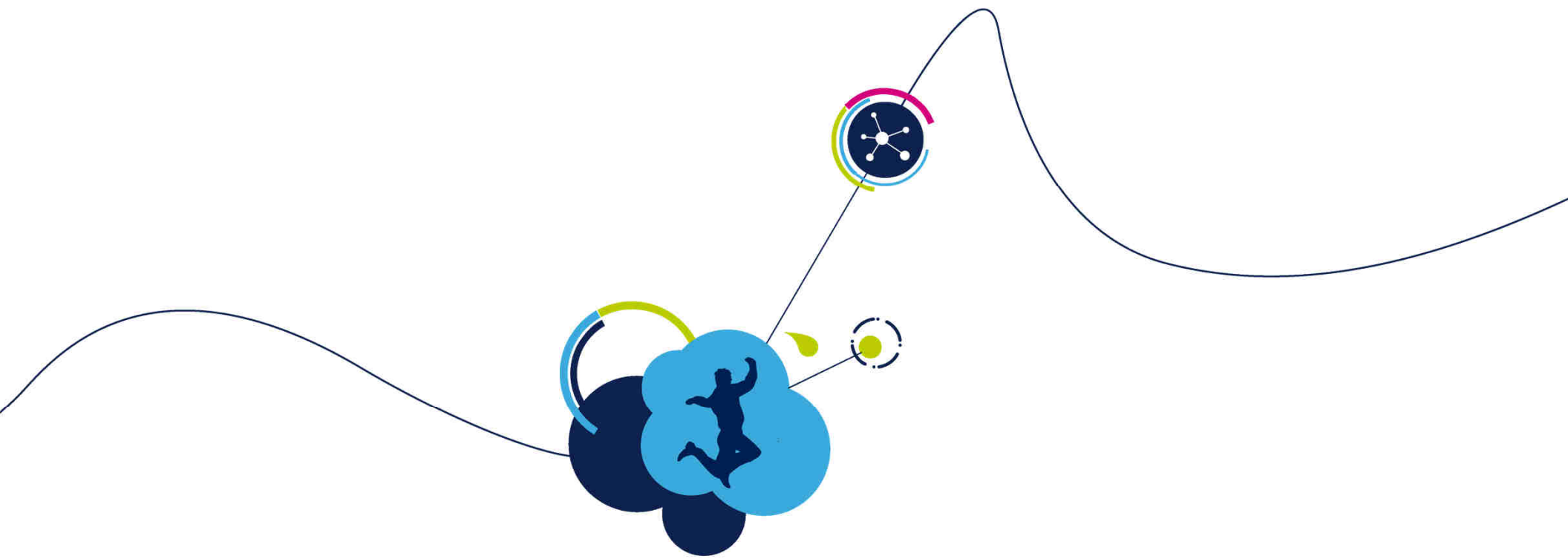
Is the TSZ121 chopper always a good choice?

21



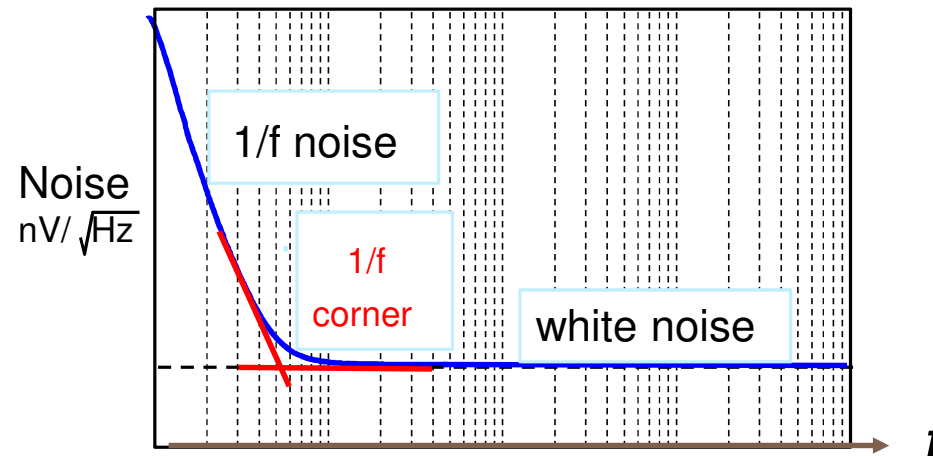
$$V_{io\ tot} = V_{io} + R_s \cdot I_n \quad (1)$$

$$R_s > \frac{V_{io}}{I_n} \quad (2)$$



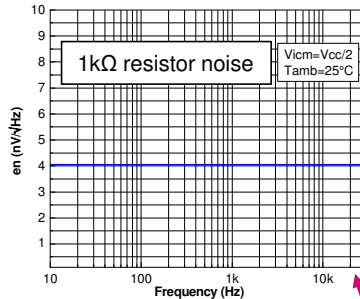
Op Amps: Noise

- **Equivalent input noise voltage (e_n)**: expressed in $\text{nV}/\sqrt{\text{Hz}}$, it is the internally generated noise voltage
 - Equivalent input noise voltage is bandwidth dependent, and includes the spectral density component $\sqrt{\text{Hz}}$

