PLC Temperature Sensing Input Module Introduction

PLC 溫度感測輸入模組導論

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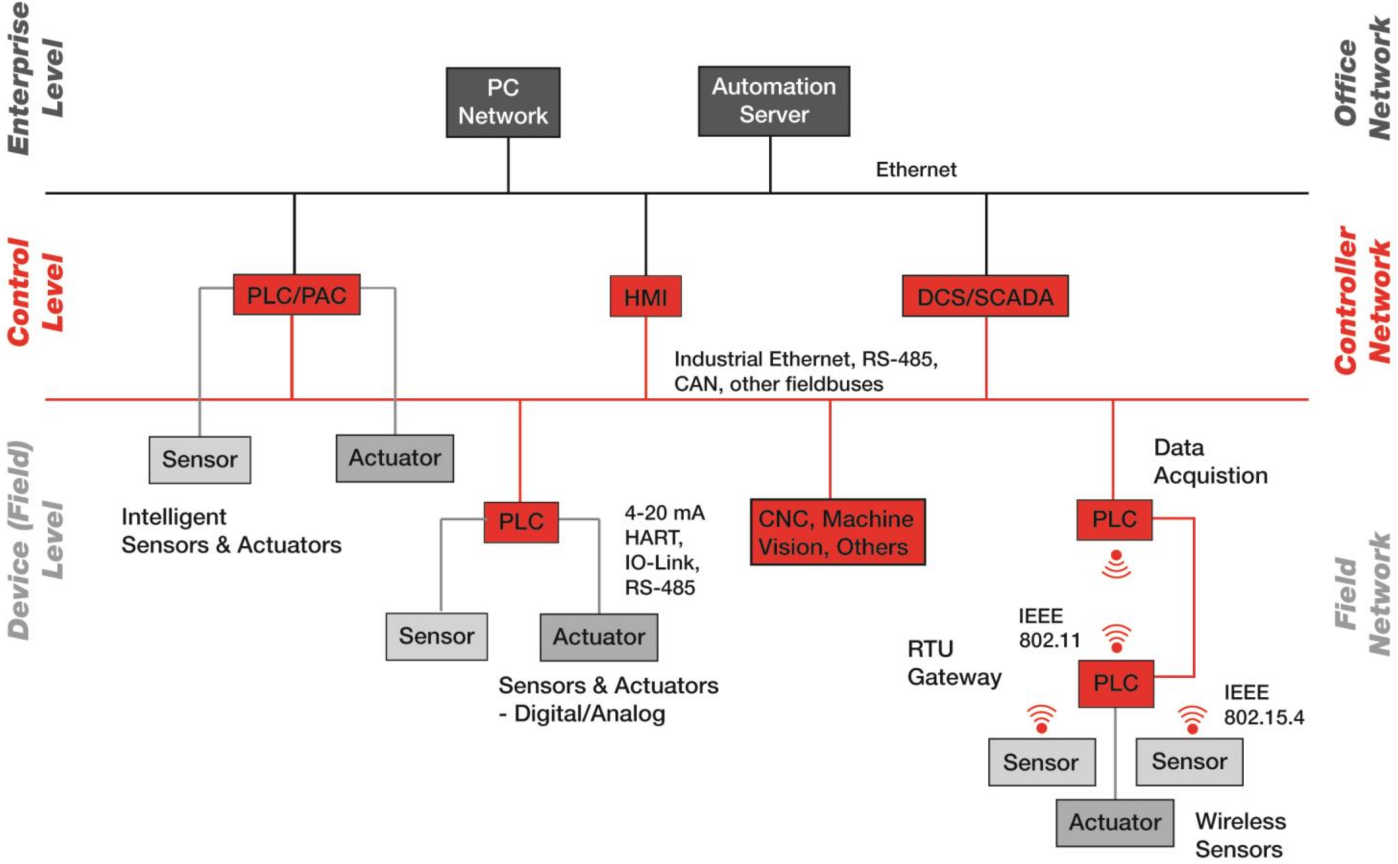
Agenda

- Overview
  - Where/how are temperature sensing used in PLC?
  - What are the different types of sensor for temperature sensing?
- Designing Thermocouple
  - Theory of Operation
  - Design Examples
- Designing RTD
  - Theory of Operation
  - Design Examples

Overview

Where/how are temperature sensing used in PLC? What are the different types of sensor for temperature sensing?

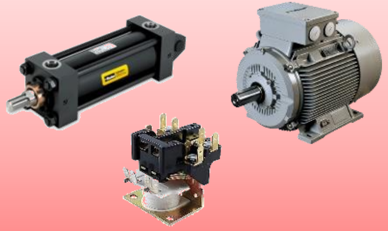
Industrial Automation Overview



Introduction to PLCs

What is a PLC?

- **PLC** = Programmable Logic Controller
- Control system for automated industrial processes



Input from Sensors

- *Voltage (±10V)*
- *Current (4-20mA)*
- *Temperature (RTD, TC)*
- *Bridge (Pressure, Flow)*

PLC Module Types

Analog Input (AI) / Analog Output (AO)

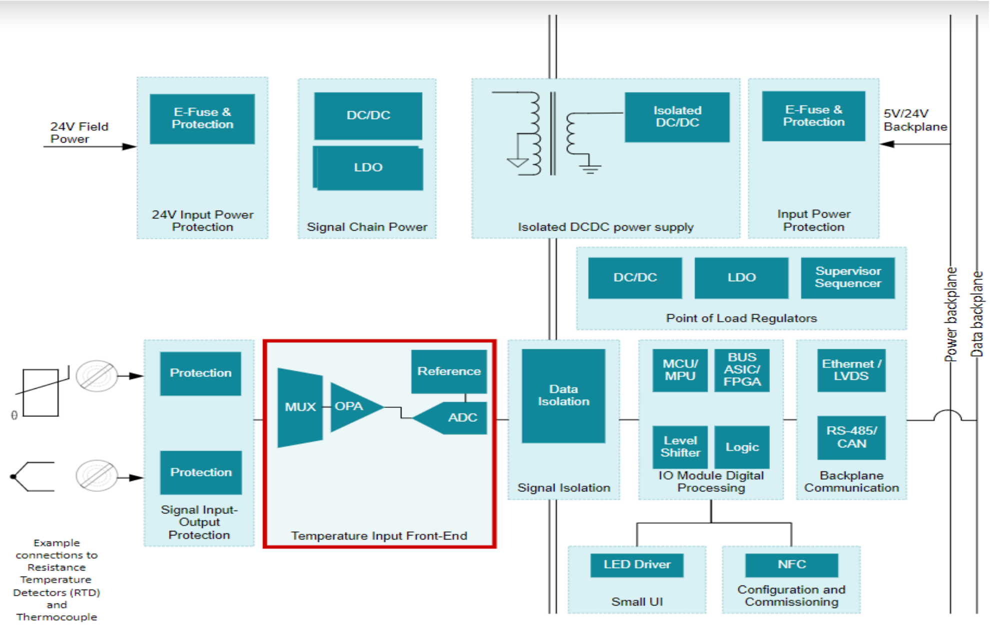
Digital Input (DI) / Digital Output (DO)

Output to Actuators

- *Hydraulic Cylinders*
- *Motors*
- *Magnetic Relays*

Where do I find Temperature Sensing in PLCs?

Analog Input Module (Temperature Transducer) EERD



Key Signal Chain Specs

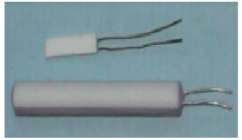
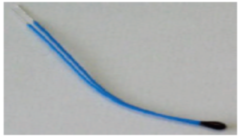
- Input impedance (>1 MΩ)
- High voltage input (up to ±10 V)
- Group- or channel-isolated
- Universal input (TC, RTD, ±10 V, 4-20 mA)
- Update rate per channel
- Common-mode range
- System size

Important Terms

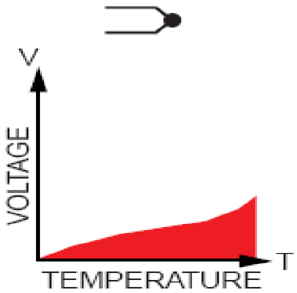
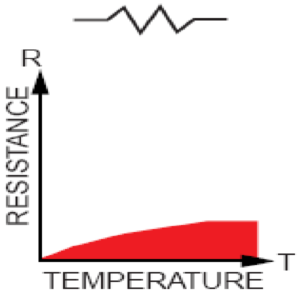
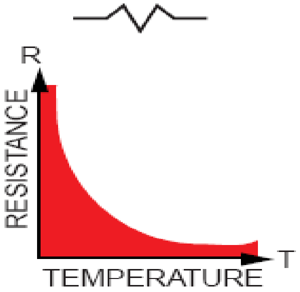
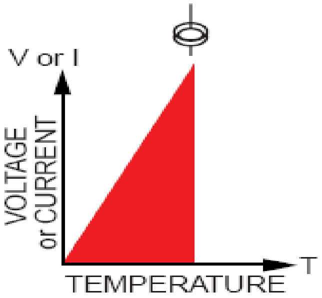
Channel-to-channel isolated – each input is ground-isolated from each other input to minimize ground loops between channels → requires one ADC per channel

Group-isolated – several inputs share a ground but are generally separated from earth ground → requires one ADC per group

Different types of temperature sensor

	THERMOCOUPLE	RESISTANCE TEMPERATURE DETECTOR (RTD)	THERMISTOR	SEMICONDUCTOR TEMPERATURE SENSOR IC
Range	–270°C to 2000°C	–200°C to 850°C	–50°C to 300°C	–55°C to 200°C
Changing Physical Characteristic	Voltage	Resistance	Resistance	Voltage or current
Excitation	Self-powered	Current excitation	Current excitation	Power Supply (μA)
Cost	Low	High	Low to moderate	Low
Response	Medium to fast	Medium	Medium to fast	Medium to fast
Accuracy	Less	Best	Good	Better
Repeatability	Reasonable	Excellent	Fair to Good	Good to excellent
Ruggedness	Very high (Can withstand high shock and vibration)	Less	High	Medium
Special Requirements	Amplification, Filtering, Cold junction compensation, Linearization	Lead Compensation, Filtering	Linearization	Power supply, Self-contained
Sensitivity at 20°C	Low (40 μV per °C for K-Type)	Medium	Very high	High (Typically 10 mV/°C)
Self-Heating	No	Very low to low	High	Very low to low
Lead Wire Resistance	Not a problem	Problematic	Not a problem	Not a problem
Interchangeability	Good	Excellent	Poor to fair	Better
Long Term Stability	Poor	Stable over long period; Typically Less than 0.1°C per year	Poor	Good
Noise Susceptibility	High	Medium	Low	Medium
Linearity	Fair	Good	Poor (Logarithmic)	Good
Size	Small to large	Medium to small	Small to medium	Small to medium but limited package choices
				

Different types of temperature sensor

	Thermocouple	RTD	Thermistor	I. C. Sensor
				
Advantages	☐ Self-powered ☐ Simple ☐ Rugged ☐ Inexpensive ☐ Wide variety ☐ Wide temperature range	☐ Most stable ☐ Most accurate ☐ More linear than thermocouple	☐ High output ☐ Fast ☐ Two-wire ohms measurement	☐ Most linear ☐ Highest output ☐ Inexpensive
Disadvantages	☐ Non-linear ☐ Low voltage ☐ Reference required ☐ Least stable ☐ Least sensitive	☐ Expensive ☐ Current source re-quired ☐ Small Δ R ☐ Low absolute resistance ☐ Self-heating	☐ Non-linear ☐ Limited temperature range ☐ Fragile ☐ Current source re-quired ☐ Self-heating	☐ T<200°C ☐ Power supply re-quired ☐ Slow ☐ Self-heating ☐ Limited configurations

Designing Thermocouple

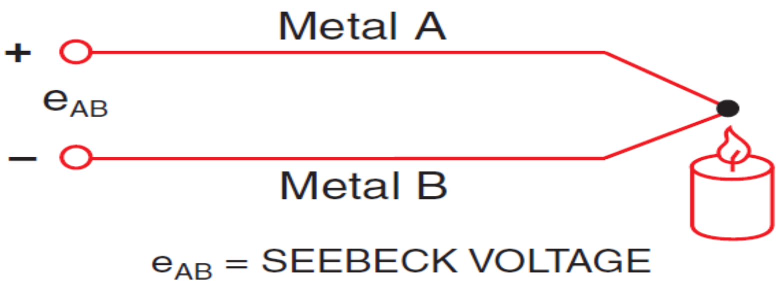
Theory of Operation & Design Examples

Thermocouple
Basics I

Seeback Effect

Any conductor that is subjected to a thermal gradient will generate a voltage between its ends.

- Consists of two dissimilar metal alloys
- Most common types:
  - Chromel-Alumel (Type K)
  - Iron-Constantan (Type J)
  - Copper-Constantan (Type T)



Source: Omega Engineering

Thermocouple
Basics II

Advantages

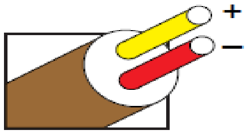
- Wide temperature range (-260°C to +2000°C) Only contact temperature measurement device for T >850°C
- Self-powered
- Very fast response, fractions of sec
- Simple and durable in construction
- Inexpensive
- Wide variety of physical forms

Disadvantages

- Thermocouple voltage non-linear with temperature
- Low measurement voltages (≤ 60mV)
- Low accuracy: ±2°C
- Least stable and sensitive
- Requires a known junction temperature

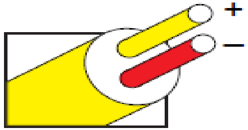
Type-K Thermocouple

MAXIMUM TEMPERATURE RANGE
Thermocouple Grade
– 328 to 2282°F
– 200 to 1250°C
Extension Grade
32 to 392°F
0 to 200°C
LIMITS OF ERROR
(whichever is greater)
Standard: 2.2°C or 0.75% Above 0°C
2.2°C or 2.0% Below 0°C
Special: 1.1°C or 0.4%
COMMENTS, BARE WIRE ENVIRONMENT:
Clean Oxidizing and Inert; Limited Use in Vacuum or Reducing; Wide Temperature Range; Most Popular Calibration
TEMPERATURE IN DEGREES °C
REFERENCE JUNCTION AT 0°C



Thermocouple Grade

Nickel-Chromium vs. Nickel-Aluminum



Extension Grade

Revised Thermocouple Reference Tables

TYPE K

Reference Tables
N.I.S.T. Monograph 175
Revised to ITS-90

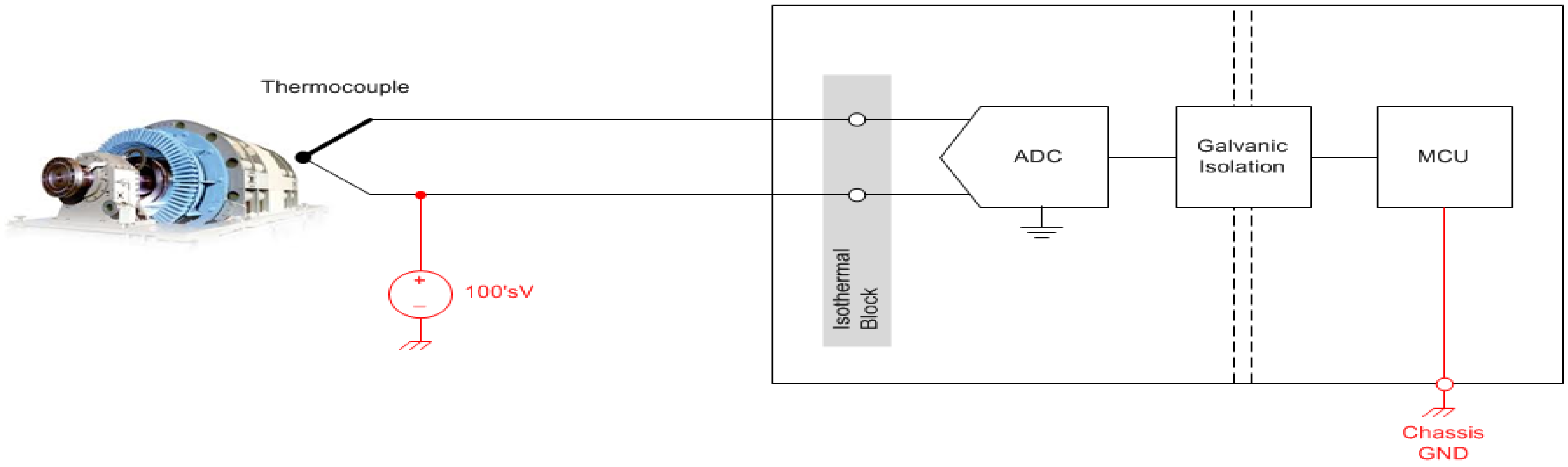
Thermoelectric Voltage in Millivolts

°C	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	°C
-260	-6.458	-6.457	-6.456	-6.455	-6.453	-6.452	-6.450	-6.448	-6.446	-6.444	-6.441	-260
-250	-6.441	-6.438	-6.435	-6.432	-6.429	-6.425	-6.421	-6.417	-6.413	-6.408	-6.404	-250

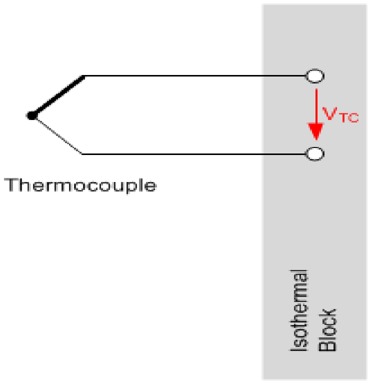
°C	0	1	2	3	4	5	6	7	8	9	10	°C
1350	54.138	54.172	54.206	54.240	54.274	54.308	54.343	54.377	54.411	54.445	54.479	1350
1360	54.479	54.513	54.547	54.581	54.615	54.649	54.683	54.717	54.751	54.785	54.819	1360
1370	54.819	54.852	54.886									1370

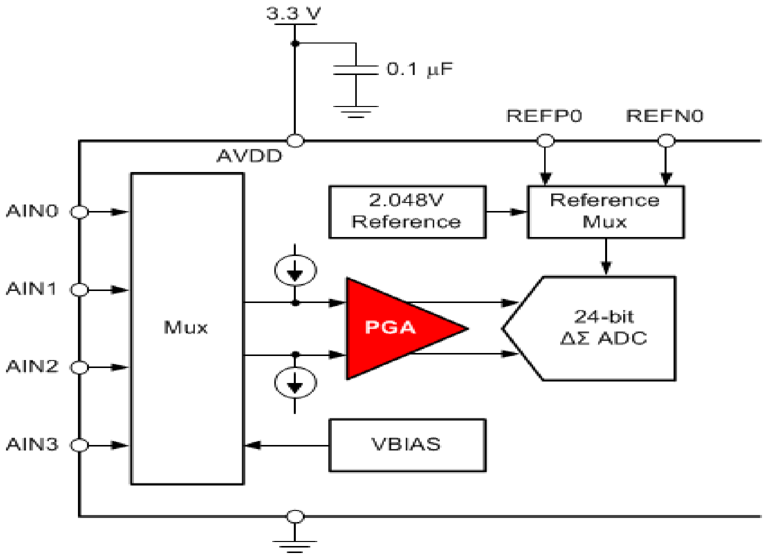
- Max. Temperature Range: -260°C to 1370°C
- Thermocouple Voltage V_{TC}: -6.458mV to 54.886mV

Need for Isolation



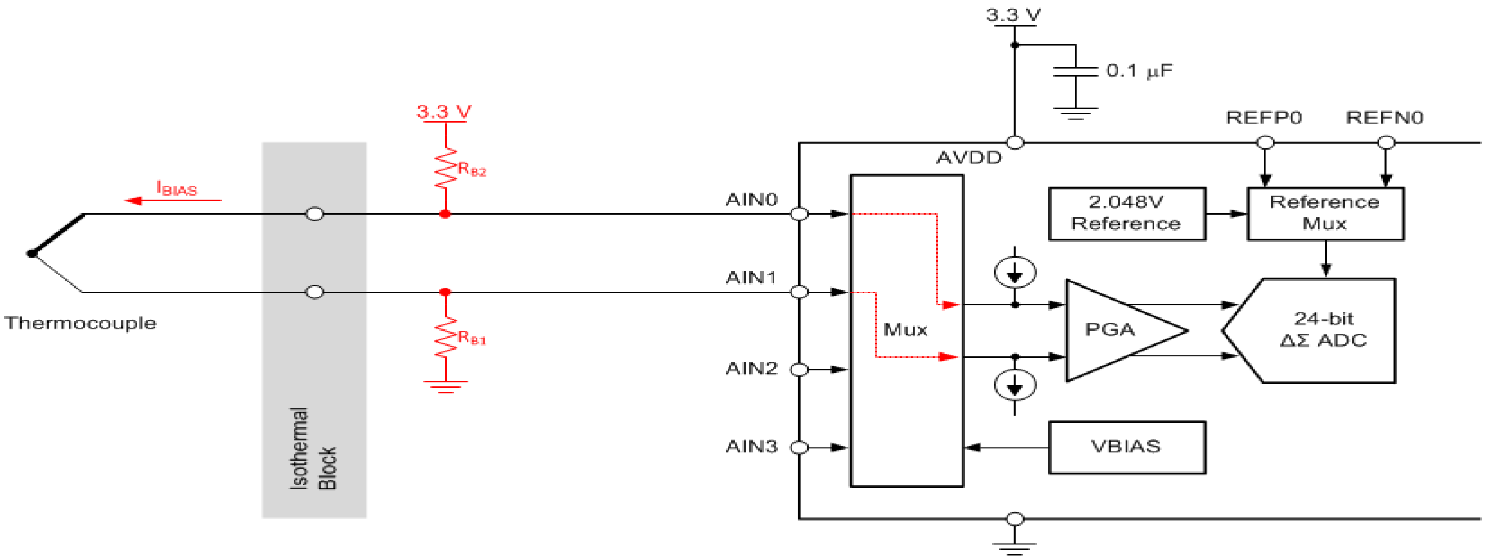
Choosing the PGA Gain





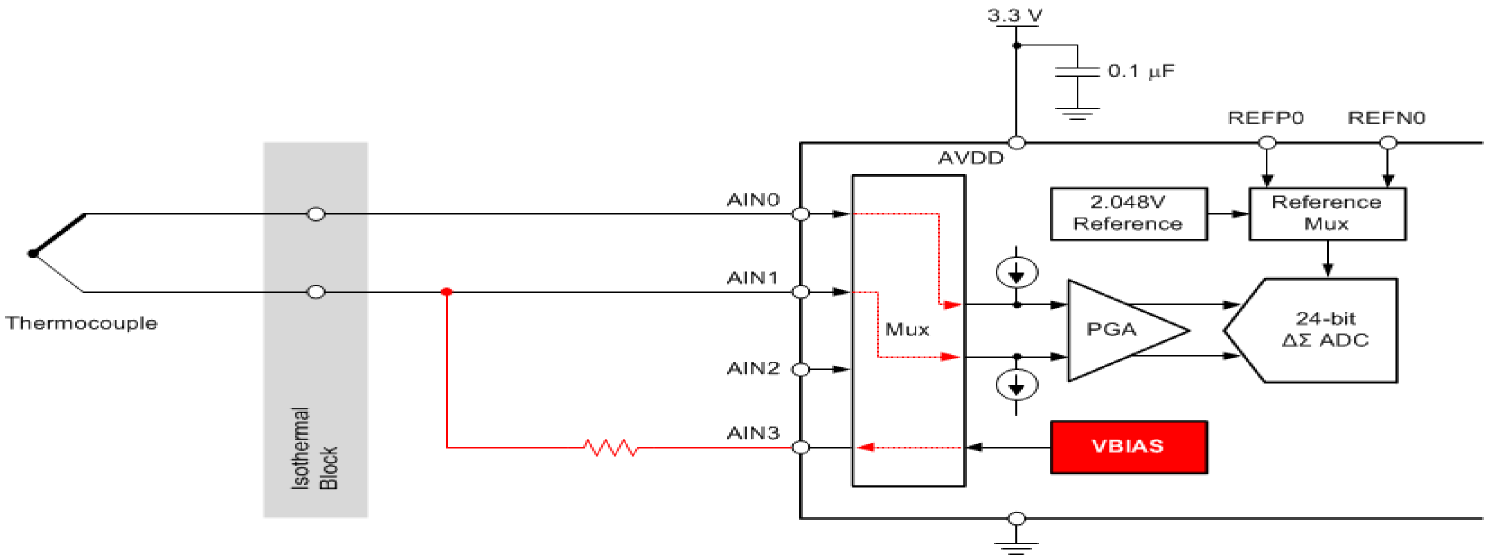
- Thermocouple Voltage: $V_{TC\ MAX} = 54.886mV$
- Max. Gain: $V_{REF}/V_{TC\ MAX} = 2.048V / 54.886mV = 37.3\ V/V$
- Next smaller PGA Gain: 32 V/V

Biasing the Thermocouple – Option I



- Biasing necessary to meet PGA common-mode voltage requirement
- Bias resistor value: Compromise between self-heating (bias current) and noise pickup. Typ. 500kΩ – 10MΩ
- Thermocouple can have lead resistance of up to 10kΩ per lead. Bias current causes additional offset error.

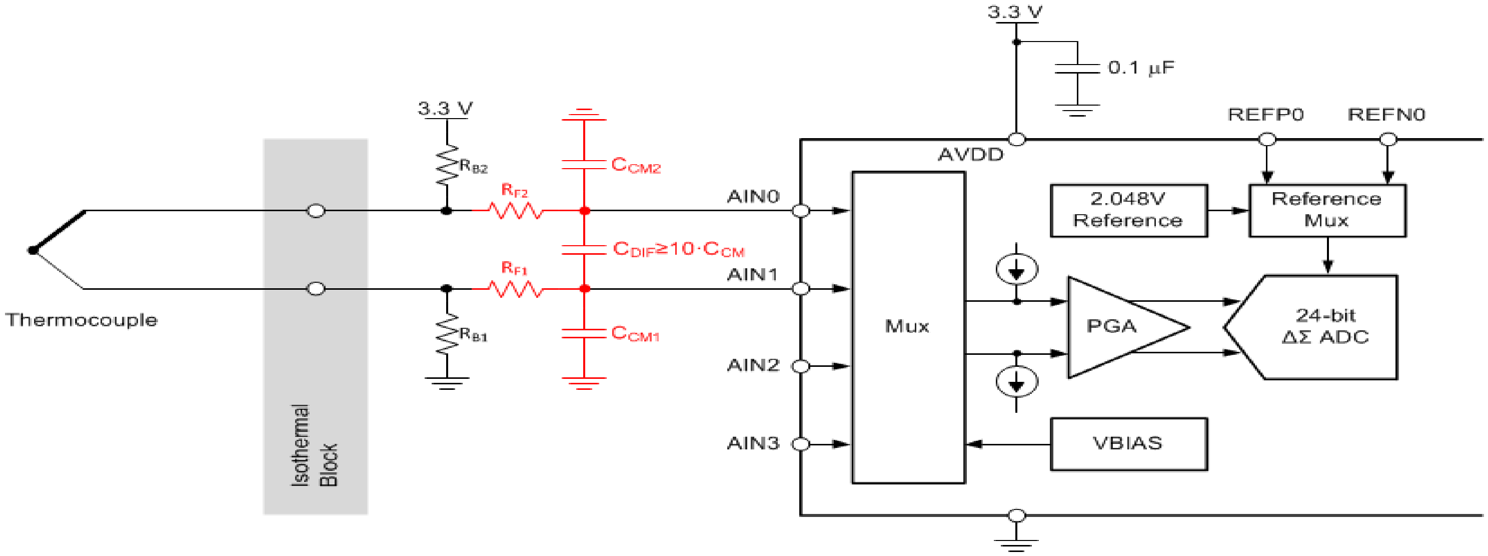
Biasing the Thermocouple – Option II



- V_{BIAS} = AVDD/2 = 1.65V
- No error due to additional bias current
- Alternatively VREFOUT can be used for biasing instead of V_{BIAS}

(*) *V_{BIAS} not available in ADS1220*

Input Filter



- Noise and antialiasing filter
- Series resistor serves as overvoltage protection by limiting the input current

$$f_{-3dB\_DIF} = \frac{1}{2 \times \pi \times C_{DIF} \times (R_{F1} + R_{F2})}$$

$$f_{-3dB\_CM} = \frac{1}{2 \times \pi \times C_{CM1} \times R_{F1}}$$

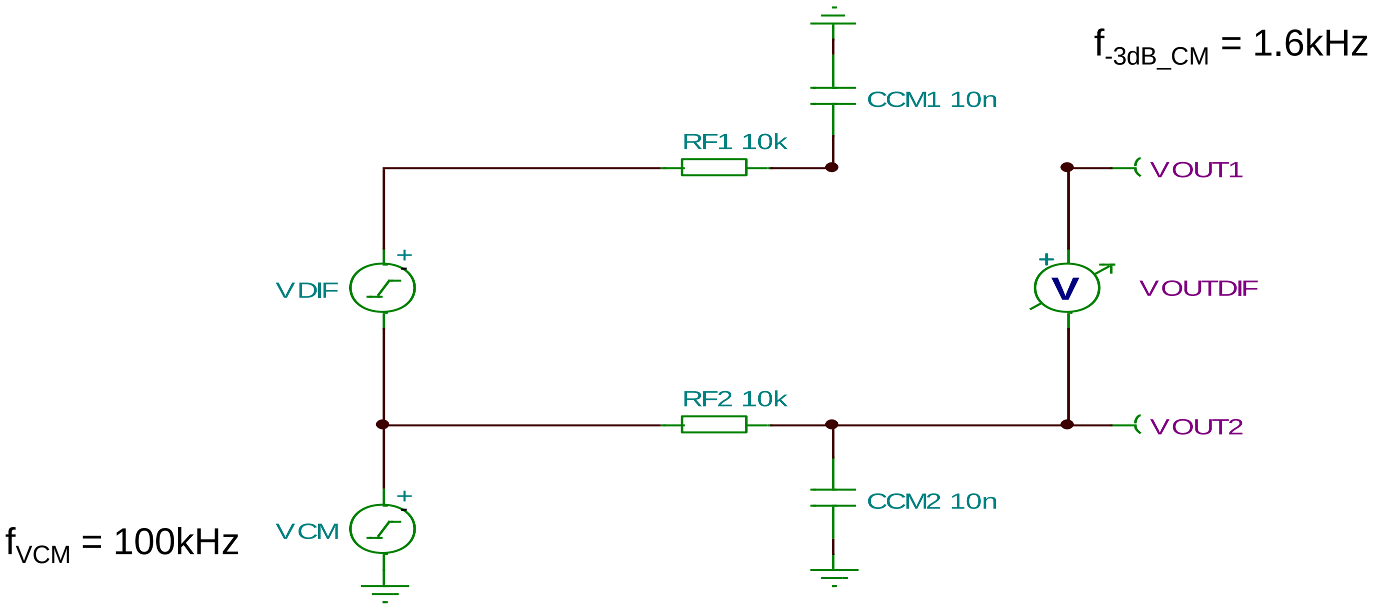
Input Filter - Guidelines

- $C_{DIF} \geq 10 \cdot C_{CM}$
  Corner frequency of differential filter lower than common-mode filter
- Use of high quality caps recommended, otherwise corner frequency changes with voltage and temperature
- Limit R_F to ≤10kΩ otherwise additional offset voltage due to input currents of ADC
- Chose R_F with adequate power rating to withstand overvoltage condition
- Biasing should be placed in front of filter so bias current does not flow through R_F which would create additional offset error
- Large filter increases settling time in MUX applications

Simulation explaining why $C_{DIF} \geq 10 \cdot C_{CM}$

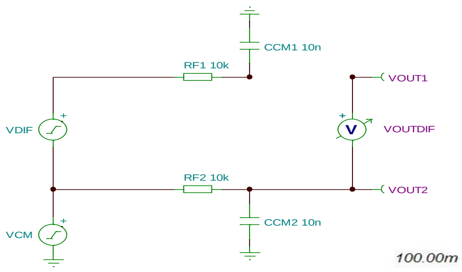
Common-mode filter only

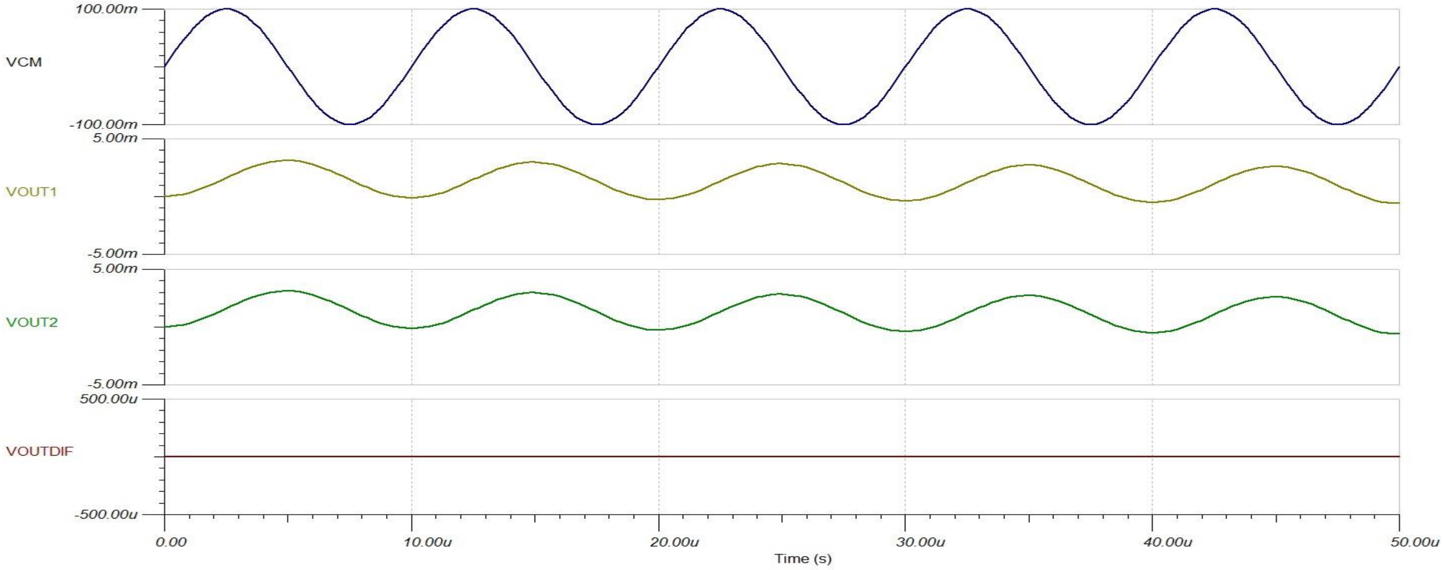
-



Simulation explaining why $C_{DIF} \geq 10 \cdot C_{CM}$

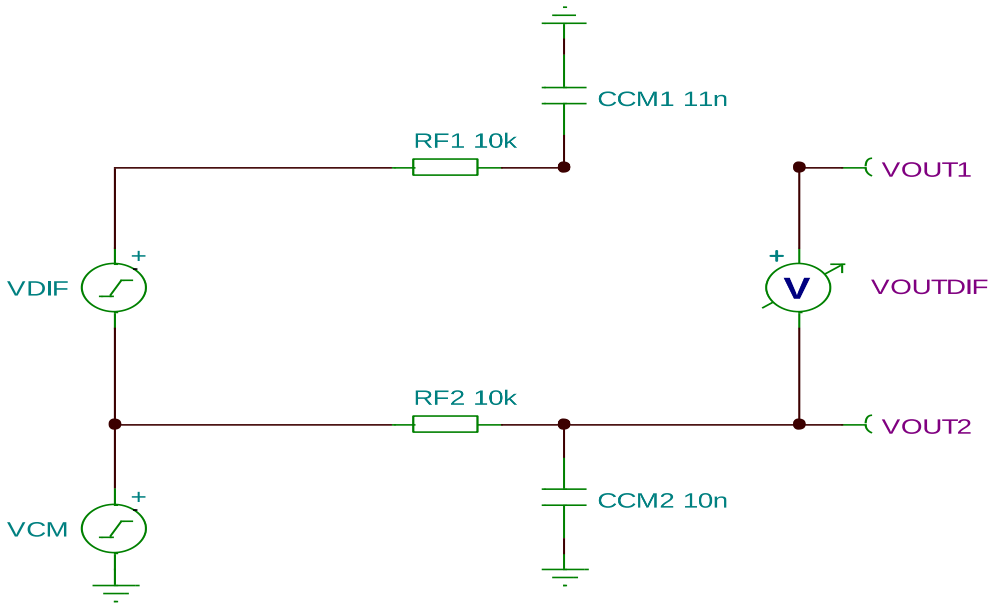
Common-mode filter only





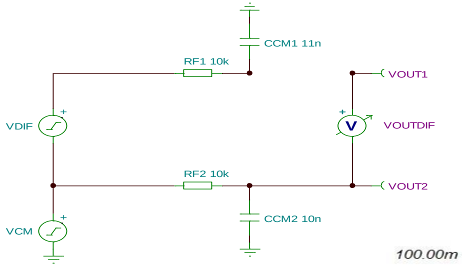
Simulation explaining why $C_{DIF} \geq 10 \cdot C_{CM}$