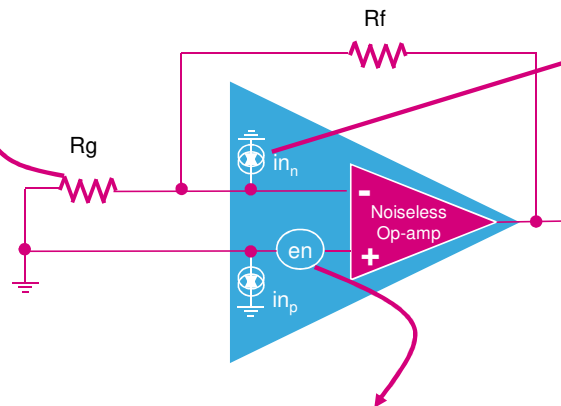


Noise sources of an op amp

24



There are 5 sources of noise



Resistors R_f & R_g generate a white noise with a spectral density of:

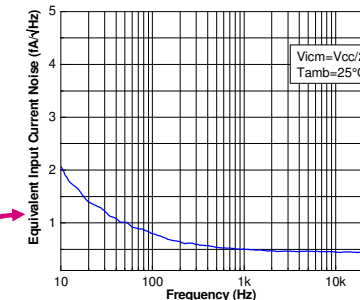
$$e_n = \sqrt{4kTR} \quad \text{VHz}^{-\frac{1}{2}}$$

Where $k = 1.38 \cdot 10^{-23} \text{ JK}^{-1}$

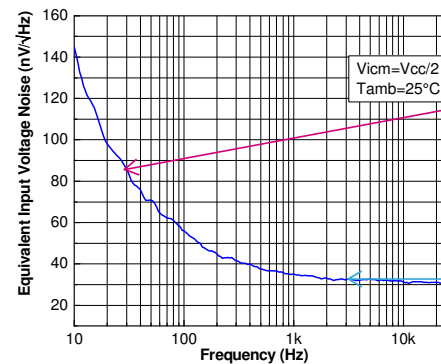
(Boltzmann's constant)

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

(Temperature in Kelvin)



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



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

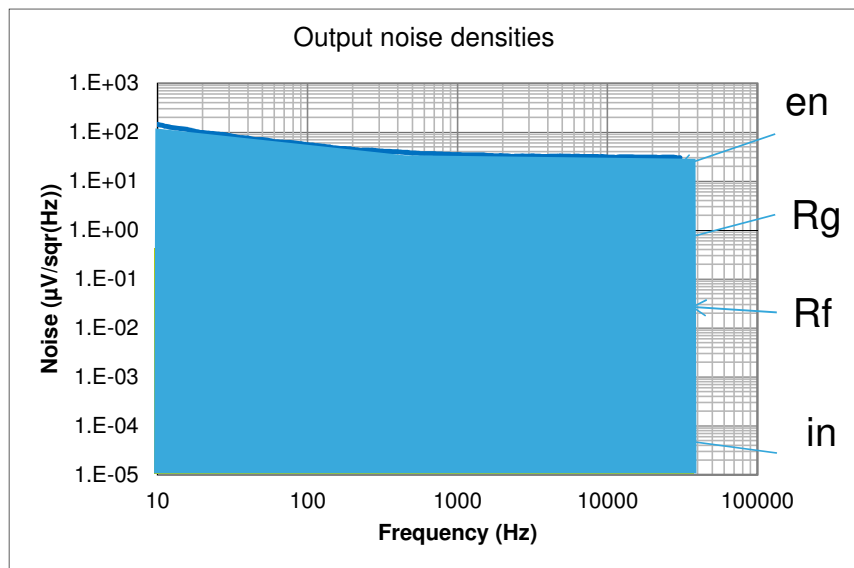
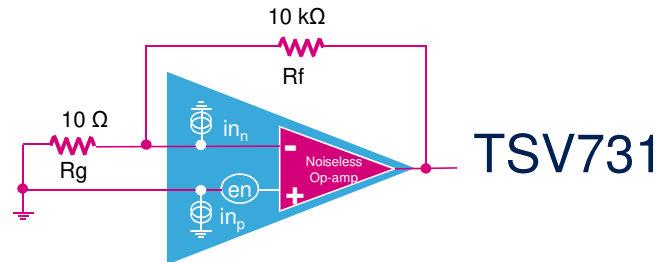
Input noise voltage: $e_{nf}(f) = \sqrt{\frac{e_{nf}(1\text{Hz})}{f}} \text{ V}/\sqrt{\text{Hz}}$