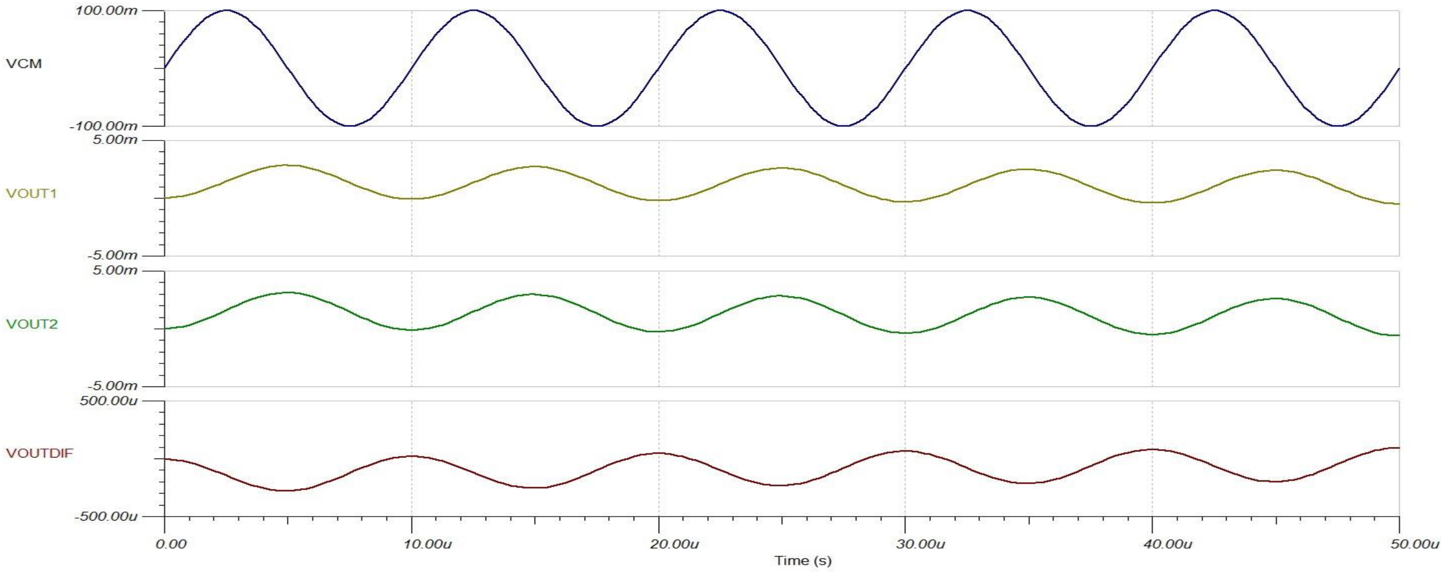
Mismatch in common-mode capacitors



Simulation explaining why $C_{DIF} \geq 10 \cdot C_{CM}$

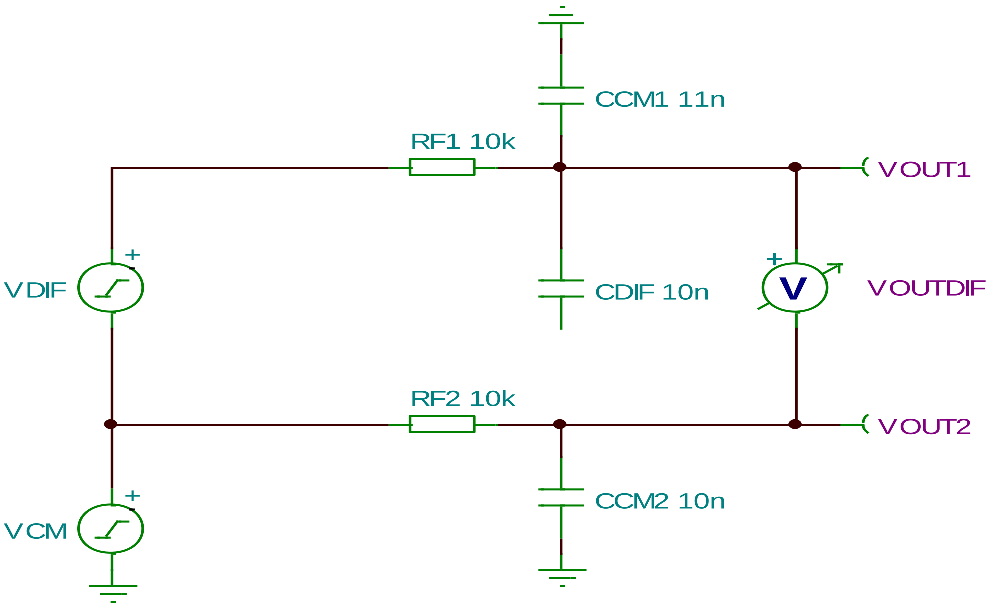
Mismatch in common-mode capacitors





Simulation explaining why $C_{DIF} \geq 10 \cdot C_{CM}$

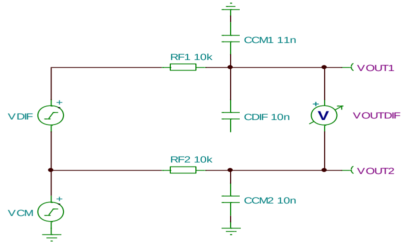
Adding differential mode filter

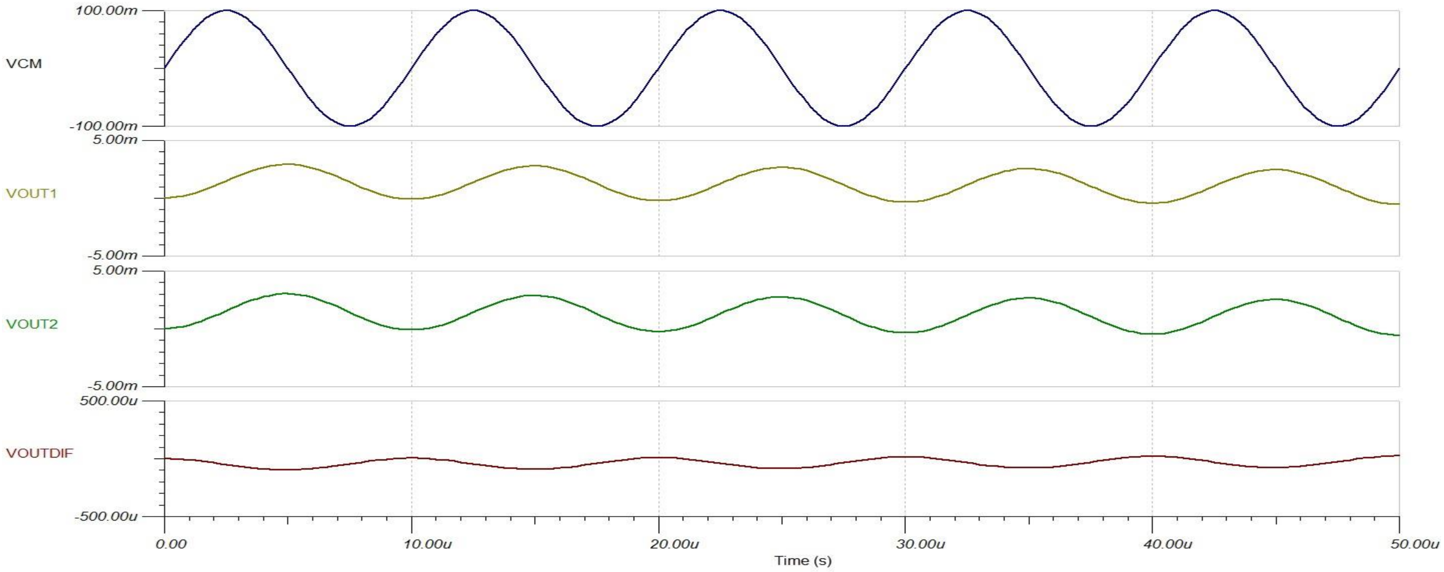


$f_{-3dB\_DIF} = 800Hz$

Simulation explaining why $C_{DIF} \geq 10 \cdot C_{CM}$

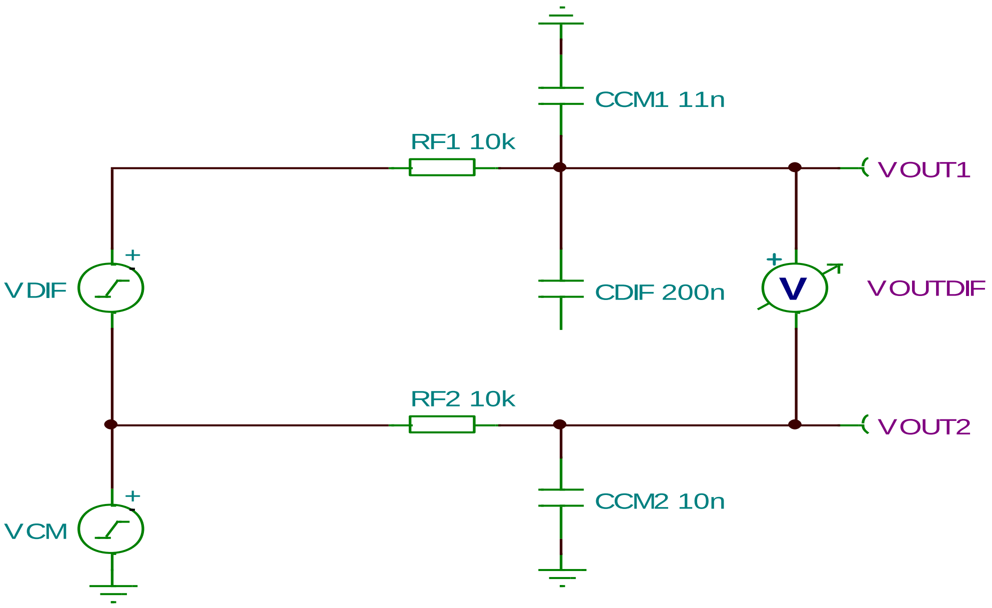
Adding differential mode filter





Simulation explaining why $C_{DIF} \geq 10 \cdot C_{CM}$

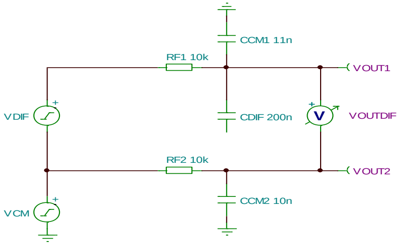
Increase differential mode filter capacitor

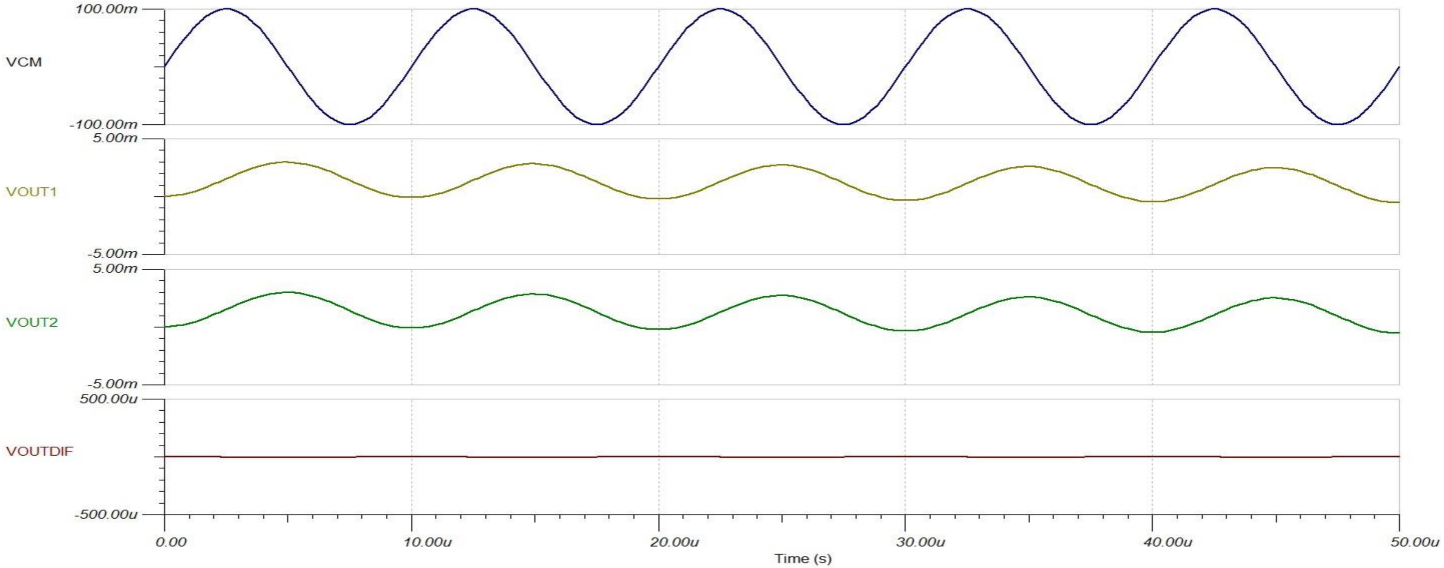


$f_{-3dB\_DIF} = 40\text{Hz}$

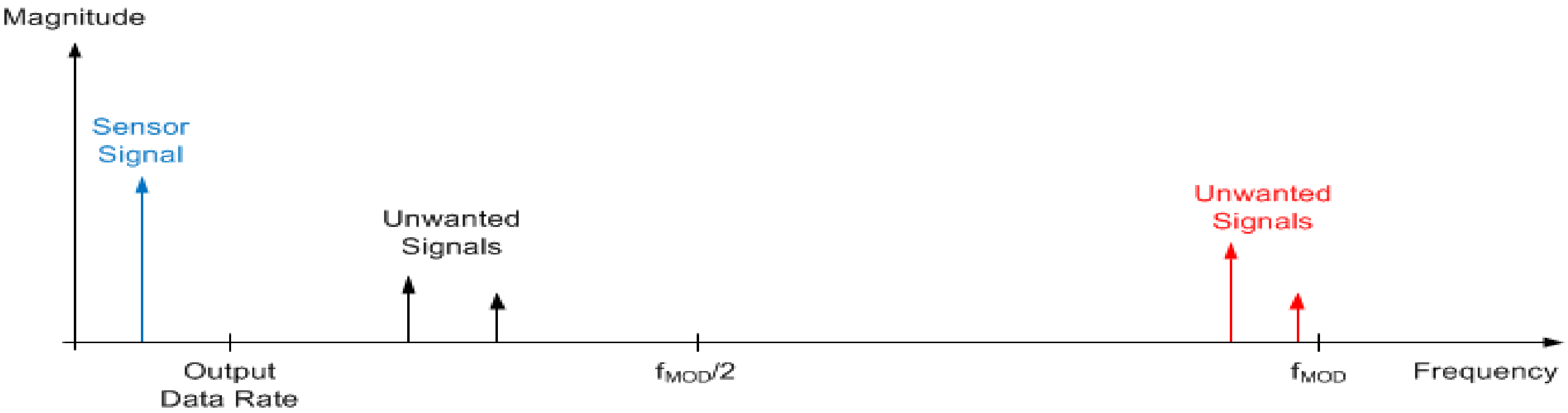
Simulation explaining why $C_{DIF} \geq 10 \cdot C_{CM}$

Increase differential mode filter capacitor



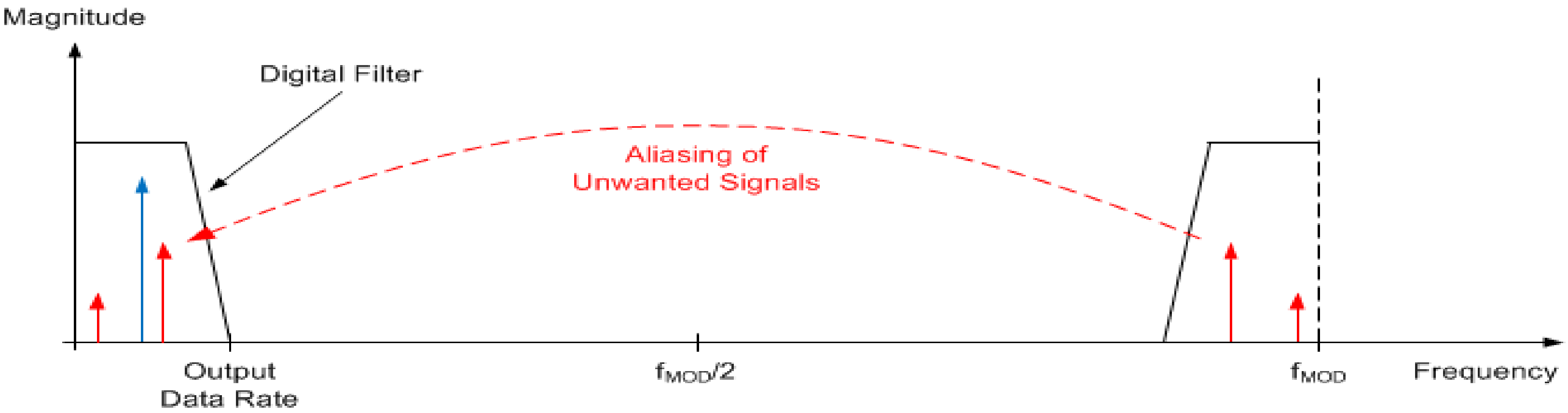


Aliasing I

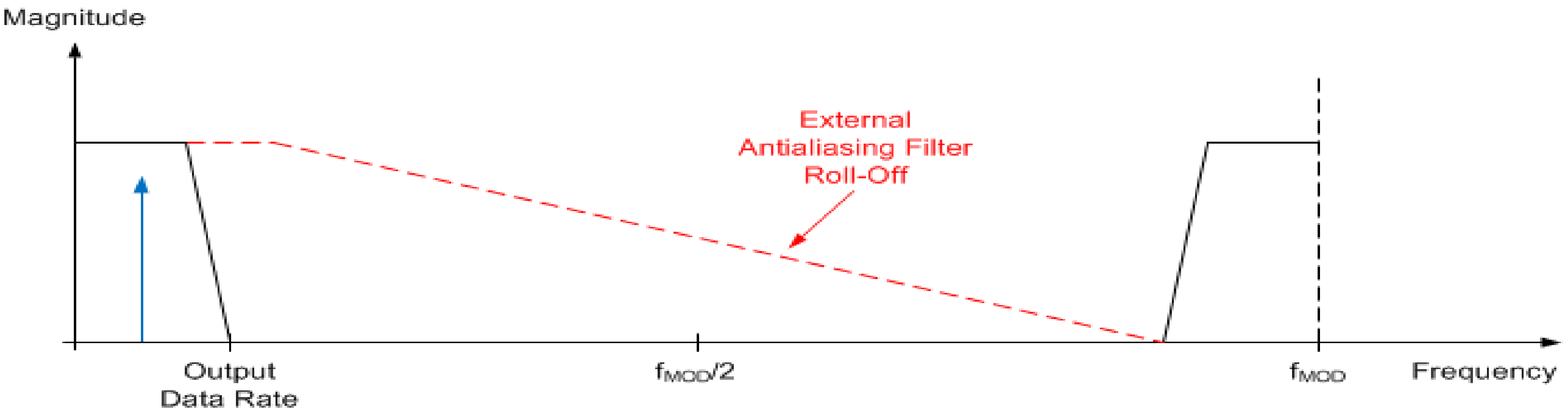


Magnitude
Sensor Signal
Unwanted Signals
Unwanted Signals
Output Data Rate
$f_{MOD}/2$
f_{MOD}
Frequency

Aliasing II


Magnitude
Digital Filter
Aliasing of
Unwanted Signals
Output
Data Rate
fMOD/2
fMOD
Frequency

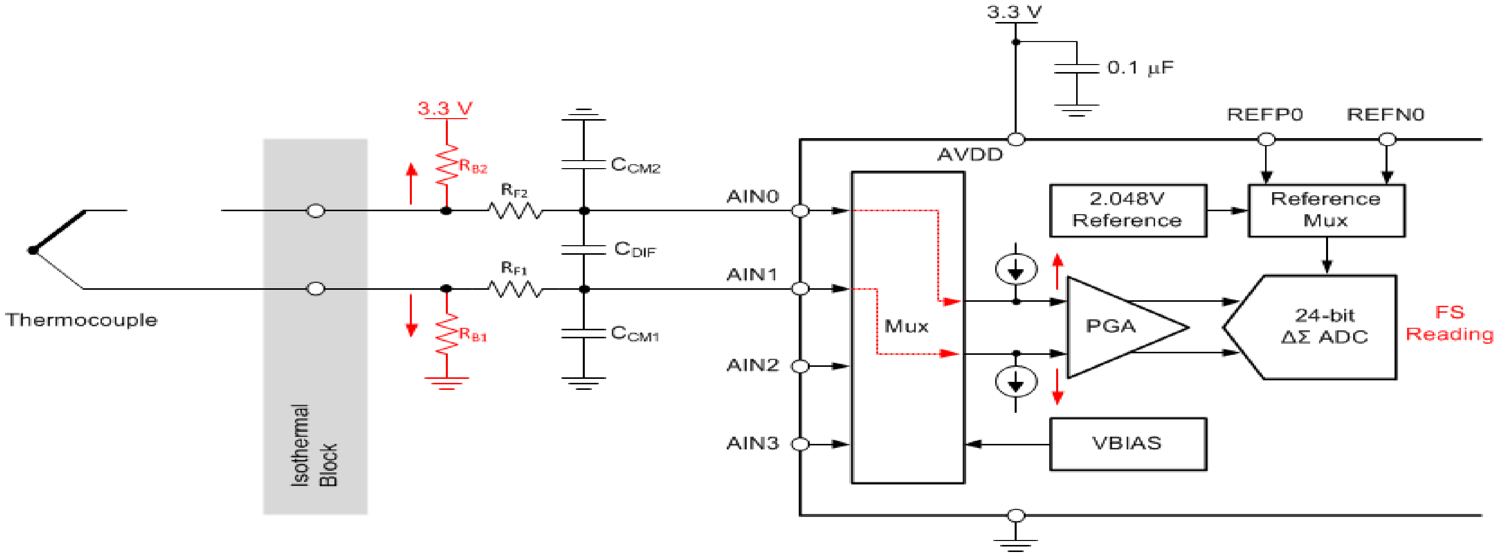
Aliasing III



- Knock down signals at f_{MOD} so they don't alias back into the band of interest
- Set $f_C \geq 10 \cdot f_{Data}$ so that droop of external filter does not effect the signal

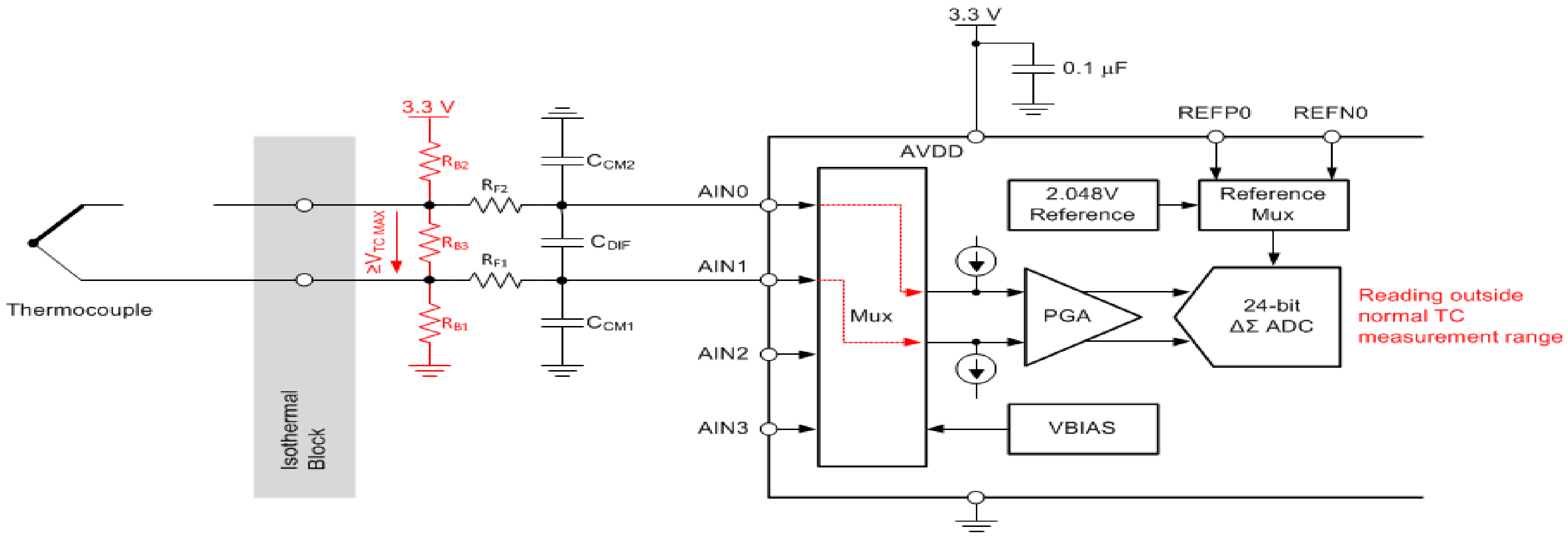
OPEN SENSOR DETECTION

Open Sensor Detection – Option Ia



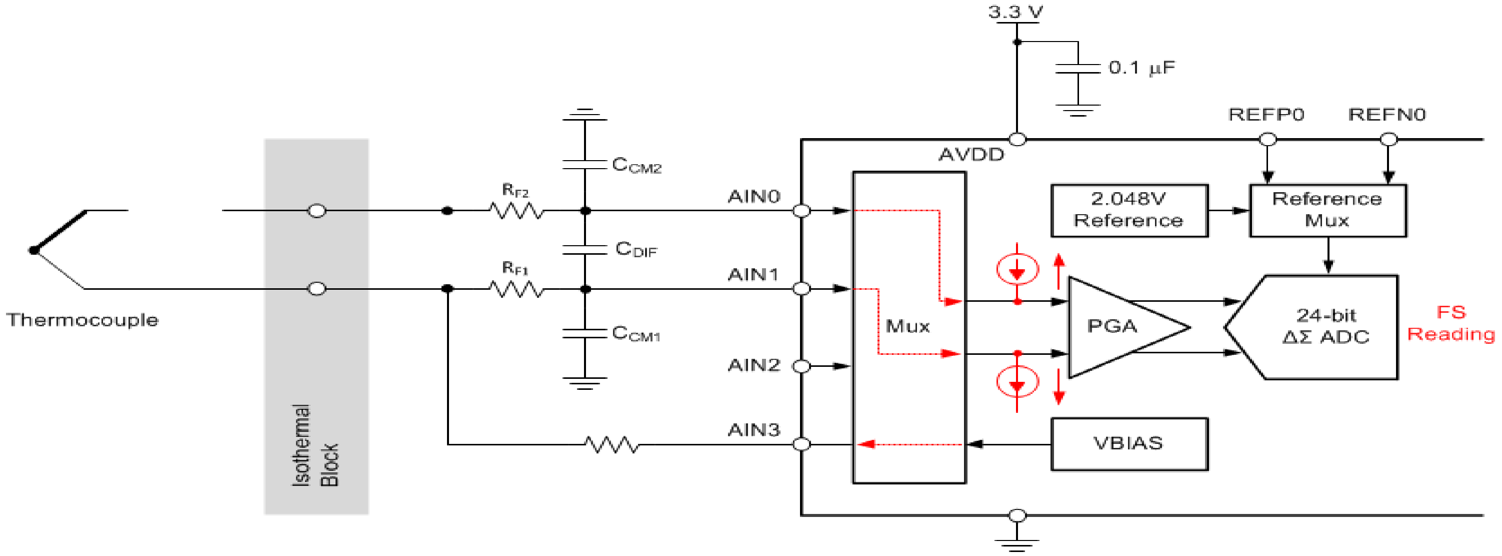
- Use of pull-up/down resistors
- Detection continuosly 'on the fly'
- Additional errors due to biasing current possible
- Open sensor condition will saturate PGA

Open Sensor Detection – Option Ib



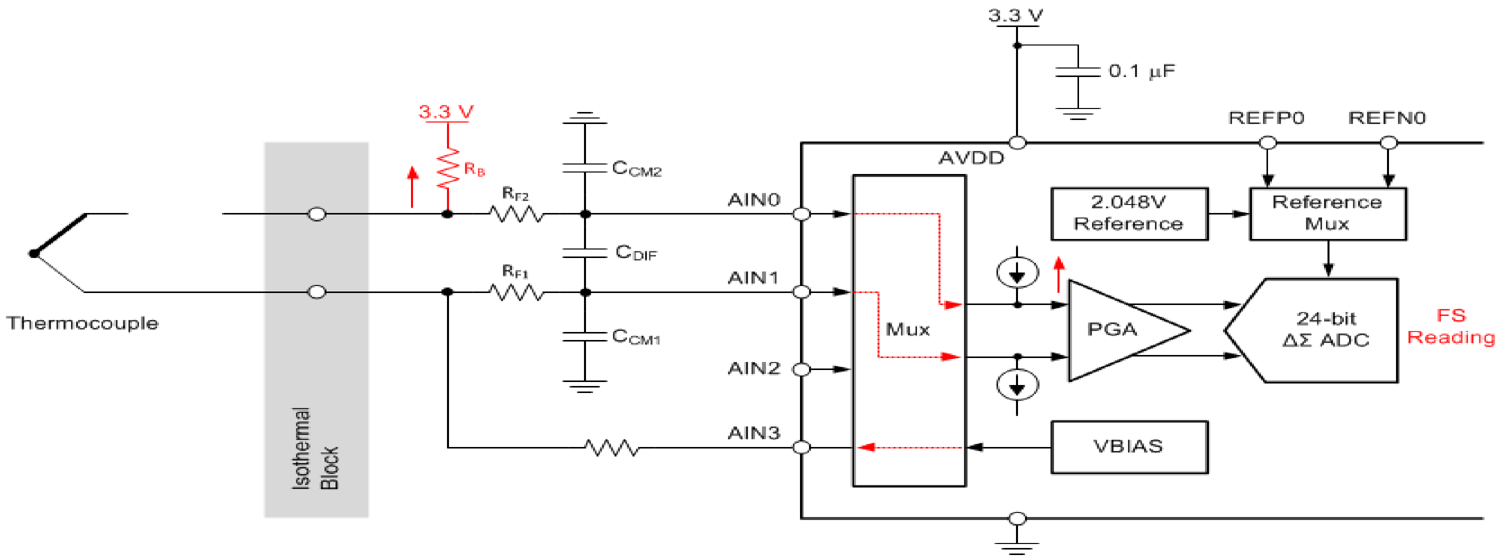
- $V_{TC\ MAX} \leq V_{RB3} \leq FS$
- Open sensor condition does not saturate PGA
- Improves settling in MUX applications

Open Sensor Detection – Option II



- Use of BOCS (Burnout Current Sources)
- Use a separate diagnostic cycle to turn BOCS on otherwise the currents will cause additional offset errors

Open Sensor Detection – Option III

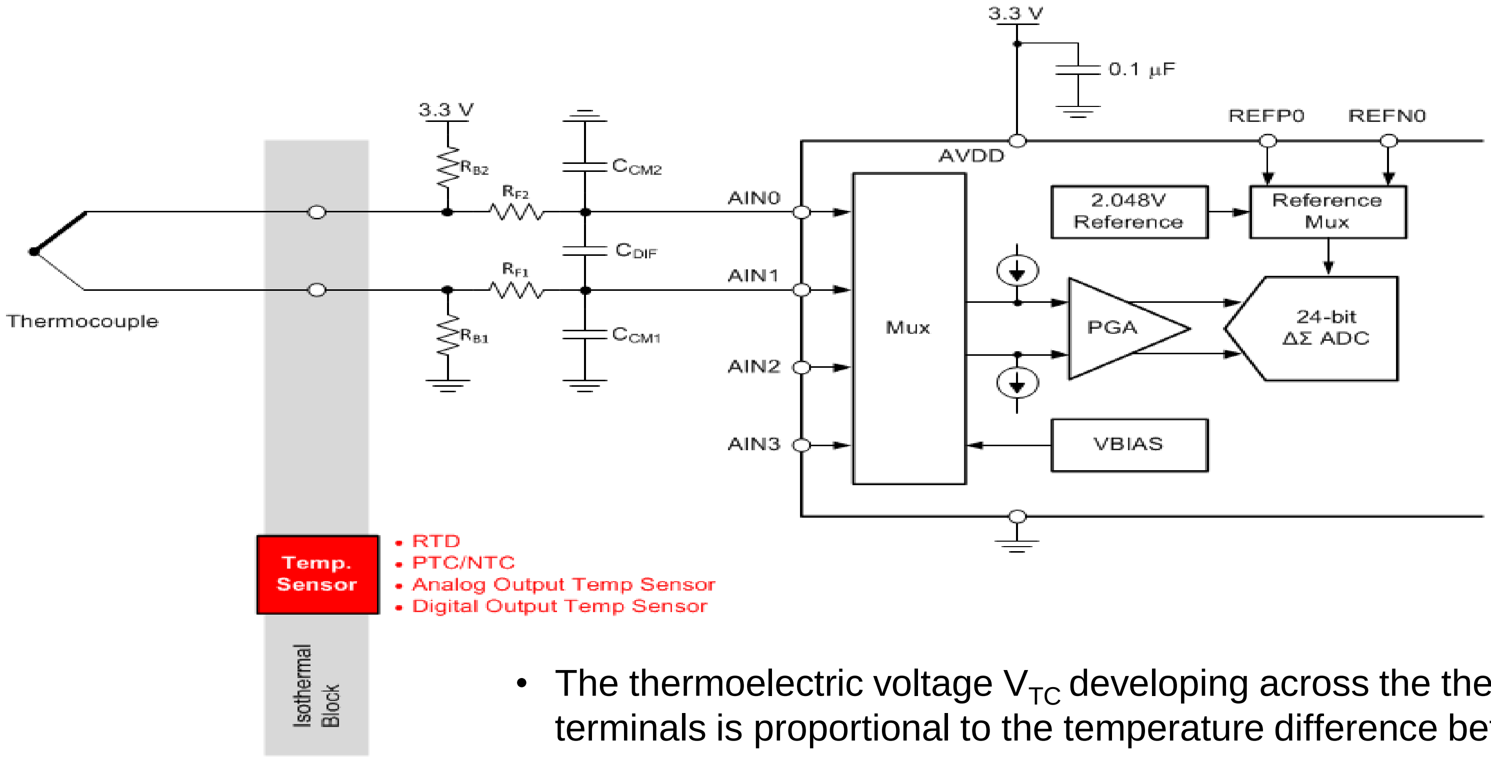


- Use of pull-up resistor together with V_{BIAS}
- Detection 'on the fly' but again potential issue of bias current causing additional errors

Cold Junction Compensation

CJC

CJC (Cold Junction Compensation)



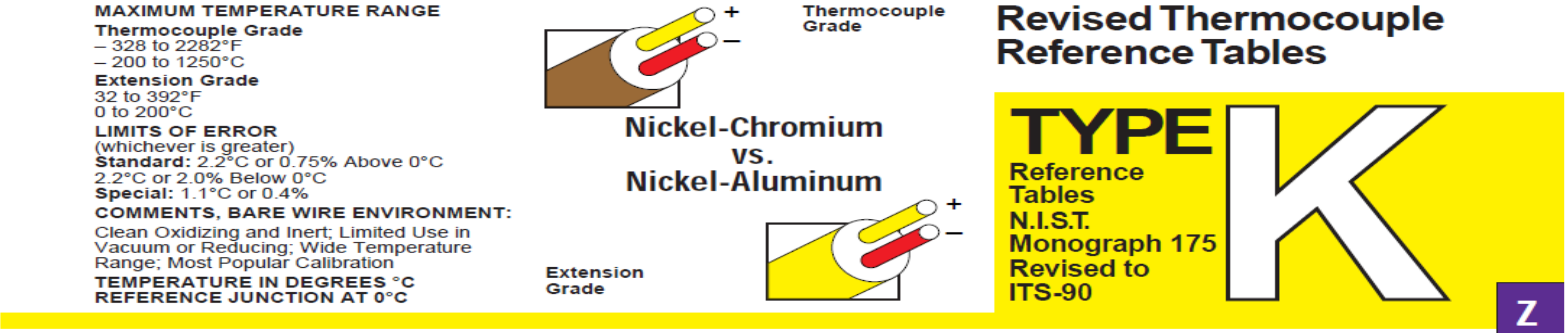
- The thermoelectric voltage V_{TC} developing across the thermocouple terminals is proportional to the temperature difference between the thermocouple tip and the terminals (cold junction)
- Therefore the temperature of the cold junction has to be known

CJC Algorithm

- CJC not automatically performed in our ADCs.
  Has to be implemented in the MCU

- Algorithm:
  1. Measure the thermocouple voltage, V_{TC}
  2. Measure the temperature of the cold junction, T_{CJ}
  3. Convert the cold-junction temperature into an equivalent thermoelectric voltage, V_{CJ}, using the tables or equations provided by NIST.
  4. Add V_{TC} and V_{CJ} and translate the summation back into a thermocouple temperature using the NIST tables or equations again.

CJC Example



°C	0	1	2	3	4	5	6	7	8	9	10
0	0.000	0.039	0.079	0.119	0.158	0.198	0.238	0.277	0.317	0.357	0.397
10	0.397	0.437	0.477	0.517	0.557	0.597	0.637	0.677	0.718	0.758	0.798
20	0.798	0.838	0.879	0.919	0.960	1.000	1.041	1.081	1.122	1.163	1.203
30	1.203	1.244	1.285	1.326	1.366	1.407	1.448	1.489	1.530	1.571	1.612
40	1.612	1.653	1.694	1.735	1.776	1.817	1.858	1.899	1.941	1.982	2.023

°C	0	1	2	3	4	5	6	7	8	9	10	°C
1100	45.119	45.157	45.194	45.232	45.270	45.308	45.346	45.383	45.421	45.459	45.497	1100
1110	45.497	45.534	45.572	45.610	45.647	45.685	45.723	45.760	45.798	45.836	45.873	1110
1120	45.873	45.911	45.948	45.986	46.024	46.061	46.099	46.136	46.174	46.211	46.249	1120
1130	46.249	46.286	46.324	46.361	46.398	46.436	46.473	46.511	46.548	46.585	46.623	1130
1140	46.623	46.660	46.697	46.735	46.772	46.809	46.847	46.884	46.921	46.958	46.995	1140

- T_{CJ} = 25°C
- V_{TC} = 45.809mV
- T_{TC} = ?

Accuracy

Resolution

ERROR ANALYSIS

Error Analysis using ADS1248

ADS1248	TYP	Unit
Offset	15	uV
Offset Drift	0.01	uV/°C
Gain Error	0.005	%
Gain Error Drift	3	ppm/°C
INL	6	ppm
Reference Voltage	2.048	V
Reference Voltage Initial Accuracy	0.015	%
Reference Drift	6	ppm/°C
PGA Gain	32	V/V
rms Noise @ 20SPS/Gain=32	0.12	uV

Initial ADC Errors at T_A = 25°C

Errors due to 'Error Source x' (ESx) at max. thermocouple temperature ($V_{TC\ MAX}$ = 54.886mV @ 1370°C)

ES1 **Offset Voltage**	15uV
ES2 **INL**	$(INL \cdot FS_{ADC})$ / Gain = $(INL \cdot 2 \cdot V_{REF})$ / Gain = (6ppm · 2·2.048V) / 32 = 0.77uV
ES3 **Gain Error**	$(GE \cdot V_{TC\ MAX})$ = 0.005% · 54.886mV = 2.74uV
ES4 **Reference Accuracy**	0.015% · 54.886mV = 8.23uV

Overall ADC Error @ T_A=25°C	$\sqrt{ES1^2 + ES2^2 + ES3^2 + ES4^2} = 17.3uV$

(*) Errors due to bias or ADC input currents and external filter components have been neglected

Overall ADC Error at T_A = 25°C

- Overall Voltage Error @ T_A=25°C: 17.3uV
- Type-K Thermocouple Sensitivity: 40uV/°C
- Temperature Error: 17.3uV / 40uV/°C = 0.43°C
- This is the error introduced by the ADC only.
  It can typically be calibrated using offset and gain calibration.
- Other errors like
  - Accuracy of the CJC measurement
  - Offset voltages due to bias and input leakage currents
  - Accuracy of the thermocouple itself
  - Non-linearity of thermocouple

  have to be taken into account as well in order to determine the overall system accuracy.

ADC Errors due to Temperature Drift

- Ambient Temperature Range: -40°C to 85°C
- Max. Deviation from 25°C: 65°C

ES1 **Offset Voltage Drift**	0.01uV/°C · 65°C = 0.65uV
ES2 **Gain Error Drift**	3ppm/°C · 54.886mV · 65°C = 10.7uV
ES3 **Reference Drift**	6ppm/°C · 54.886mV · 65°C = 21.4uV

Overall Drift Error $\sqrt{ES1^2 + ES2^2 + ES3^2} = 23.9uV$

Errors due to Temperature Drift

- Overall Temperature Drift Error: 23.9uV
- Type-K Thermocouple Sensitivity: 40uV/°C
- Temperature Error: 23.9uV / 40uV/°C = 0.59°C

- Chopping the inputs can eliminate offset drift errors.
  You need to make sure the input signal is settled before taking a reading using the swapped inputs.

Achievable Resolution with ADS1248

Table 1. Noise in μV_{RMS} and (μV_{PP})
at AVDD = 5V, AVSS = 0V, and External Reference = 2.5V

DATA RATE (SPS)	PGA SETTING							
	1	2	4	8	16	32	64	128
5	1.1 (4.99)	0.68 (3.8)	0.37 (1.9)	0.19 (0.98)	0.1 (0.44)	0.07 (0.31)	0.05 (0.27)	0.05 (0.21)
10	1.53 (8.82)	0.82 (3.71)	0.5 (2.69)	0.27 (1.33)	0.15 (0.67)	0.08 (0.5)	0.06 (0.36)	0.07 (0.34)
20	2.32 (13.37)	1.23 (6.69)	0.71 (3.83)	0.34 (1.9)	0.18 (1.01)	0.12 (0.71)	0.10 (0.51)	0.09 (0.54)

- LSB size: $\frac{2 \times V_{REF}}{2^{24} \times Gain} = \frac{2 \times 2.048V}{2^{24} \times 32} = 7.6nV$
- Input referrerd Noise: $0.71uV_{pp}$
- Type-K Thermocouple Sensitivity: 40uV/°C
- Temperature Resolution per Code: 7.6nV / 40uV/°C = 0.0002°C
- Noise Free Temperature Resolution: $0.71uV_{pp}$ / 40uV/°C = 0.018°C

Suitable ADCs

High-End PLC Input Modules, Data Loggers

ADS1262
ADS1263

Temperature Transmitters, Data Loggers, Lower-End PLC Input Modules

ADS1247/48
ADS124S06/08

Temperature Transmitters

ADS1220
ADS122C04

Integration
Accuracy/Resolution
Power Consumption

ADS1248

24-bit, 7-Ch, 2kSPS Low Noise ADC | Reference | Oscillator | PGA | Temp Sensor | Current Sources

Features

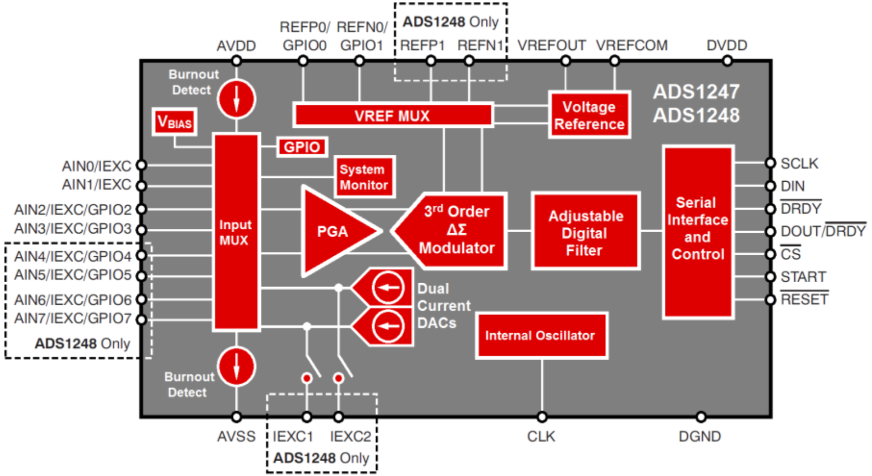
- **Flexible Device Family:**
  - Inputs: **7 Single-Ended | 4 Differential**
  - Supply Range: **±2.5V (Bipolar) / 5V (Unipolar)**
  - Variable Output Data Rate: **5SPS to 2kSPS**
- 50/60Hz Simultaneous Rejection Mode (20SPS)
- **On-Chip Integration:**
  - Low Drift Reference: **2.048V**
  - Low Noise PGA: **80nV @ G = 128**
  - Dual, Matched IDACs: **50–1500µA**
  - Oscillator | Temp Sensor | Burnout Detect
  - GPIO's: **8**

Benefits

- With all of the necessary parts on board coupled with no sacrifice in performance, the ADS1248 is the ultimate temperature sensor measurement solution
- Very flexible analog front end enables an easy design path for developers and allows for integration into a wide range of applications
- A high level of integration eliminates the need for several discrete components, reducing board space as well as BOM costs
- Large family of sensor-ready products provides a scalable solution

Applications

- Temperature Measurement: **RTDs | Thermocouples | Thermistors**
- Flow/Pressure Measurement
- Industrial Process Control



ADS124S06 / ADS124S08

24-bit, 4 kSPS, 6/12-Ch ΔΣ ADC for Precision Sensor Measurement

Features

Resolution	24
# of Ch	6 / 12
Sample Rate	4 kSPS
Interface	SPI
AVDD	2.7 V to 5.25 V ±2.5 V
DVDD	2.7 V to 3.6 V
Input Type	Single-Ended Differential
Temperature Range	-50°C to +125°C
Package	5 mm x 5 mm (QFN-32 / TQFP-32)

Low-Noise PGA (19 nV @ G=128)

Low-Drift Reference (10 ppm/°C max)

2x Current Sources (IDACs)

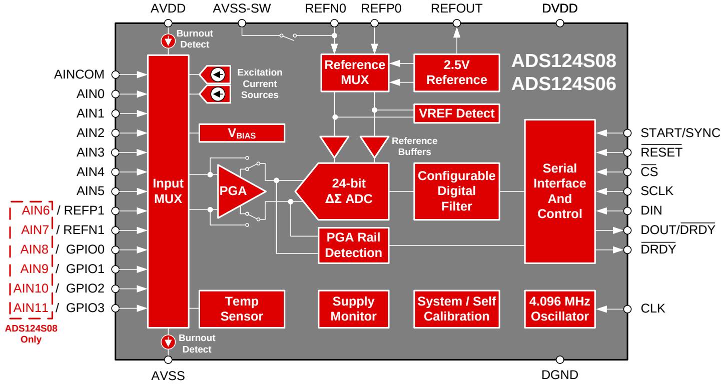
High Accuracy Oscillator (1.5%)

Applications

- Temperature Measurement: **RTDs | Thermocouples | Thermistors**
- Pressure Sensors
- Electro-Magnetic Flow Meters
- Universal PLC / DCS Analog Input Modules
- Weigh Scales

Benefits

- **Low-noise PGA** enables precision measurements for the smallest input signals
- **Low-drift integrated voltage reference** reduces system cost and size while still offering high precision and accuracy
- **Dual, matched IDACs** can used for RTD biasing, reducing BOM size and solution cost
- **High-accuracy oscillator** enables better 50/60 Hz rejection than competitors for noisy industrial environments



Device	# of Ch	Resolution	Device	# of Ch	Resolution
ADS124S08	12	24	ADS114S08	12	16
ADS124S06	6		ADS114S06	6	

ADS124S06/8 – Improved Features

24-bit, 6/12-Ch, 4kSPS Delta-Sigma ADC for Precision Sensor Measurement

Better Performance vs. ADS1248

- 30% lower power consumption (280µA w/ PGA bypassed & external reference)
- 20% lower noise (19nV$_{RMS}$ @ G = 128, 2.5SPS)
- 60% smaller package (5x5mm QFN & 7x7mm TQFP)
- 1.5% accurate oscillator
- Guaranteed input leakage current of 2nA over temperature
- Single-ended input measurement capability @ G=1
- Wider temperature range: -50°C to +125°C

Improved Design vs. ADS1248

- Additional data rate options: 2.5 | 16.6 | 50 | 60 | 4000
- Increased reference voltage: 2.5V
- Extended reference input voltage range → now includes AVDD
- Improved IDAC performance: compliance voltage, noise, drift, matching, etc.
- Expanded feature set: Reference Detect | PGA Out-of-Range Detection | Low-Side Switch
- Simplified SPI interface
- Optional 8-bit CRC

ADS1120 / ADS1220

Low Power, 16/24-bit, 2 kSPS, 4-Ch ΔΣ ADC for Small Signal Sensors

Features

Resolution	**16 / 24**
# of Ch	**4**
Sample Rate	**2 kSPS**
Interface	**SPI**
AVDD	**2.3 V to 5.5 V ±2.5 V**
DVDD	**2.3 V to 5.5 V**
Input Type	**Single-Ended Differential**
Temperature Range	**-40°C to +125°C**
Package	**3.5 x 3.5 mm (QFN-16) 5 x 4.4 mm (TSSOP-16)**

Integration: PGA, VREF, OSC, Temp Sensor

2x Current Sources (IDACs)

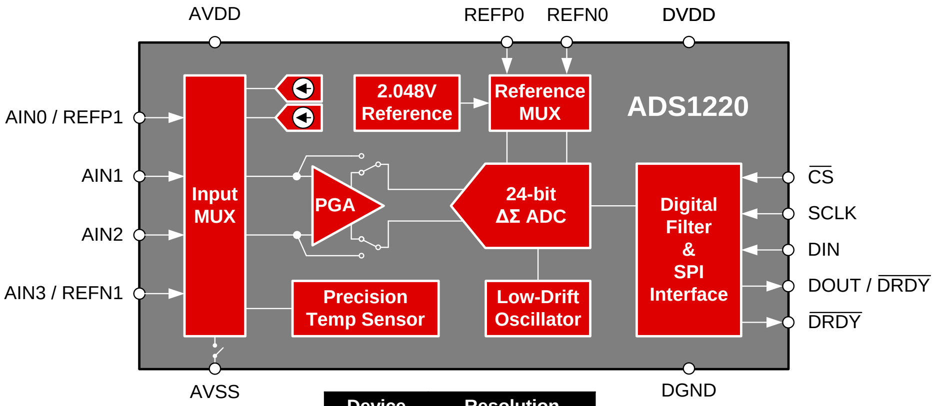
Low-Side Bridge Switch

2x VREF Input & External CLKIN

- Temperature Measurement: **RTDs | Thermocouples | Thermistors**
- Heat Meters
- 4-20mA Loop-Powered Transmitters
- Pressure / Bridge Sensors
- Electro-Magnetic Flow Meters
- Portable Instrumentation