White noise

$e_n \text{ V}/\sqrt{\text{Hz}}$

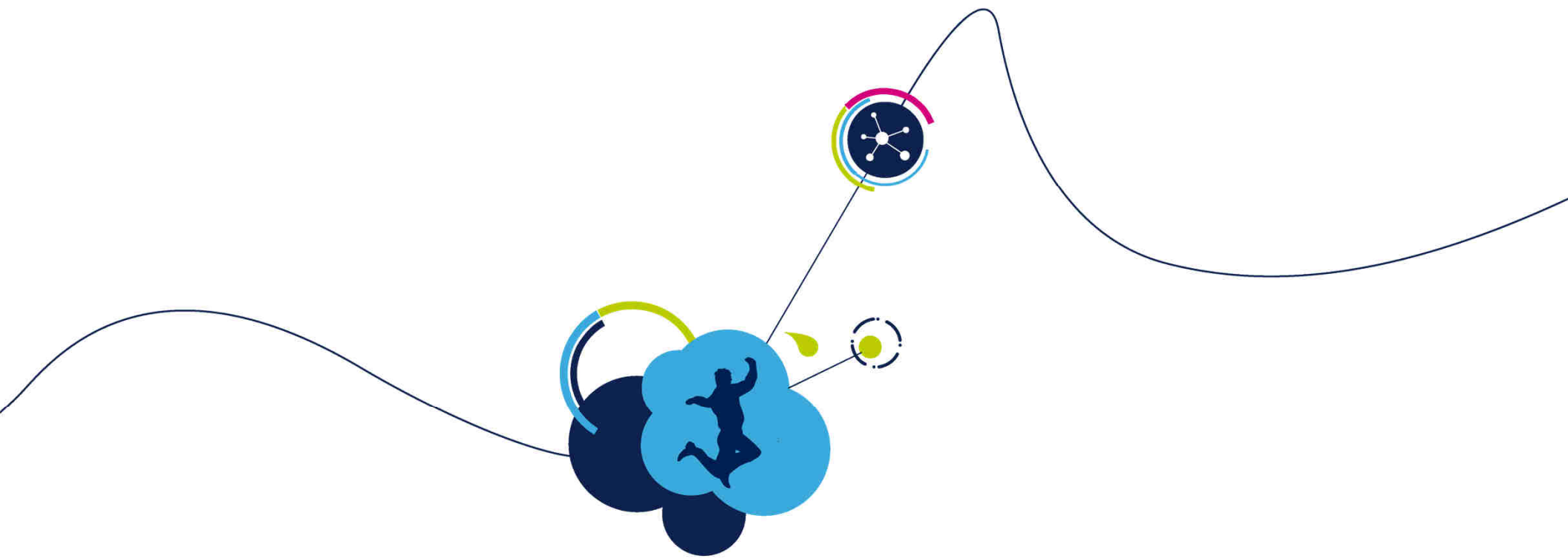
Contribution of each source of noise

25



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

$$V_{\text{outRms}} = \sqrt{en^2 + In^2 + Rf^2 + Rg^2}$$



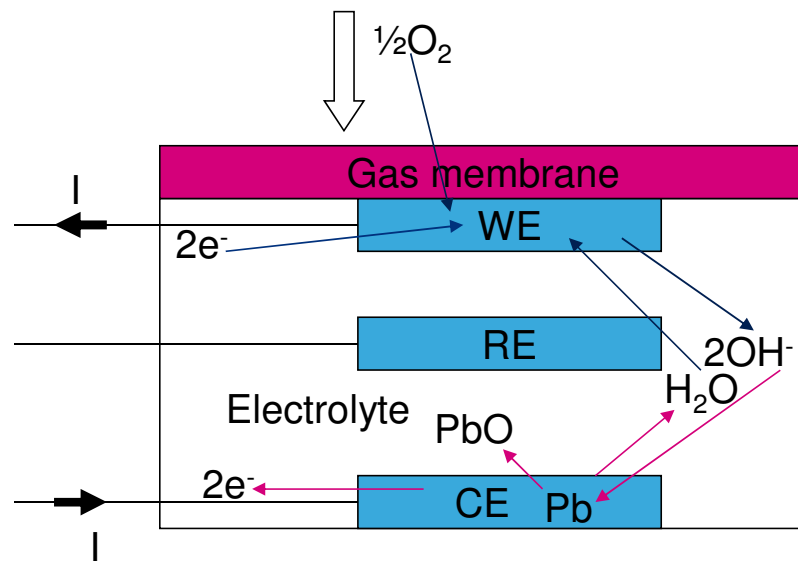
Use-case study: Gas sensor

- 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

28

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



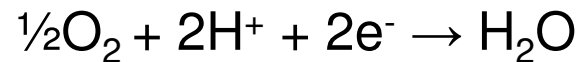
Oxygen sensor

Case of O₂ sensor:

Oxidation on Working Electrode (WE)



Reduction on Counter Electrode (CE)



Reference Electrode (RE)

no chemical reaction at the surface,
no current flows.