Benefits

- Lots of **integrated features** provide a complete analog front end for DC sensing applications that reduce system cost and size
- **Dual, matched IDACs** can used for RTD biasing, reducing BOM size and solution cost
- **Low-side switch** saves power when measuring resistive bridges by breaking current path
- **Dual VREF inputs** along with **CLKIN pin** enable maximum design flexibility when external components are required



Device	Resolution
ADS1220	24-bit
ADS1120	16-bit

ADS112C04 / ADS122C04

16/24-bit, 2 kSPS, 4-Ch Sensor Measurement ΔΣ ADC with 2-Wire I2C Interface

Features

Resolution	**16 / 24**
# of Ch	**4**
Sample Rate	**2 kSPS**
Interface	**I2C**
AVDD	**2.3 V to 5.5 V**
DVDD	**2.3 V to 5.5 V**
Input Type	**Single-Ended Differential**
Temperature Range	**-40°C to +125°C**
Package	**3 x 3 mm (QFN-16) 5 x 4.4 mm (TSSOP-16)**

2-Wire I2C Interface

2x Current Sources (IDACs)

Integration: PGA, VREF, OSC, Temp Sensor

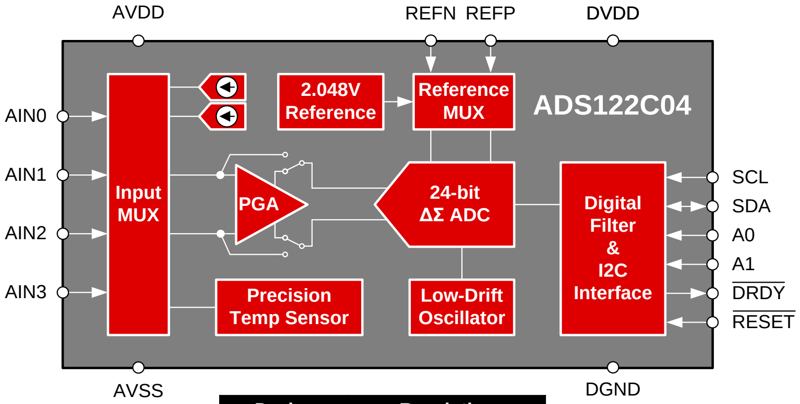
Conversion Counter & CRC

Applications

- Temperature Measurement: **RTDs | Thermocouples | Thermistors**
- Heat Meters
- 4-20mA Loop-Powered Transmitters
- Pressure / Bridge Sensors
- Portable Instrumentation

Benefits

- **Simple, 2-wire I²C interface** requires fewer isolation lines compared to SPI interface
- **Dual, matched IDACs** can used for RTD biasing, reducing BOM size and solution cost
- Lots of **integrated features** provide a complete analog front end for DC sensing applications that reduce system cost and size
- **Conversion counter & CRC** provide device health feedback to help maintain reliable system operation



Device	Resolution
ADS122C04	24-bit
ADS112C04	16-bit

Texas Instruments

ADS1260 / ADS1261

24-bit, 40 kSPS, 5/10-Ch ΔΣ ADC w/ Low Noise in 5 mm x 5 mm QFN

Features

Resolution	24
# of Ch	5 / 10
Sample Rate	40 kSPS
Interface	SPI
AVDD	4.75 V to 5.25 V ±2.5 V
DVDD	2.7 V to 5.25 V
Input Type	Single-Ended Differential
Temperature Range	-40°C to +125°C
Package	5 mm x 5 mm (QFN-32)

Low-Noise PGA
(6 nV_{RMS} @ G=128, 2.5 SPS)

Small 5 mm x 5 mm QFN Package

AC Excitation (ADS1261 only)

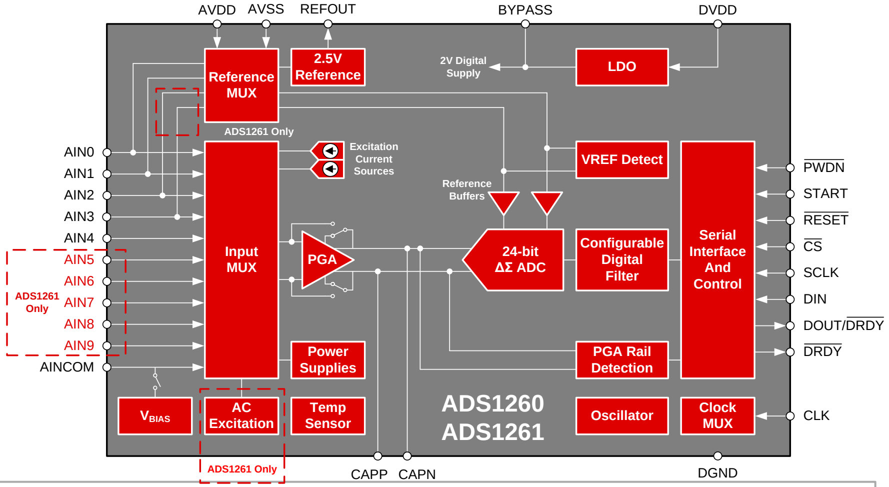
Monitoring & Diagnostics

Benefits

- **Low-noise PGA** enables precision measurements for the smallest input signals
- **Small 5x5 mm QFN package** reduces system footprint while still providing a highly-integrated, high-performance solution
- **AC-excitation** drive for H-bridge chopping helps remove offset and offset drift errors to improve system accuracy
- **Monitoring & diagnostic** features help improve system reliability

Applications

- PLC Analog Input Modules:
  - 4-20 mA | 10 V | RTD | Thermocouple
- DAQ and Dynamic Strain Analyzers
- Gas Chromatographs / Flow Meters
- Weigh Scale / Resistive Bridge Measurements



ADS1262 / ADS1263

32-bit, 38 kSPS, 10-Ch, Best-in-Class Industrial ΔΣ ADC

Features

Resolution	32
# of Ch	10
Sample Rate	38 kSPS
Interface	SPI
AVDD	4.75 V to 5.25 V ±2.5 V
DVDD	1.8 V to 3.6 V
Input Type	Single-Ended Differential
Temperature Range	-40°C to +125°C
Package	9.7 mm x 4.4 mm (TSSOP-28)

Low Noise: 7 nV_{RMS}
Low Offset Drift: 1 nV/°C
Highly-Linear: 3 ppm

Highly-Integrated:
PGA, VREF, OSC, IDACs

Fault Diagnostics & Monitoring

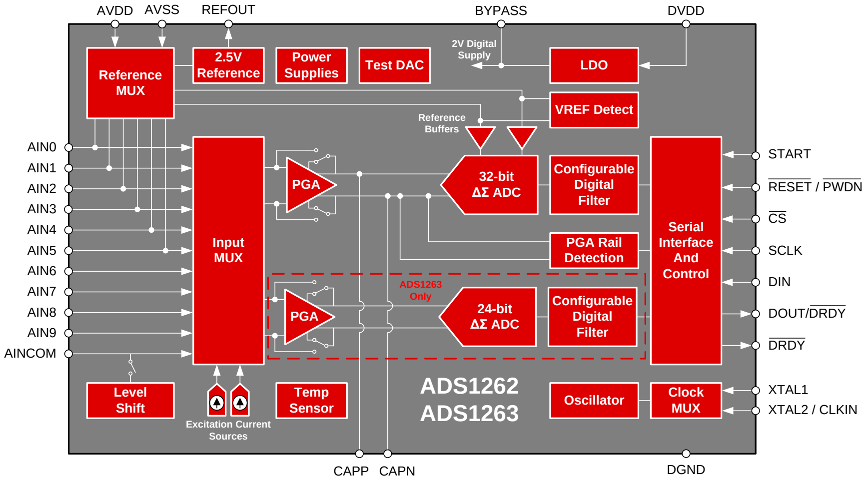
Auxiliary 24-bit ADC (ADS1263 only)

Benefits

- **High-resolution, low-drift** architecture provides the industry's best performing ADC
- **A high level of integration** reduces necessary external components saving cost & space while reducing complexity
- **Fault detection** improves reliability in industrial systems
- Use ADS1263's **auxiliary, 24-bit signal path** for temp monitoring in precision applications such as flow meters & weigh scales

Applications

- PLC Analog Input Modules
- Differential Pressure Flow Meters
- High Precision Weigh Scales
- Gas Chromatography
- Analytical Equipment



Samples: NOW
RTM**: 4Q19

ADS125H01** / ADS125H02

Industry's First ±20 V Input, 24-bit, 40kSPS, 1-/2-Ch ΔΣ ADC with High Input Impedance

Features

Resolution	24
# of Ch	1 / 2
Sample Rate	40 kSPS
Interface	SPI
CM Range	±15.5 V
HV AVDD	±18 V / 0 V to 36 V
AVDD	4.75 V to 5.25 V
DVDD	2.7 V to 5.25 V
PGA Gains	0.125 to 128 (binary)
Input Type	Single-Ended Differential
Temp Range	-40°C to +125°C
Package	5 mm x 5 mm (QFN-32)

Wide FS Input Signal Range:
±20 mV to ±20 V

Ultra-Low Noise:
45 nV_{RMS} (20 SPS)

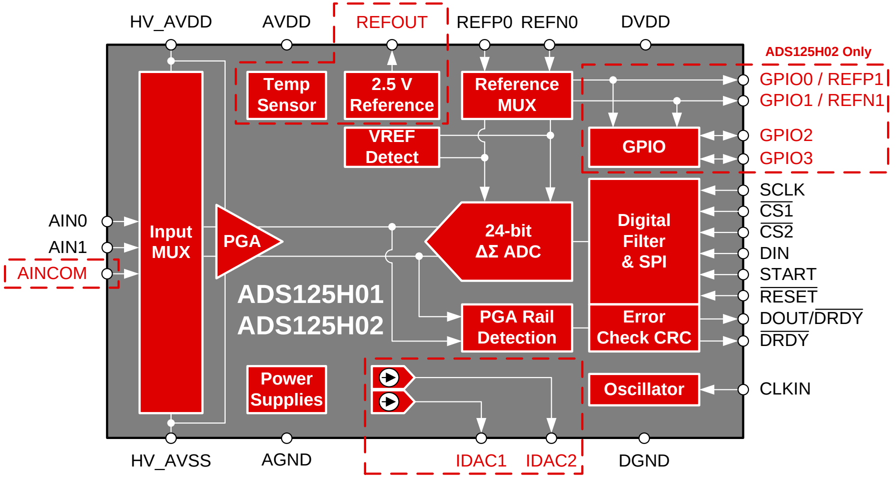
Small Solution Size:
5 mm x 5 mm QFN

High Input Impedance:
1 GΩ

- PLC Analog Input Modules:
  - ±10 V / 4-20 mA
  - Thermocouple / RTD
  - Universal Input
- High-Voltage, Precision T&M
  - Battery Test Equipment

Benefits

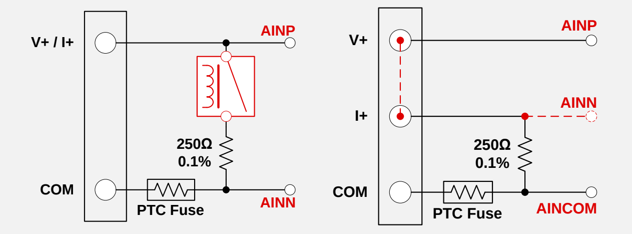
- **Programmable input signal range** accepts high-voltage inputs **and** low-voltage inputs
- **Low noise PGA + high-resolution 24-bit ADC** suitable for direct connection to bridge / RTD / thermocouple sensors
- **Small form factor, single-chip solution** is >50% smaller than discrete devices, reducing PCB area and simplifying design
- **1-GΩ input impedance** eliminates measurement errors caused by sensor loading



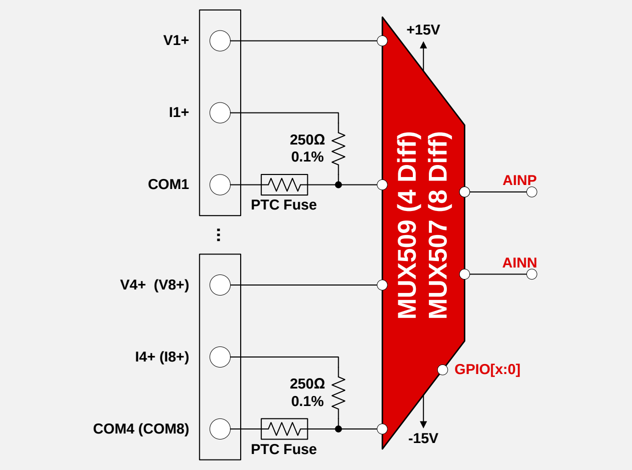
ADS125H0x – Platform Solution

Industry's First ±20 V Input, 24-bit, 40kSPS, 1-/2-Ch ΔΣ ADC with High Input Impedance

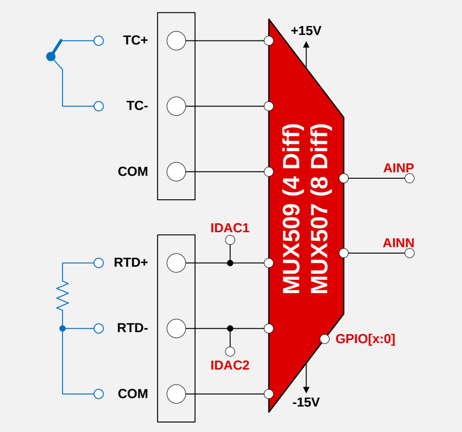
2- or 3-Terminal V/I Input



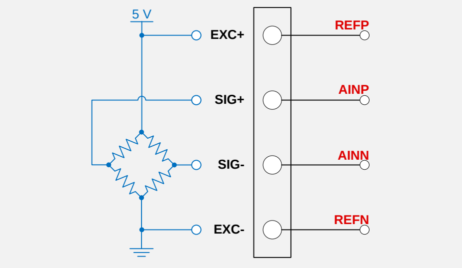
4- / 8-Channel V/I Input



Temperature Input

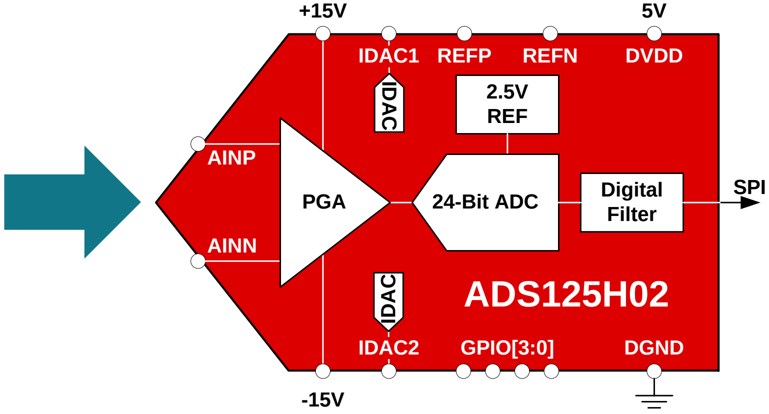


Pressure / Weight Input



ADS125H02 is a platform solution = supports all types of analog inputs and input ranges with 1x ADC:

- **Voltage** (±10V, 0-10V, ±5V 0-5V)
- **Current** (0-20 mA, 4-20 mA)
- **Temperature** (RTD, TC, thermistor)
- **Pressure / Weight** (resistive bridge)

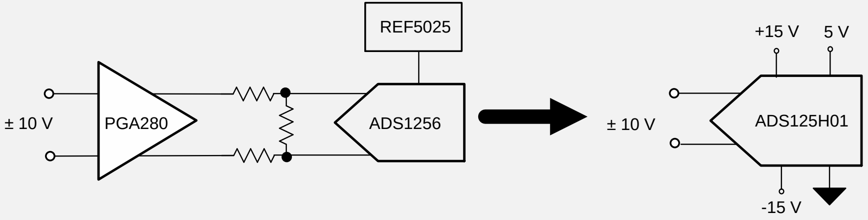


**Note: protection / filtering circuitry not shown

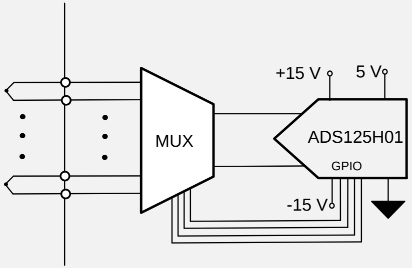
ADS125H0x – Applications

Industry's First ±20 V Input, 24-bit, 40kSPS, 1-/2-Ch ΔΣ ADC with High Input Impedance

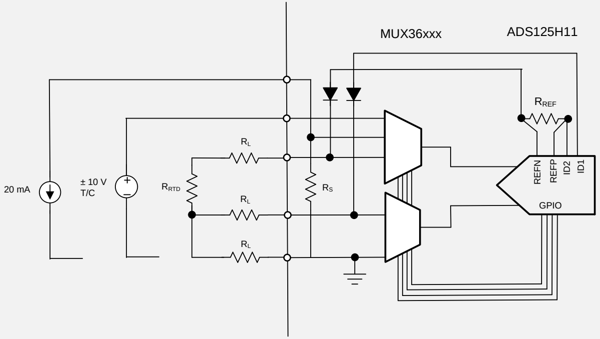
PLC Single-ch Module (Consolidation)



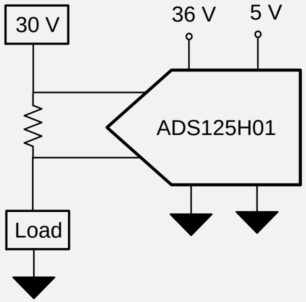
High CMV Multi-ch Thermocouple



High-Voltage Universal Input Module



High-Side Precision Sensing

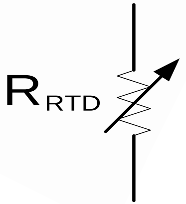


Designing RTD

Theory of Operation & Design Examples

RTD
Resistance Temperature Detector

- Principle of Operation:
  Predictable resistance change
- Mostly made of Platinum
  - linear resistance-temperature relationship
  - chemical inertness
- Pt100 most common device used in industry
  - Nominal Resistance R = 100Ω @ 0°C
  - Sensitivity = 0.385Ω/°C (typ.)
- Slowly replacing thermocouples in many industrial applications below 600°C
- …racy, stability and repeatability



Advantages

- ➔ **High accuracy: < ±1°C**
- ➔ **Best stability over time**
- ➔ **Temperature range: -200°C to +850°C**
- ➔ **Good linearity**

Disadvantages

- ➔ **Expensive**
- ➔ **Excitation required**
- ➔ **Self-heating**
- ➔ **Lead resistance**
- ➔ **Low sensitivity**

What is an RTD made of?

- Platinum (Pt)
- Nickel (Ni)
- Copper (Cu)

- Have relatively linear change in resistance over temp
- Have high resistivity allowing for smaller dimensions
- Either Wire-Wound or Thin-Film

Metal	Resistivity (Ohm/CMF)
Gold (Au)	13
Silver (Ag)	8.8
Copper (Cu)	9.26
Platinum (Pt)	59
Tungsten (W)	30
Nickel (Ni)	36

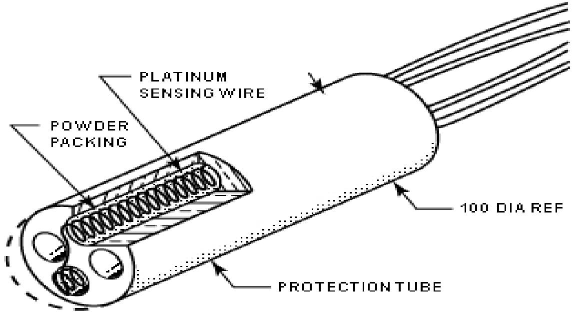


Figure 1. The coiled element sensor, made by inserting the helical sensing wires into a packed powder-filled insulating mandrel, provides a strain-free sensing element.

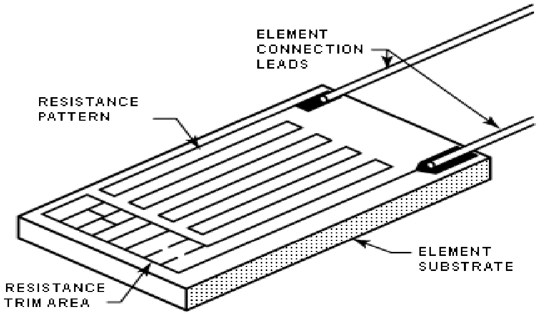


Figure 2. The thin film sensing element is made by depositing a thin layer of platinum in a resistance pattern on a ceramic substrate. A glassy layer is applied for seal and protection.