Electrochemical carbon monoxide sensor
and glucometer test strip



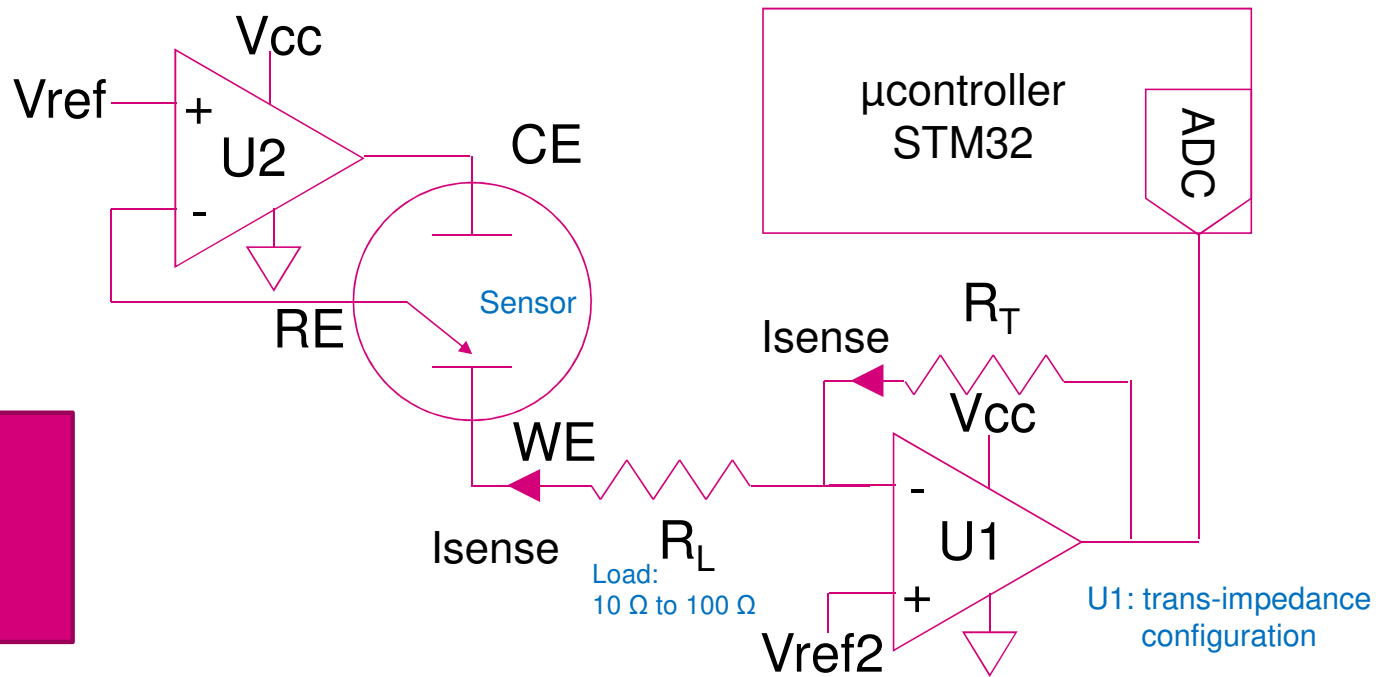
3 electrode sensors : Potentiostat

29

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

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 : $V_{out} = V_{ref2} + R_T \cdot I_{sense}$

Choosing an Op-amp key parameters

30

- 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

TSU101/TSU102/TSU104
600nA / channel

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

TSZ121/TSZ122/TSZ124
Vio 5uV max

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

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

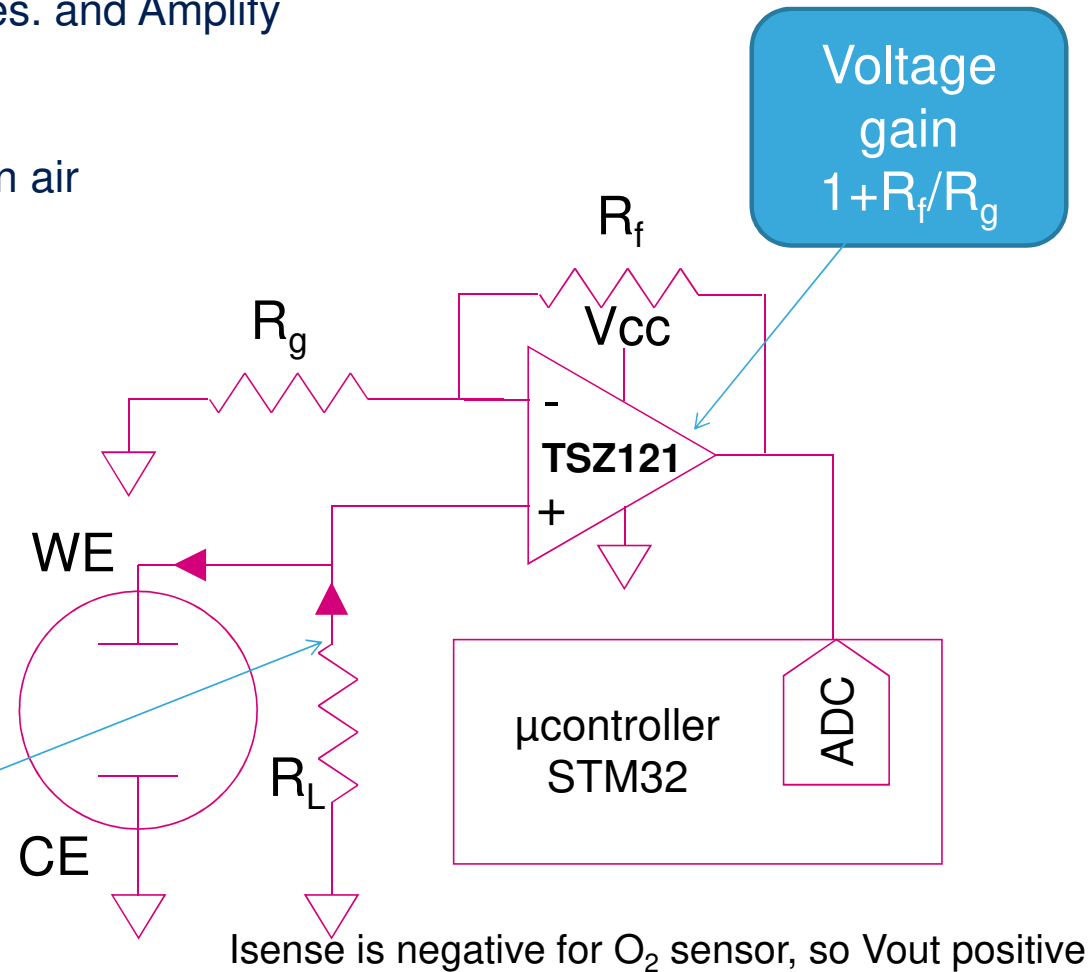
2 electrode sensors : Galvanic configuration

31

- Alternative config: Voltage drop through Load res. and Amplify
- I to V conversion done by R_L (100Ω)
- Small signal to amplify $\sim 350\mu\text{A} \times 100\Omega = 35\text{mV}$ in air
- Op-amp used in voltage gain need for accuracy

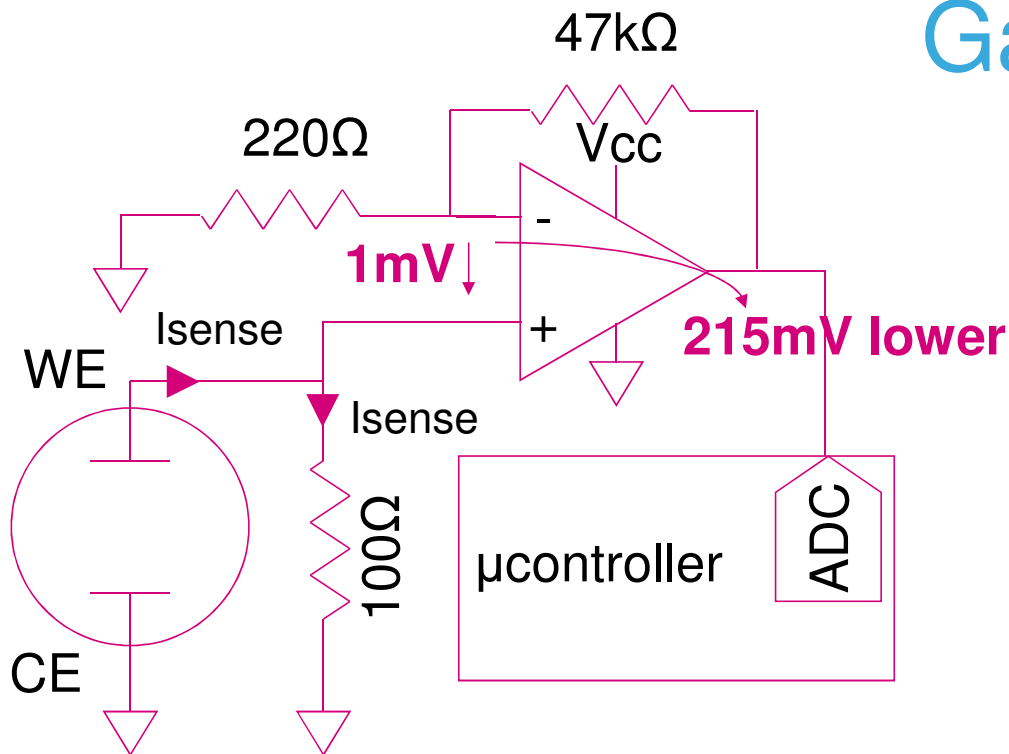
TSZ121
High precision
amplifier
5uV max
30nV/°C max
29uA typ

I to V
conversion
 $I \cdot R_L$



Galvanic sensor - Vio

25



O₂ 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
 $9.08\text{mV} \times (1 + 47/0.22) = 1.95\text{V}$
(*air means [O₂]=20.9%)