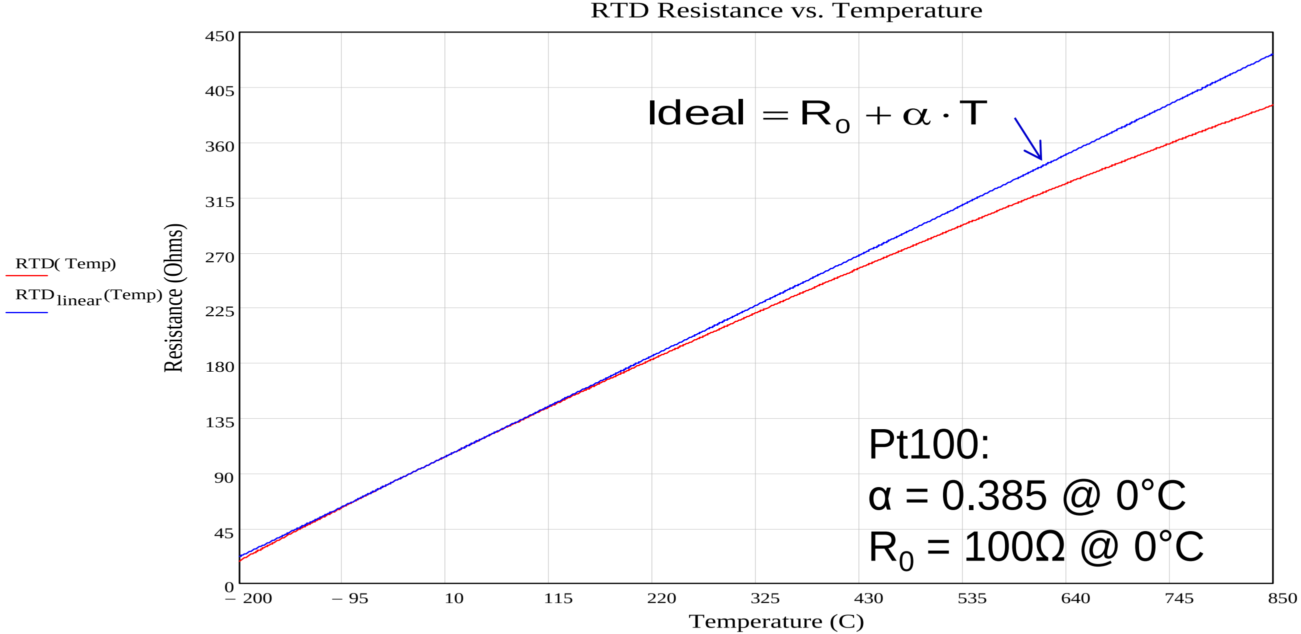
(*)*Images from RDF Corp*

RTD Resistance vs. Temperature

Callendar-Van Dusen Equations

$$T > 0: \quad R_{RTD}(T) = R_0 \cdot [1 + A \cdot T + B \cdot T^2]$$

$$T < 0: \quad R_{RTD}(T) = R_0 \cdot [1 + A \cdot T + B \cdot T^2 + C \cdot T^3 \cdot (T - 100)]$$



IEC60751 Constants:

$R_0 = 100\Omega$

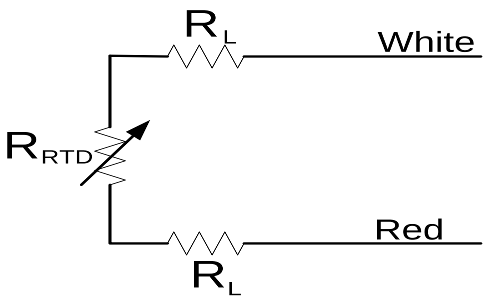
$A = 3.9083 \cdot 10^{-3}$

$B = -5.775 \cdot 10^{-7}$

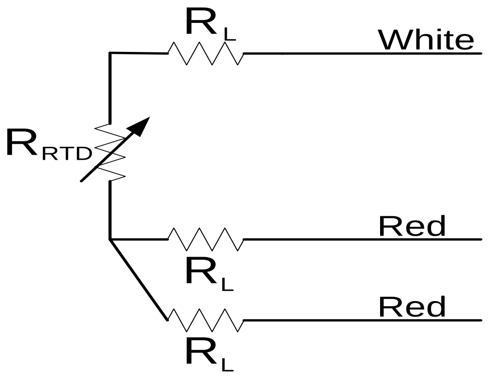
$C = -4.183 \cdot 10^{-12}$

Different RTD Types – why do they exist? (I)

- **2-Wire RTD**
  - 2-Wire measurements are simplest to implement
  - Good for close proximity to RTD (R_L is small)
  - RTD lead resistance is included in the result
  - Tradeoff:
    - Accuracy: Error = $2 \cdot R_L \cdot I_{EXC}$
    - Cost = Cheapest!

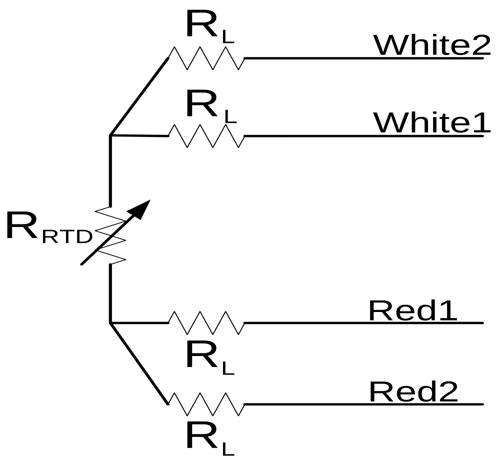


- **3-Wire RTD**
  - Allows for R_L cancellation and remote RTD placement
  - Tradeoff:
    - Accuracy = Better
    - Cost = More expensive



Different RTD Types – why do they exist? (II)

- **4-Wire RTD**
  - Kelvin Connection:
    Isolates the excitation path from the sensing path
    - 2 wires carry the excitation current,
    - 2 wires connect to high-impedance measurement circuitry
  - Useful when R_L matching becomes difficult to implement
  - Tradeoff:
    - Accuracy = Most accurate
    - Cost = Most expensive



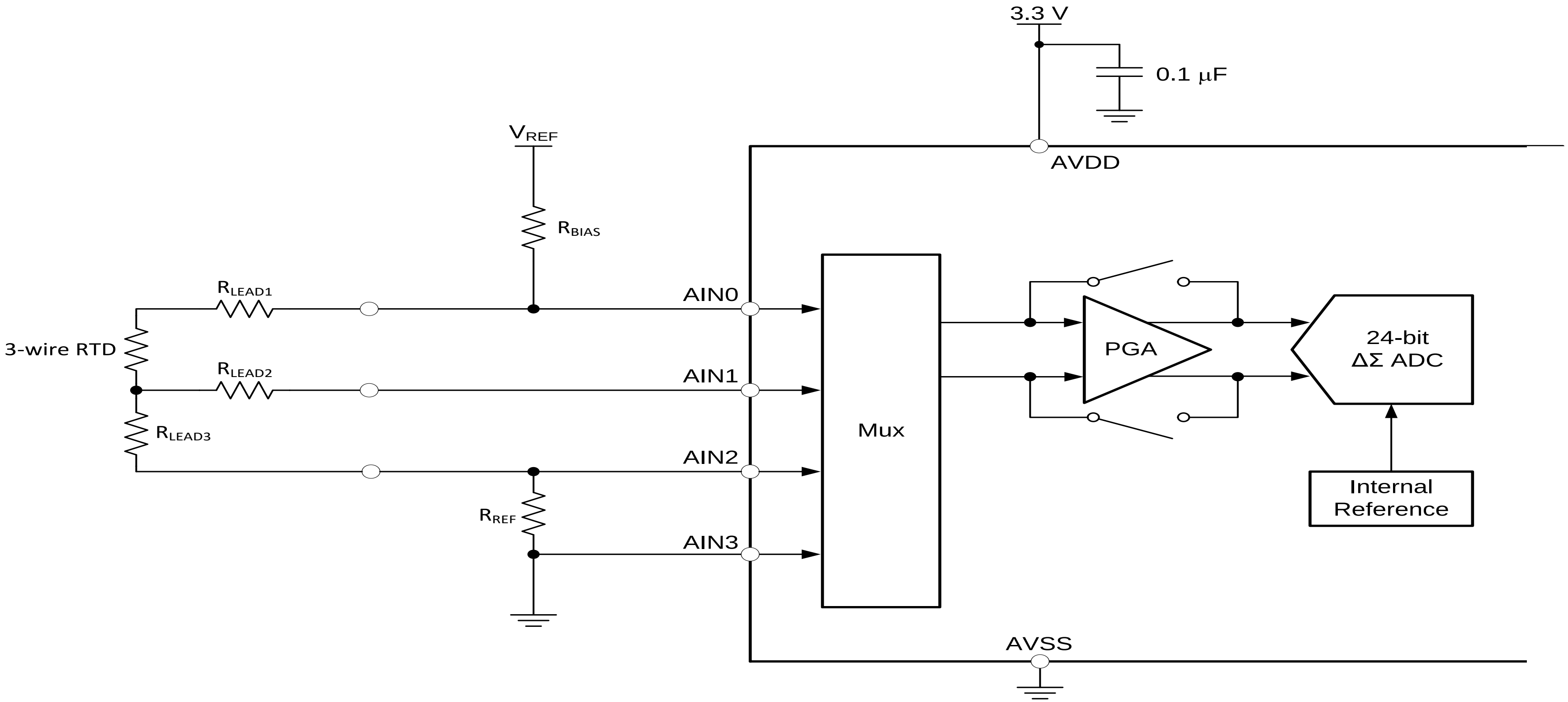
Voltage, Non-ratiometric

Voltage, Ratiometric

Current, Ratiometric

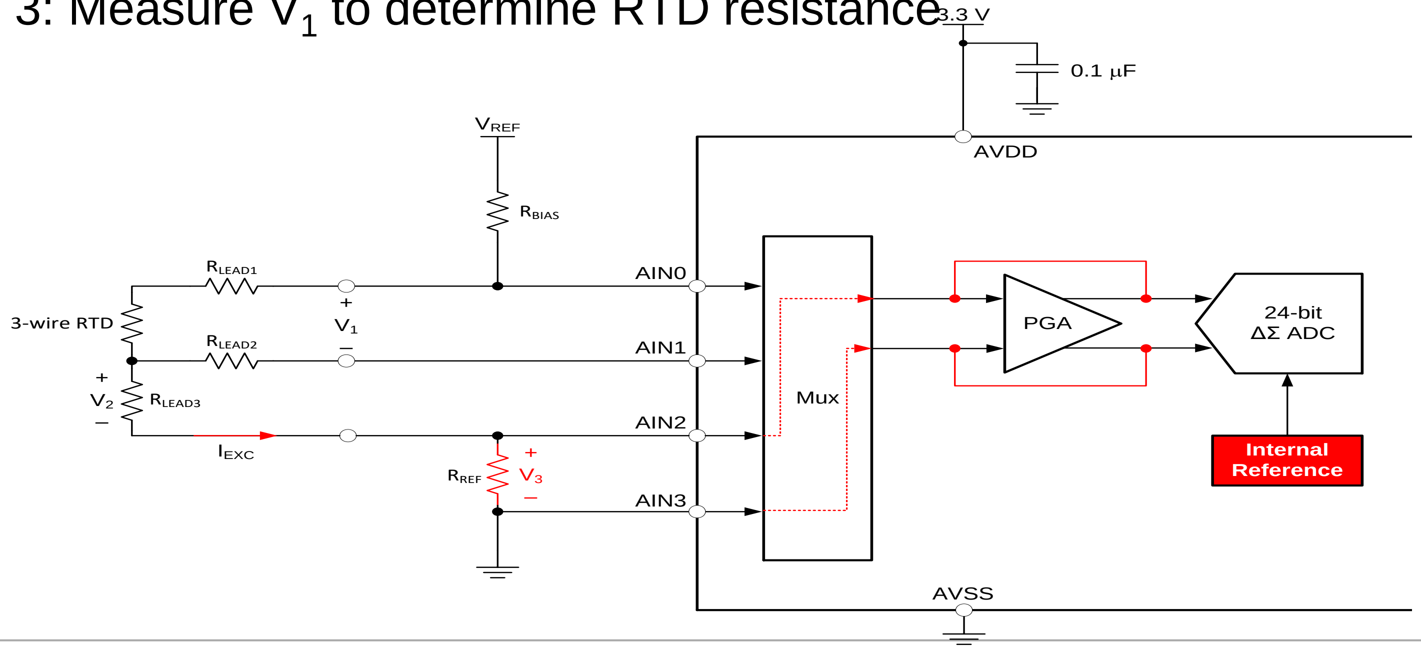
RTD EXCITATION METHODS

RTD Excitation Methods (I) Voltage, Non-ratiometric



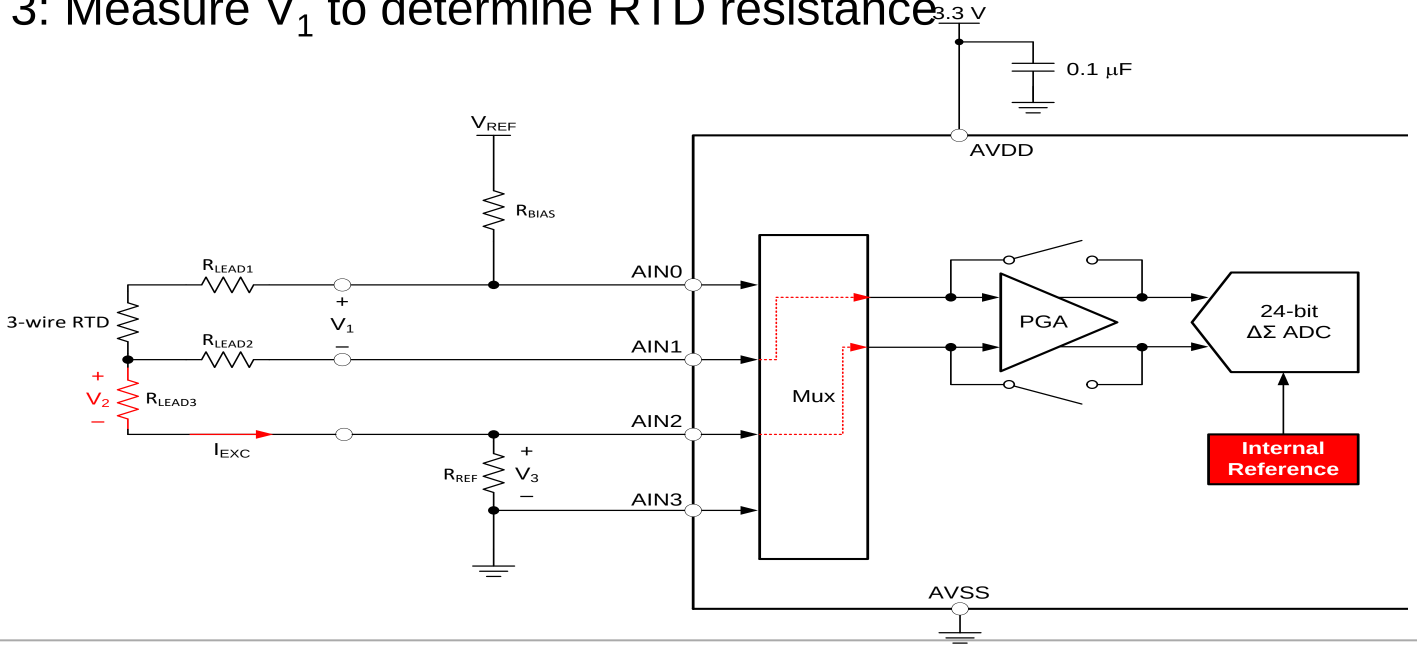
RTD Excitation Methods (I)
Voltage, Non-ratiometric

- Step 1: Measure V_3 to determine excitation current ($I_{EXC} = V_3/R_{REF}$)
- Step 2: Measure V_2 to determine lead resistance
- Step 3: Measure V_1 to determine RTD resistance



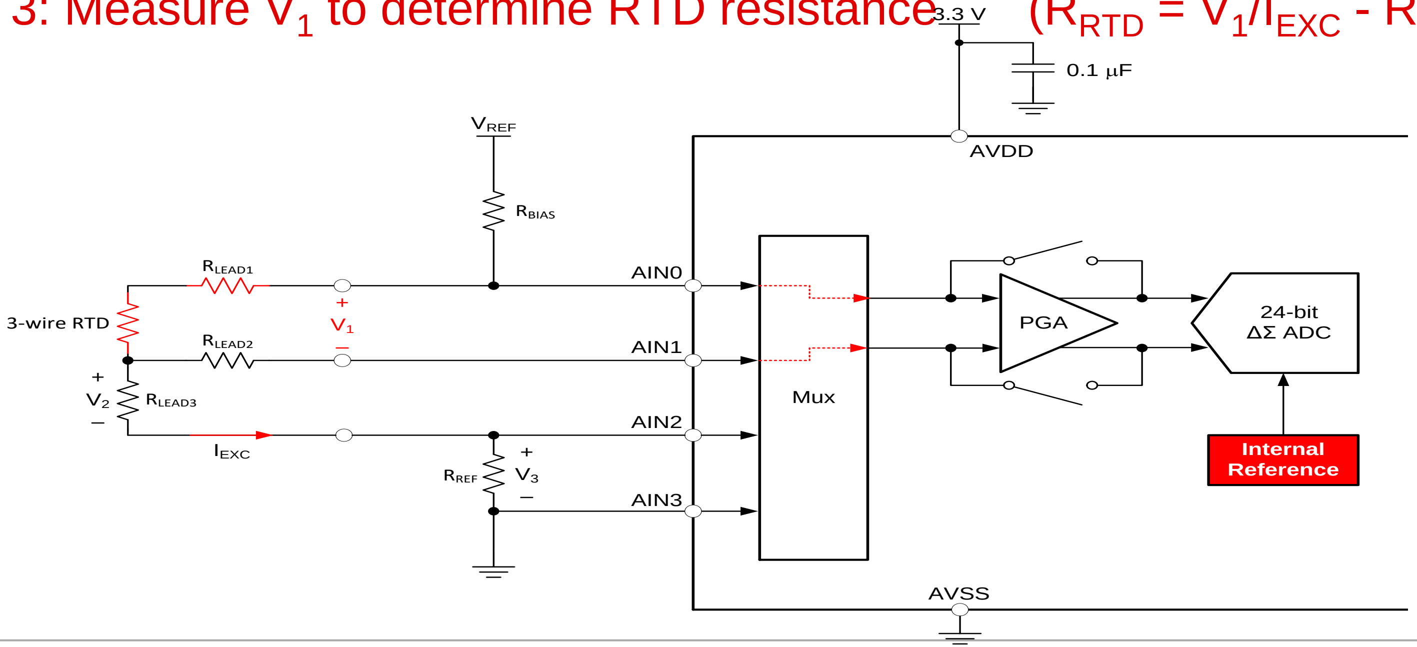
RTD Excitation Methods (I)
Voltage, Non-ratiometric

- Step 1: Measure V_3 to determine excitation current ($I_{EXC} = V_3/R_{REF}$)
- Step 2: Measure V_2 to determine lead resistance ($R_{Lead} = V_2/I_{EXC}$)
- Step 3: Measure V_1 to determine RTD resistance

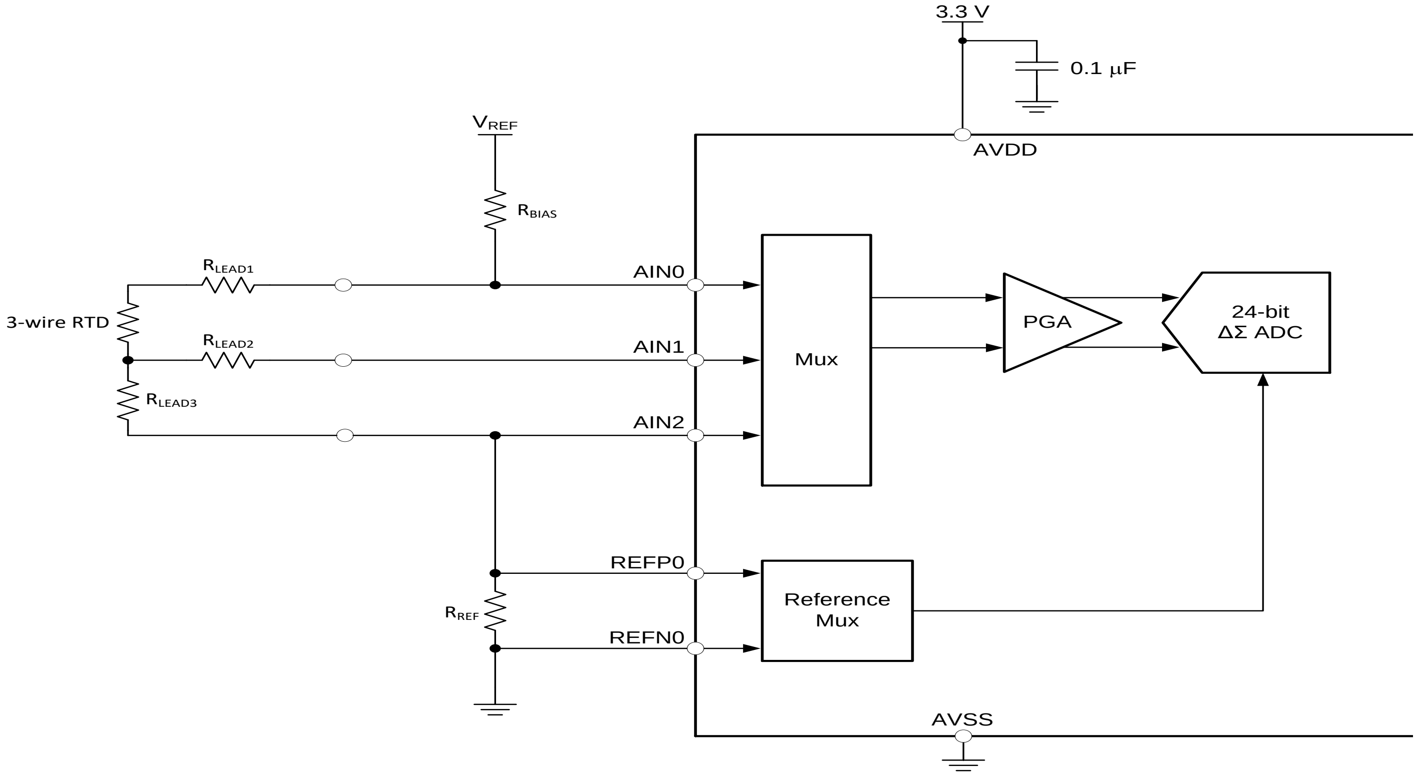


RTD Excitation Methods (I) Voltage, Non-ratiometric

- Step 1: Measure V_3 to determine excitation current ($I_{EXC} = V_3/R_{REF}$)
- Step 2: Measure V_2 to determine lead resistance ($R_{Lead} = V_2/I_{EXC}$)
- Step 3: Measure V_1 to determine RTD resistance ($R_{RTD} = V_1/I_{EXC} - R_{Lead}$)