	Output voltage	Vio	[O ₂] 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

33



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

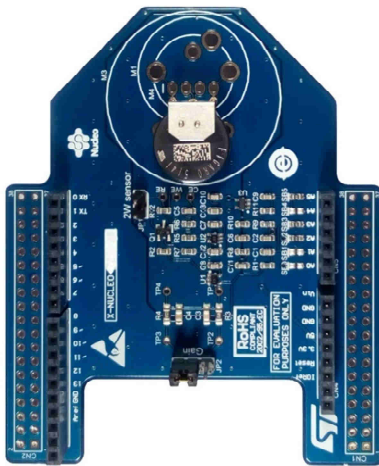
Products	Features (all specifications given at 3.3 V)
TSU111 TSU112 TSU114	Ultra low consumption: 900 nA typ Low low noise: 3.7 μVpp from 0.1 Hz to 10 Hz Good precision: 150 μV max
TSU101 TSU102 TSU104	Ultra low consumption: 600 nA typ Battery life extension
TSV711 TSV712 TSV714	Good compromise between consumption and precision I_{cc} : 9 μA typ V_{io} : 200 μV max
TSZ121 TSZ122 TSZ124	Excellent precision: V_{io} 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**



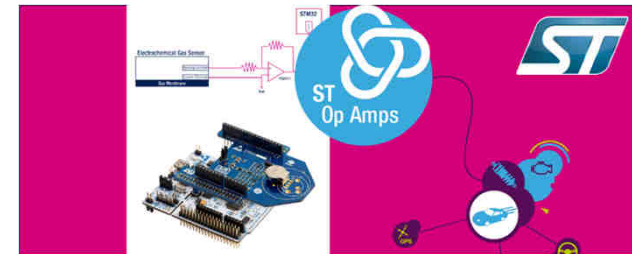
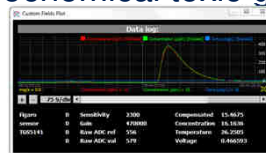
Board

- 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 with P-NUCLEO-IKA02A1

- STM32 Nucleo pack for electrochemical toxic gas sensing



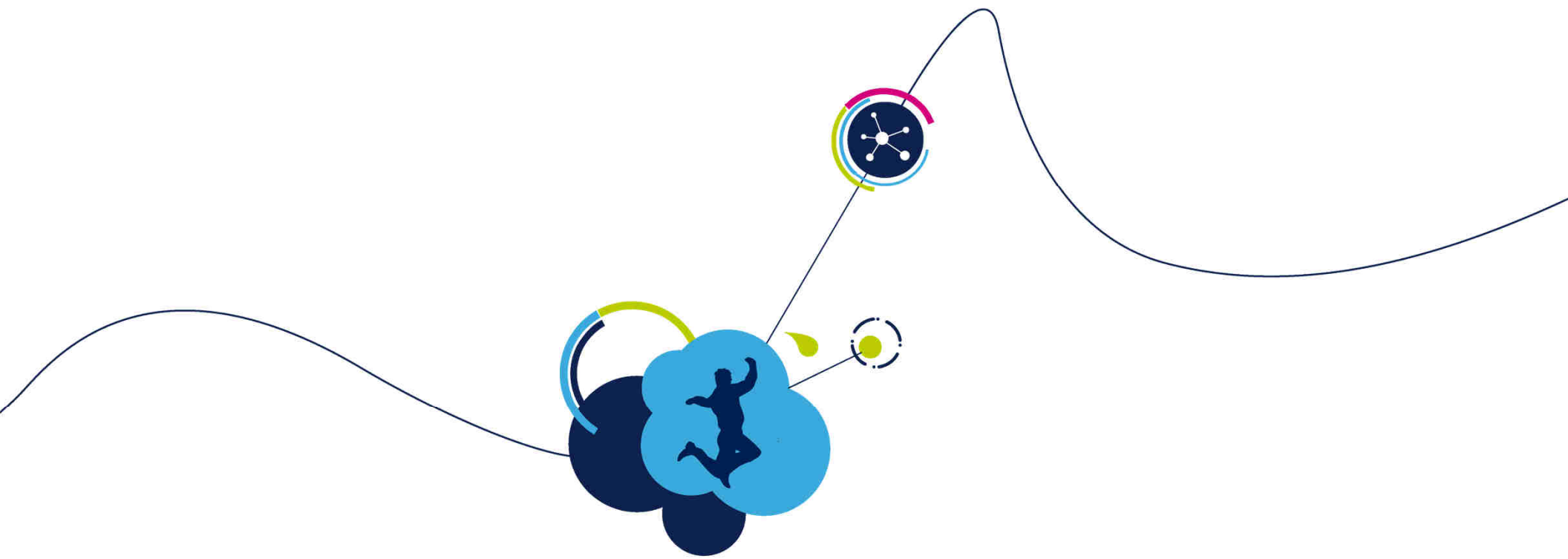
Product overview

Wireless Home CO detector

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

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

From Standard to High Performance

1980

2019

I_{cc} (LM358)

1.2mA max @25°C

power savings

*supply current enhanced by *1400*



I_{cc} (TSU101)

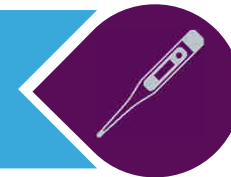
850nA max @25°C

V_{io} (LM358)

7mV max @25°C

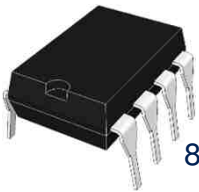
accuracy

*input offset enhanced by *1400*



V_{io} (TSZ121)

5μV max @25°C

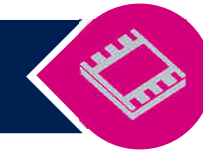


DIP8

8.8mm*6.4mm*4mm

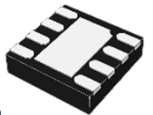
space saving

*volume enhanced by *100*



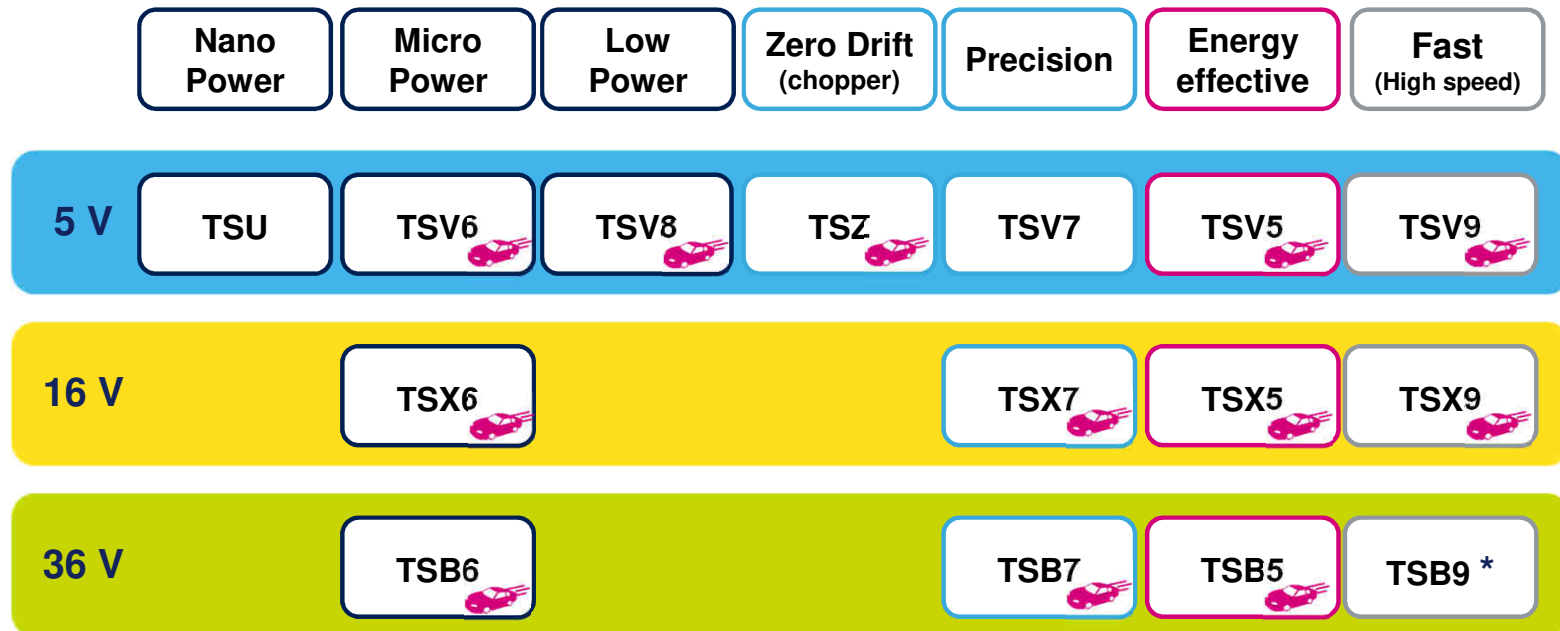
DFN8

2mm*2mm*0.55mm



High-Performance Op-Amps

38



AECQ-100

*

In development

Analog sensors for smart building

Analog Sensor	Circuit topology	Low power	High Accuracy	Wide band	App note
UV sensor Ambient light	Transimpedance amplifier	TSU401		TSV631	AN4451
Smoke detector	Transimpedance amplifier	TSV6292		TSV522	
CO detector	Potentiostat, Transimpedance ampl or 1 to V converter	TSU402	TSZ122	TSV732	AN4348
PIR detector	AC coupled filters with window comparator	TSU404			AN4368
Temperature sensing (RTD)	Current source + non-inverting amplifier or instrumentation amplifier	TSV714	TSZ124		