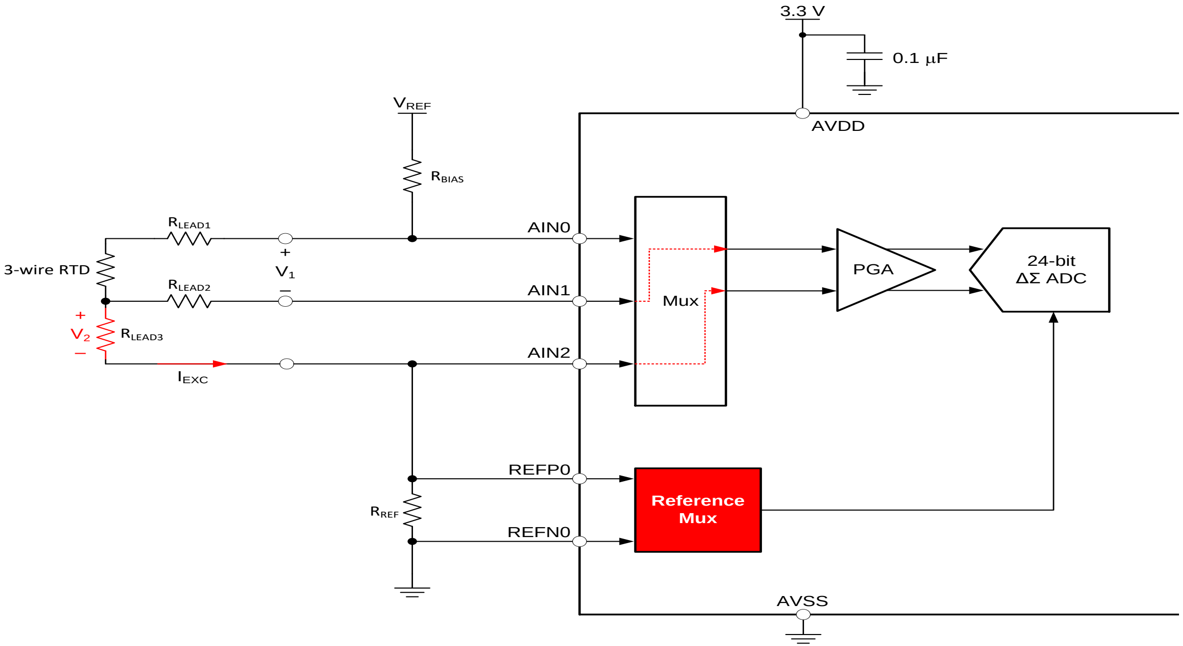


RTD Excitation Methods (II)
Voltage, Ratiometric



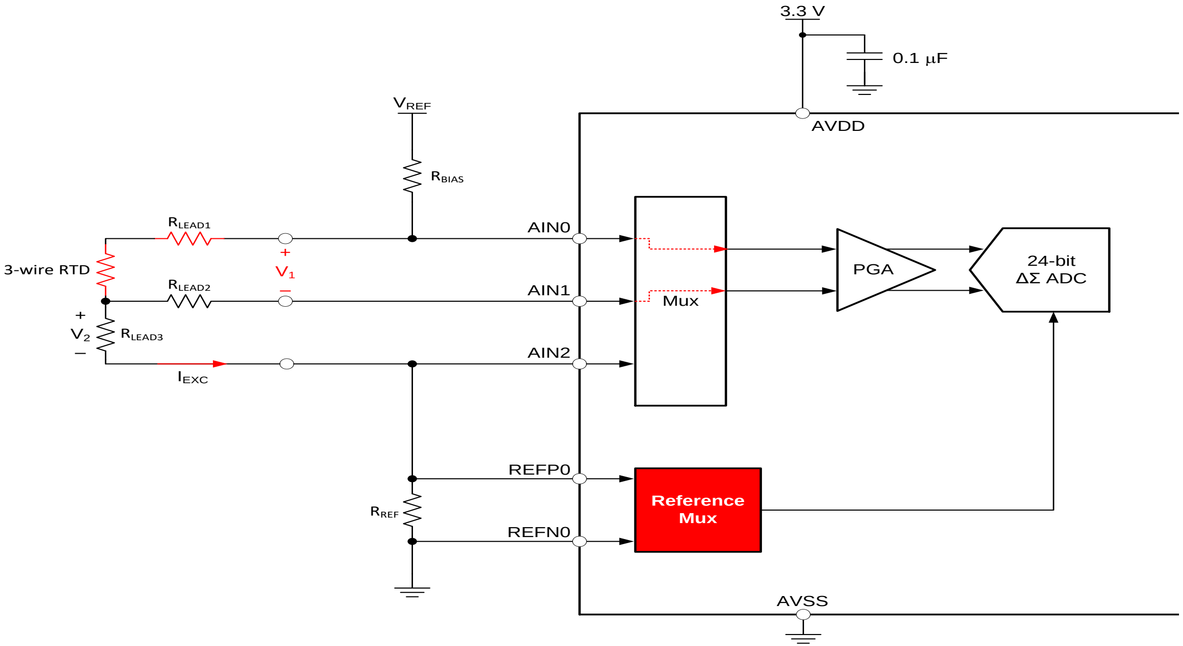
RTD Excitation Methods (II) Voltage, Ratiometric

- Step 1: Measure V_2 to determine lead resistance
- Step 2: Measure V_1 to determine RTD resistance



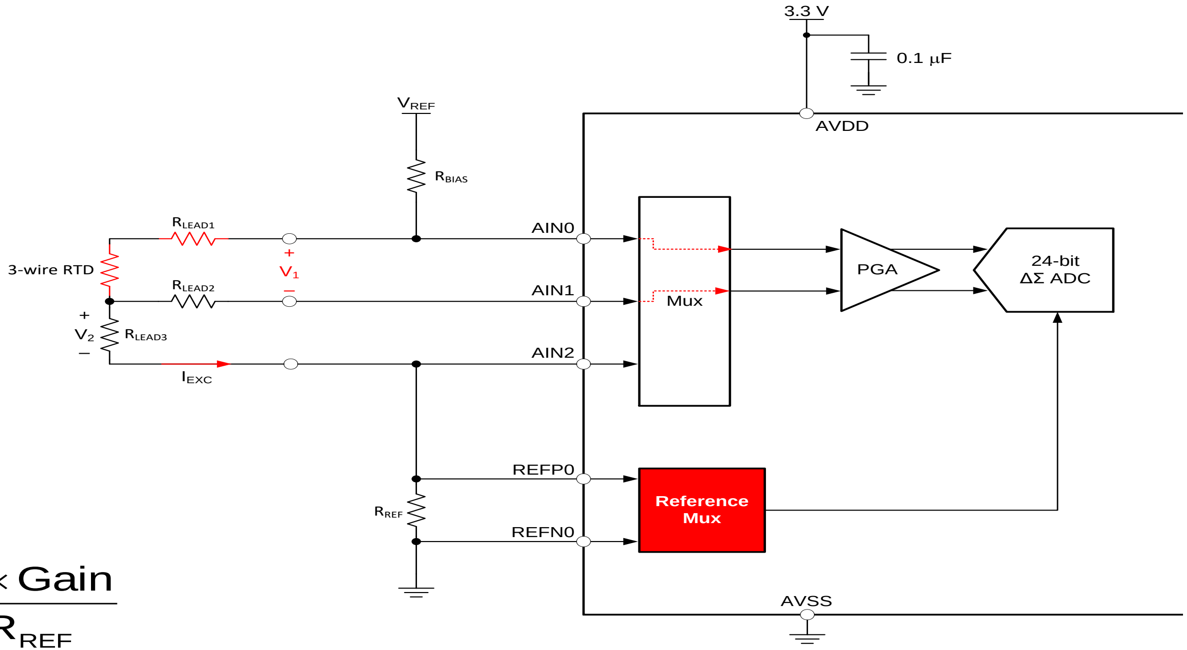
RTD Excitation Methods (II) Voltage, Ratiometric

- Step 1: Measure V_2 to determine lead resistance
- Step 2: Measure V_1 to determine RTD resistance



RTD Excitation Methods (II) Voltage, Ratiometric

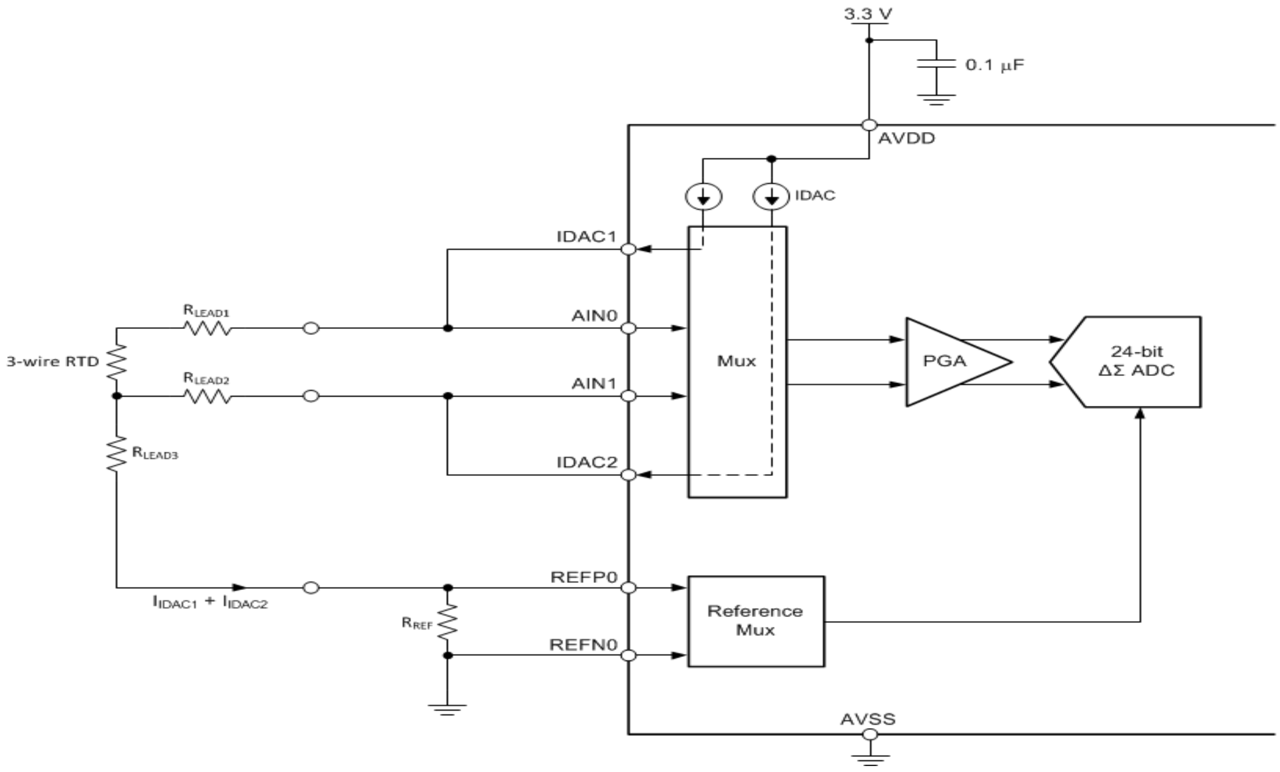
- Step 1: Measure V_2 to determine lead resistance
- Step 2: Measure V_1 to determine RTD resistance
- Code ~ R_{RTD}/R_{REF}



$$\frac{Code}{2^n} = \frac{V_{RTD} \times Gain}{2 \times V_{REF}} =$$

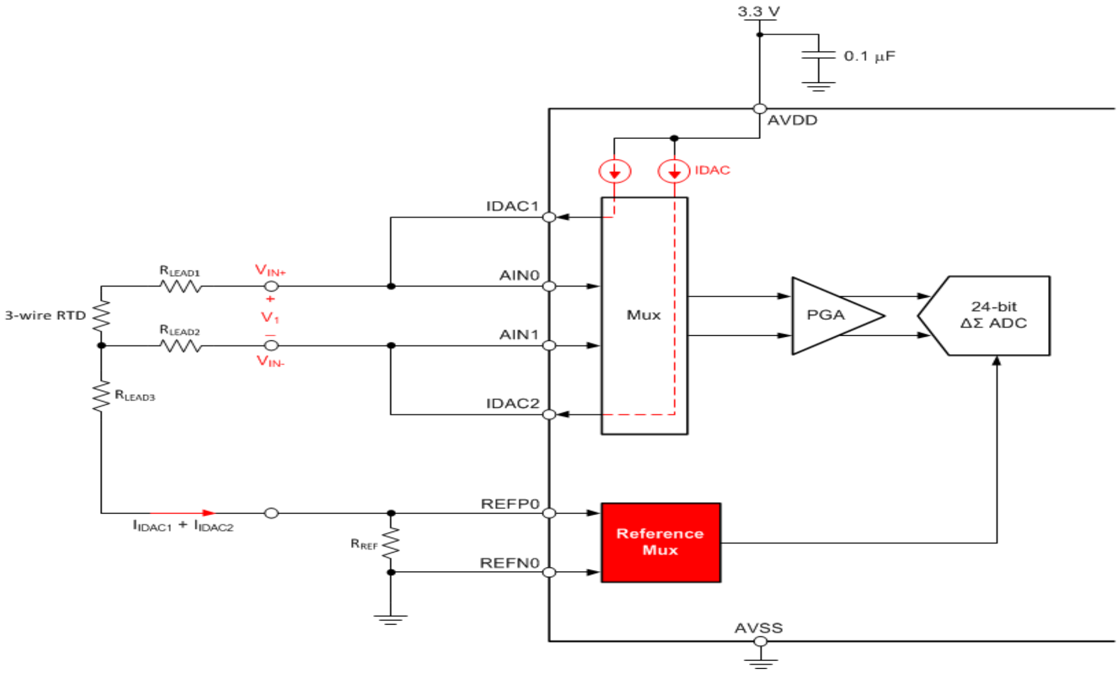
$$= \frac{I \times R_{RTD} \times Gain}{2 \times (I \times R_{REF})} = \frac{R_{RTD} \times Gain}{2 \times R_{REF}}$$

RTD Excitation Methods (III)
Current, Ratiometric



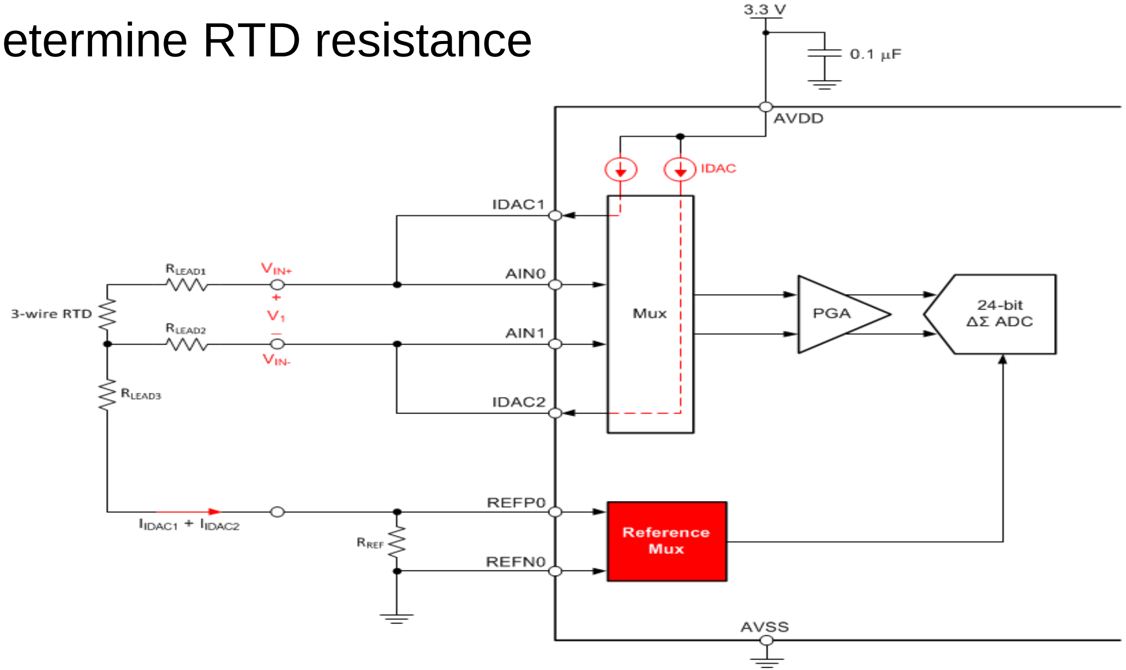
RTD Excitation Methods (III) Current, Ratiometric

- Step 1: Measure V_1 to determine RTD resistance
- Code ~ R_{RTD}/R_{REF}



RTD Excitation Methods (III) Current, Ratiometric

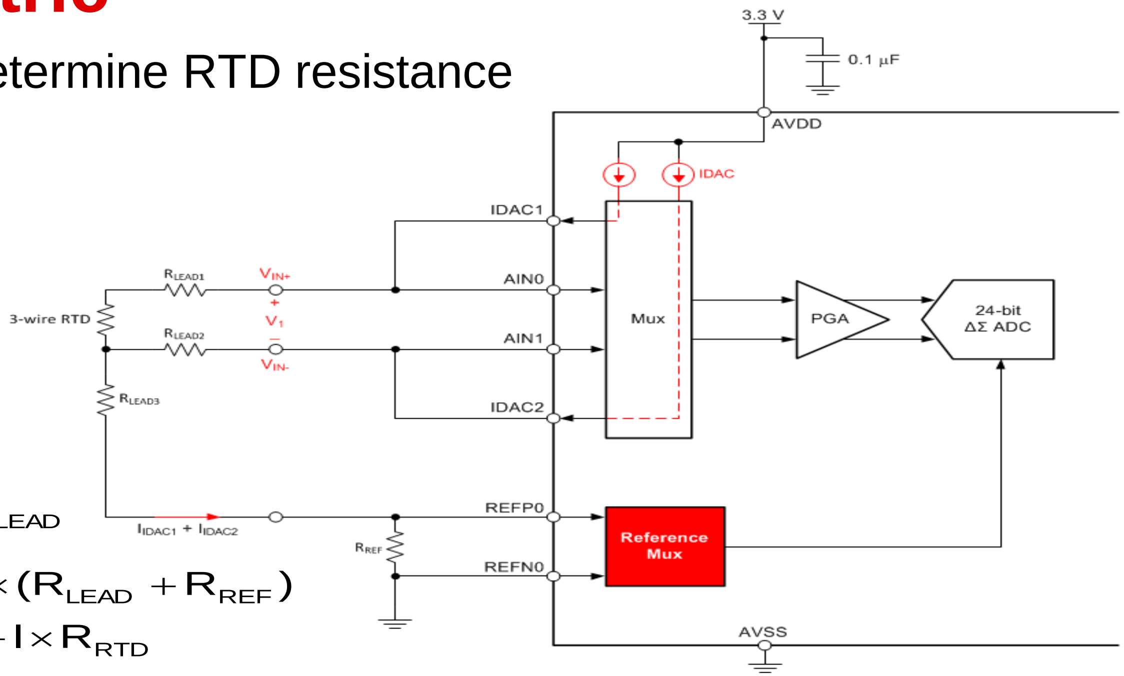
- Step 1: Measure V_1 to determine RTD resistance
- Code ~ R_{RTD}/R_{REF}



$$\frac{Code}{2^n} = \frac{V_{RTD} \times Gain}{2 \times V_{REF}} = \frac{I \times R_{RTD} \times Gain}{2 \times (2I \times R_{REF})} = \frac{R_{RTD} \times Gain}{4 \times R_{REF}}$$

RTD Excitation Methods (III)
Current, Ratiometric

- Step 1: Measure V_1 to determine RTD resistance
- Code ~ R_{RTD}/R_{REF}



R_{LEAD} Cancellation:

$$I_{IDAC1} = I_{IDAC2} = I$$

$$R_{LEAD1} = R_{LEAD2} = R_{LEAD3} = R_{LEAD}$$

$$V_{IN+} = I \times (R_{LEAD} + R_{RTD}) + 2I \times (R_{LEAD} + R_{REF})$$

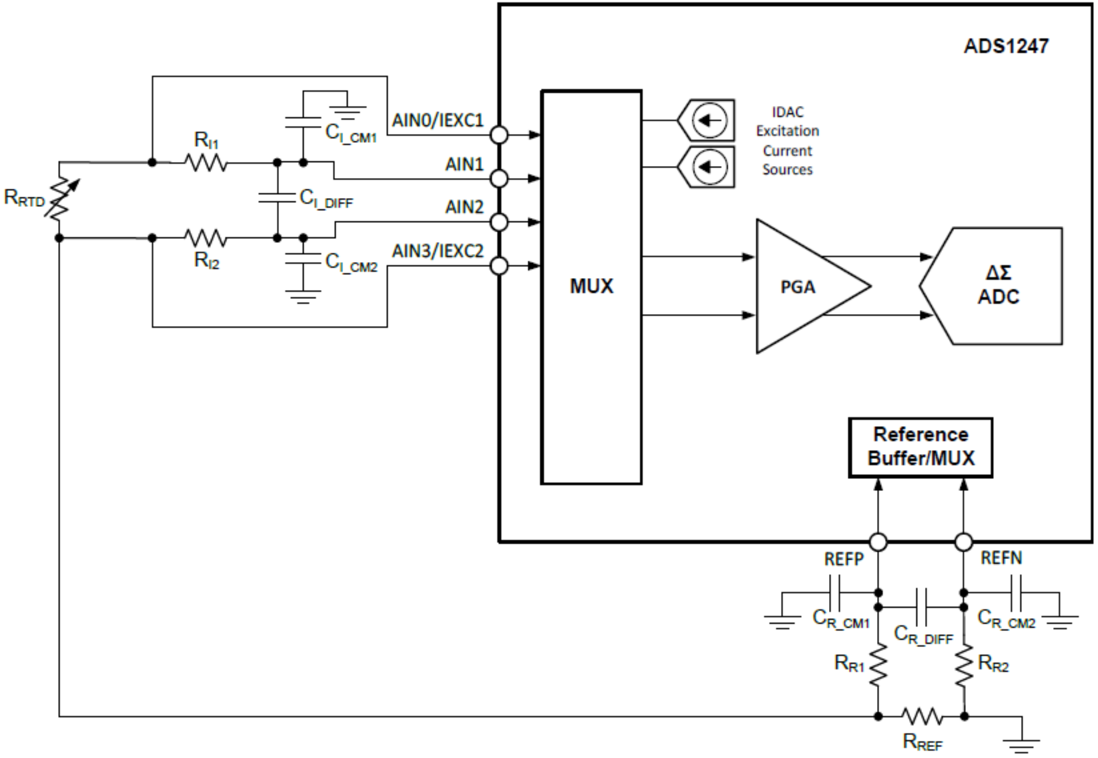
$$V_{IN+} = 3I \times R_{LEAD} + 2I \times R_{REF} + I \times R_{RTD}$$