[Next category >>](#)

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	TSU402			AN4451
Glucose meter	Reference + 2x transimpedance	TSV612	TSV712		
Blood pressure (piezo resistive)	Instrumentation amplifier (Wheatstone bridge)	TSV714	TSZ124		



[Next category >>](#)

Analog sensors for automotive

Analog Sensor	Circuit topology	Low power	High Accuracy	Wide band	App note
Rain detector Light sensor (Photodiode)	Transimpedance amplifier	TSV631 IVLT		TSV522 IVST	AN4451
Temperature sensing (Thermocouple)	Instrumentation amplifier (small signal)	TSX712 IVST	TSZ124 IVPT		
Steering angle (resolver)	Resolver	TSX564 IVPT		TSX922 IVDT	
NO _x / NH ₃ sensor	Potentiostat, Transimpedance ampl or 1 to V converter			TSV912 HYDT	
O ₂ Sensor	Potentiostat, Transimpedance ampl or 1 to V converter	TSV522 IVST		TSV912 HYDT	



[Previous category <<](#)

[Next category >>](#)

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	Instrumentation amplifier (Wheatstone bridge)	TSV714	TSZ124	TSX712	
Force / pressure (strain gauge)	Instrumentation amplifier (Wheatstone bridge)	TSV714	TSZ124	TSX712	



[Previous category <<](#)

[Next category >>](#)

ST Op Amp Mobile product selector

Select the best
product
among our

Op amps
Comparators
Current sensing

Discover the
latest news

And share
product
information



Download the latest mobile version

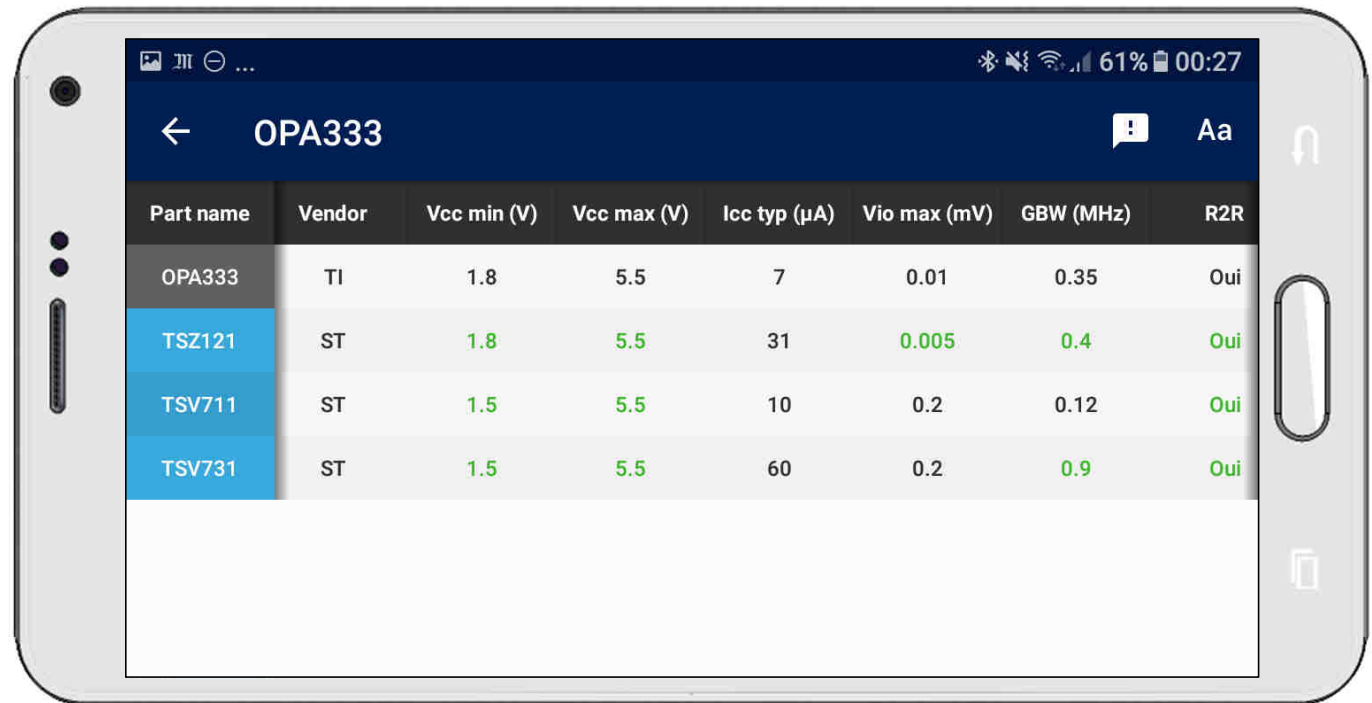


TSZ121 versus OPA333



Cross-reference
proposed by ST
Op amp mobile
application

Parameters in
green are better
or equivalent



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

Thank You

Visit [**www.st.com/opamp**](http://www.st.com/opamp)