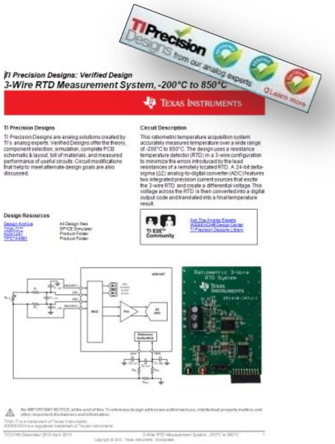
$$V_{IN-} = I \times R_{LEAD} + 2I \times (R_{LEAD} + R_{REF})$$

$$V_{IN-} = 3I \times R_{LEAD} + 2I \times R_{REF}$$

$$V_1 = V_{IN+} - V_{IN-} = I \times R_{RTD} = V_{RTD}$$

Design Example: ADS1247 3-wire RTD Measurement



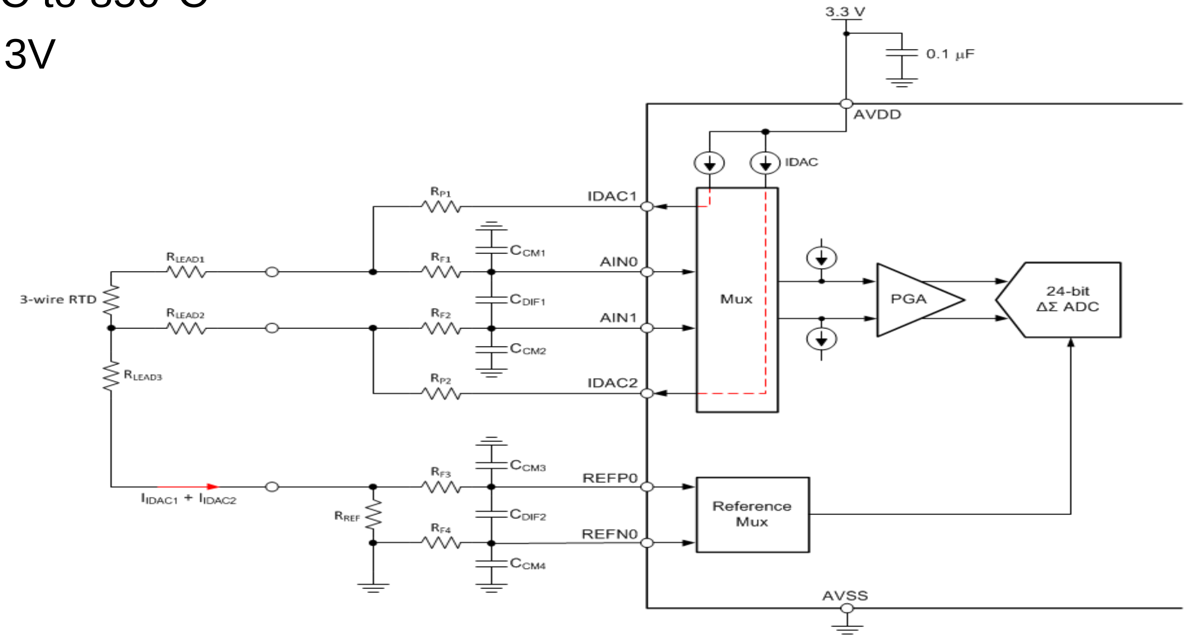


TIPD120

Step-by-Step Example with ADS1247

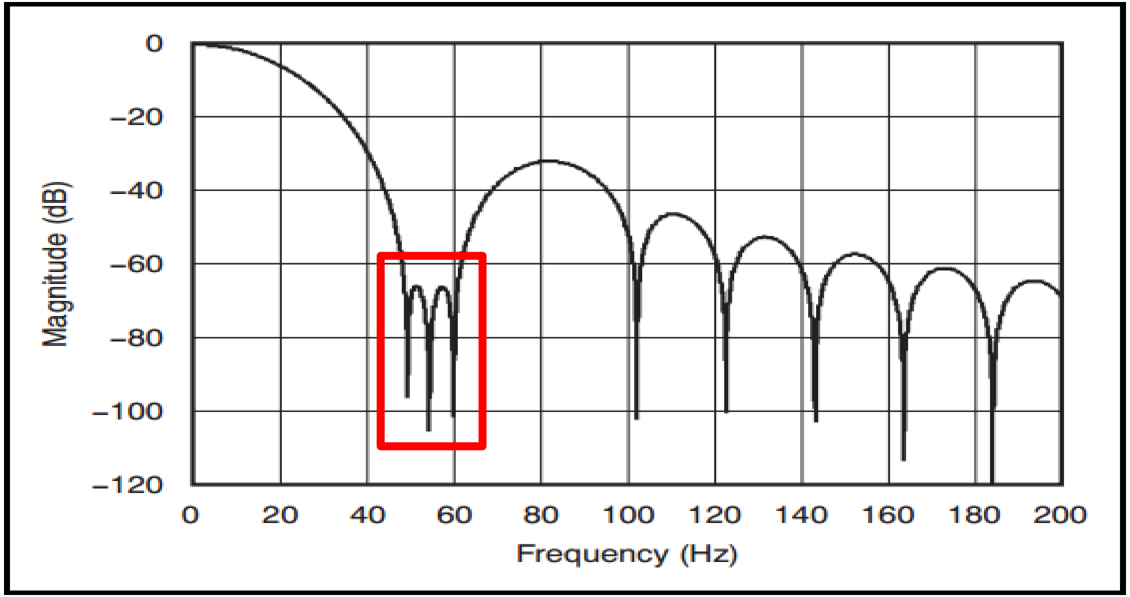
- System Requirements:
  - RTD Type: 3-Wire Pt100
  - Temperature Range: -200°C to 850°C
  - Supply Voltage: AVDD = 3.3V
  - 50/60Hz Rejection

- Design Considerations:
  - Data Rate
  - IDAC magnitude
  - R_{REF}
  - Gain
  - Low-pass Filters



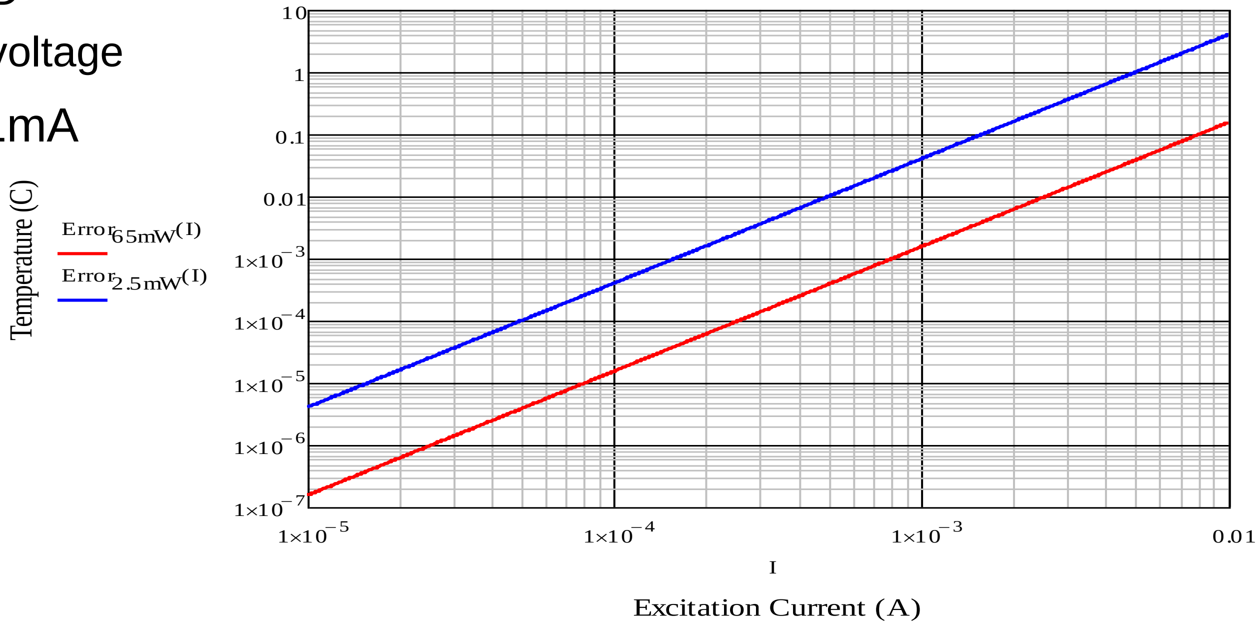
Selecting Data Rate

- At Data Rate = 20SPS or less, the ADS1247 offers simultaneous 50/60Hz rejection



Selecting IDAC Value

- Larger values produce larger signals – better resolution! (good, right?)
- Causes for concern with large IDAC values:
  1. Self-heating of RTD
  2. IDAC compliance voltage
- Start with 250µA – 1mA



Selecting R_{REF}

- Select R_{REF} such that V_{REF} is ~40% to 50% of AVDD:

$$V_{REF} = \frac{AVDD}{2} \qquad R_{REF} = \frac{V_{REF}}{2 \times I_{IDAC}}$$

- R_{REF} should be chosen with tight tolerance and low temperature drift
  - DC errors in R_{REF} *directly* affect the uncalibrated measurement gain error
  - Typical drift for R_{REF} = 5 – 20ppm/°C

$$AVDD = 3.3V,\ \ I_{IDAC} = 1mA$$

- Calculation:

$$V_{REF} = \frac{3.3V}{2} = 1.65V \qquad R_{REF} = \frac{1.65V}{2 \times 1mA} \approx 820\Omega$$

Selecting Gain

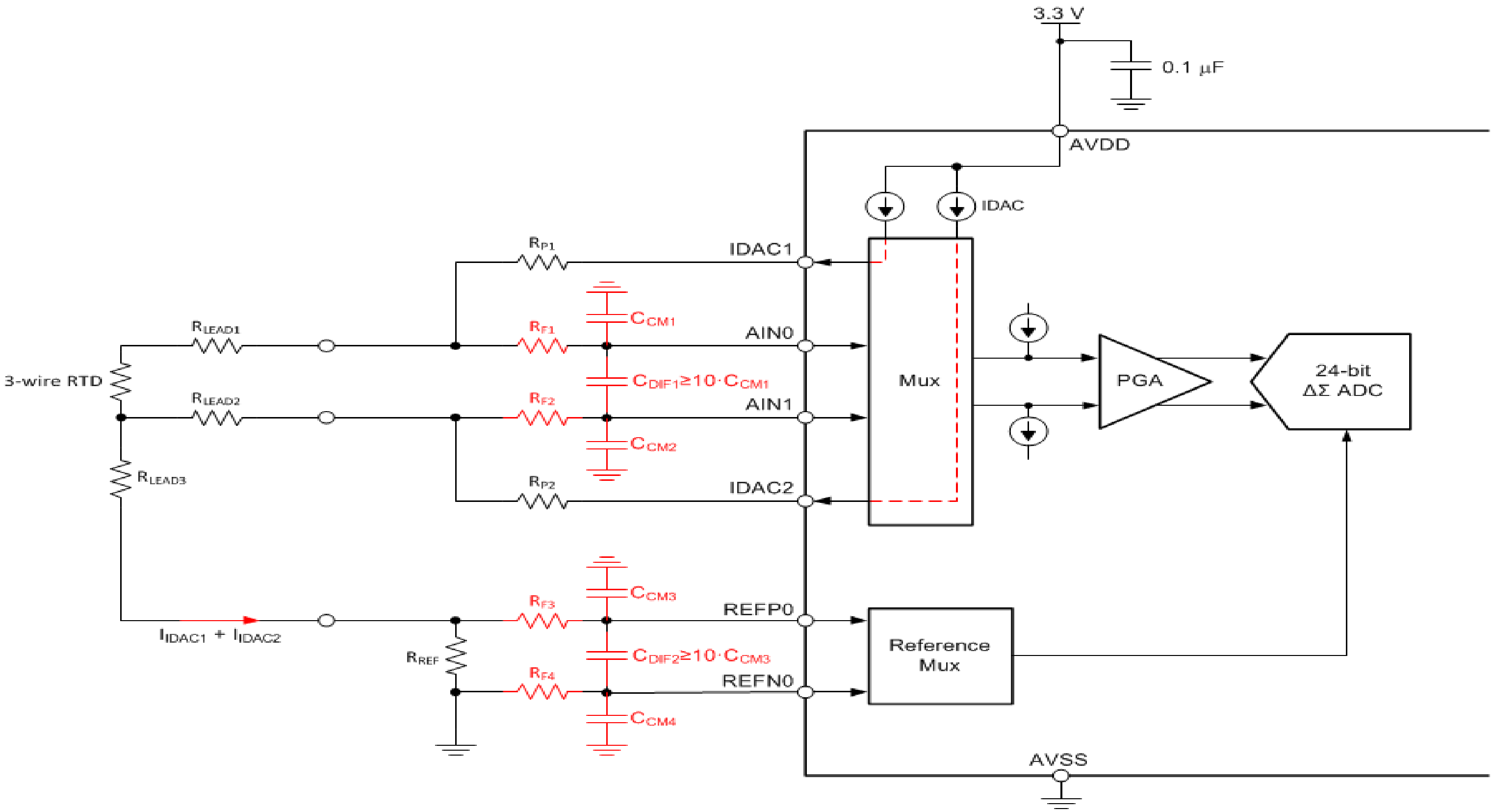
- The largest gain will yield the best resolution per °C
- Choose gain such that ADC input signal is still less than V_{REF} at the max temperature
- Calculation:

$$R_{RTD\,@\,850\,^\circ C} = 390.48\,\Omega$$

$$V_{RTD\,@\,850\,^\circ C} = 390.48\,\Omega \times 1mA = 0.39048\,V$$

$$\text{Gain} < \frac{V_{REF}}{V_{RTD\,@\,850\,^\circ C}} = \frac{1.64\,V}{0.39048\,V} = 4.2$$

Input and Reference Filters (I)



Input and Reference Filters (II)

- Used to filter high-frequency noise from aliasing into ADC passband
- At 20 SPS, ADS1247 has -3 dB bandwidth of 14.8 Hz.
- $f_{-3dB\_Dif} \approx 10 \times f_{-3dB\_DR}$

- RTD input and reference filters should have *matching* cutoff frequencies
  - If noise appears on the RTD input, but not the reference, it will not be cancelled in the ratiometric configuration
  - The RTD will change resistance over temperature;
    use the mid-point of the temperature range to calculate input filter
  - App Note: http://www.ti.com/lit/pdf/sbaa201

IDAC Compliance

Input Common-Mode Voltage

DESIGN CHECKS

Check IDAC Compliance

PARAMETER	CONDITIONS	ADS1246, ADS1247, ADS1248 MIN	TYP	MAX	UNIT
CURRENT SOURCES (IDACS)					
Output current			50, 100, 250, 500, 750, 1000, 1500		µA
Voltage compliance	All currents		AVDD – 0.7		V
Initial error	All currents, each IDAC	–6	±1	6	% of FS
Initial mismatch	All currents, between IDACs		±0.15		% of FS
Temperature drift	Each IDAC		100		ppm/°C
Temperature drift matching	Between IDACs		10		ppm/°C

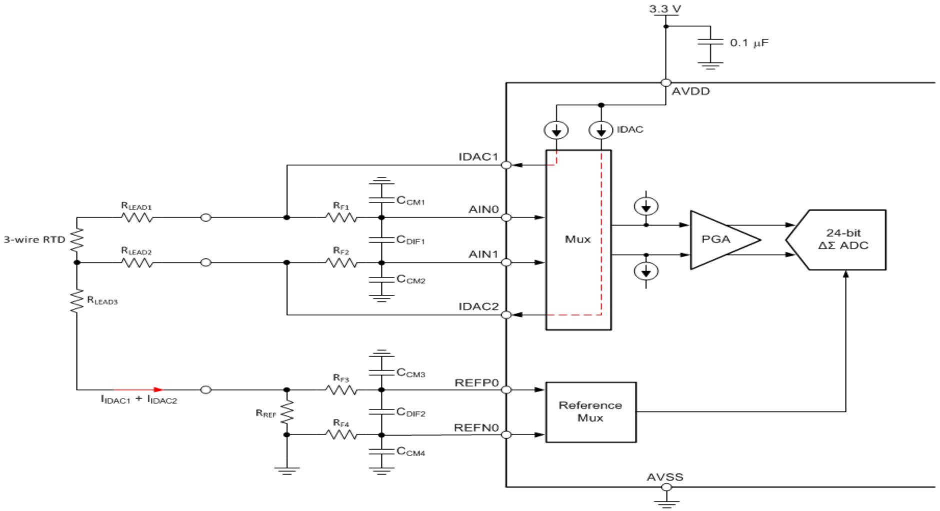
$$\text{Voltage Compliance} = AVDD - 0.7V = 2.6V$$

$$V_{IDAC1} = V_{REF} + V_{RTD} < 2.6V$$

$$R_{RTD@850^\circ C} = 390.48\Omega$$

$$V_{RTD@850^\circ C} = 390.48\Omega \times 1mA = 390.48mV$$

$$V_{IDAC1} = 1.64V + 390.48mV = 2.03V < 2.6V$$ ☑



Check IDAC Compliance

PARAMETER	CONDITIONS	ADS1246, ADS1247, ADS1248 MIN	TYP	MAX	UNIT
CURRENT SOURCES (IDACS)					
Output current		50, 100, 250, 500, 750, 1000, 1500			μA
Voltage compliance	All currents	AVDD – 0.7			V
Initial error	All currents, each IDAC	–6	±1	6	% of FS
Initial mismatch	All currents, between IDACs		±0.15		% of FS
Temperature drift	Each IDAC		100		ppm/°C
Temperature drift matching	Between IDACs		10		ppm/°C

$$\text{Voltage Compliance} = AVDD - 0.7V = 2.6V$$

$$V_{IDAC1} = V_{REF} + V_{RTD} < 2.6V$$

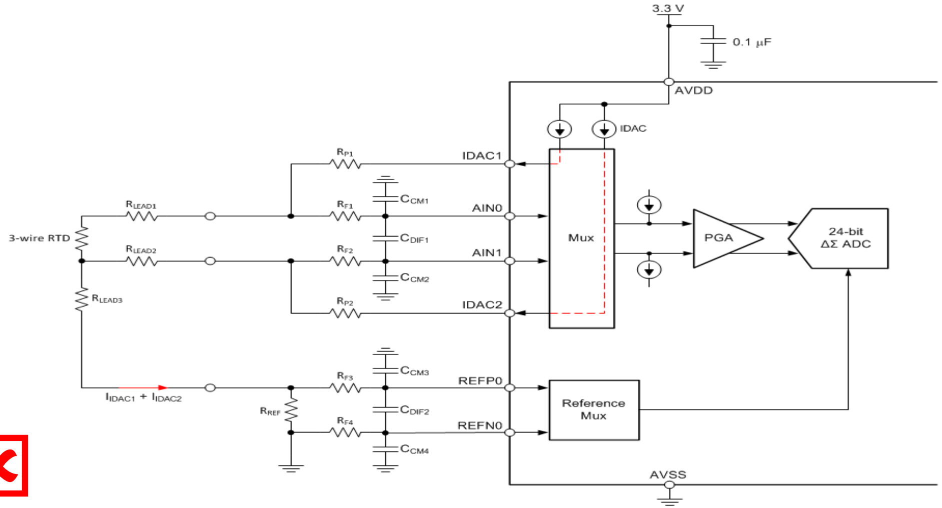
$$R_{RTD@850°C} = 390.48\Omega$$

$$V_{RTD@850°C} = 390.48\Omega \times 1mA = 390.48mV$$

$$R_{P1} = 1k\Omega$$

$$V_{RP1} = 1k\Omega \times 1mA = 1V$$

$$V_{IDAC1} = 1.64V + 390.48mV + 1V = 3.03V > 2.6V$$



Check Input Common-Mode

PARAMETER	CONDITIONS	ADS1246, ADS1247, ADS1248 MIN	TYP	MAX	UNIT
ANALOG INPUTS					
Full-scale input voltage (V_{IN} = ADCINP – ADCINN)			$\pm V_{REF}/PGA$ (1)		V
Common-mode input range		$AVSS + 0.1V + \frac{(V_{IN})(Gain)}{2}$		$AVDD - 0.1V - \frac{(V_{IN})(Gain)}{2}$	V
Differential input current			100		pA
Absolute input current			See Table 7		
PGA gain settings			1, 2, 4, 8, 16, 32, 64, 128		

$$V_{CM(MIN)} = V_{REF} = 1.64V$$

$$V_{CM(MAX)} = V_{REF} + \frac{V_{RTD(MAX)}}{2} = 1.64V + \frac{390.48mV}{2} = 1.84V$$

$$0.1V + \frac{390.48mV \times 4}{2} \leq V_{CM} \leq 3.3V - 0.1V - \frac{390.48mV \times 4}{2}$$

$$881mV \leq V_{CM} \leq 2.32V$$

☑

ADS1247 - Things to be Aware of

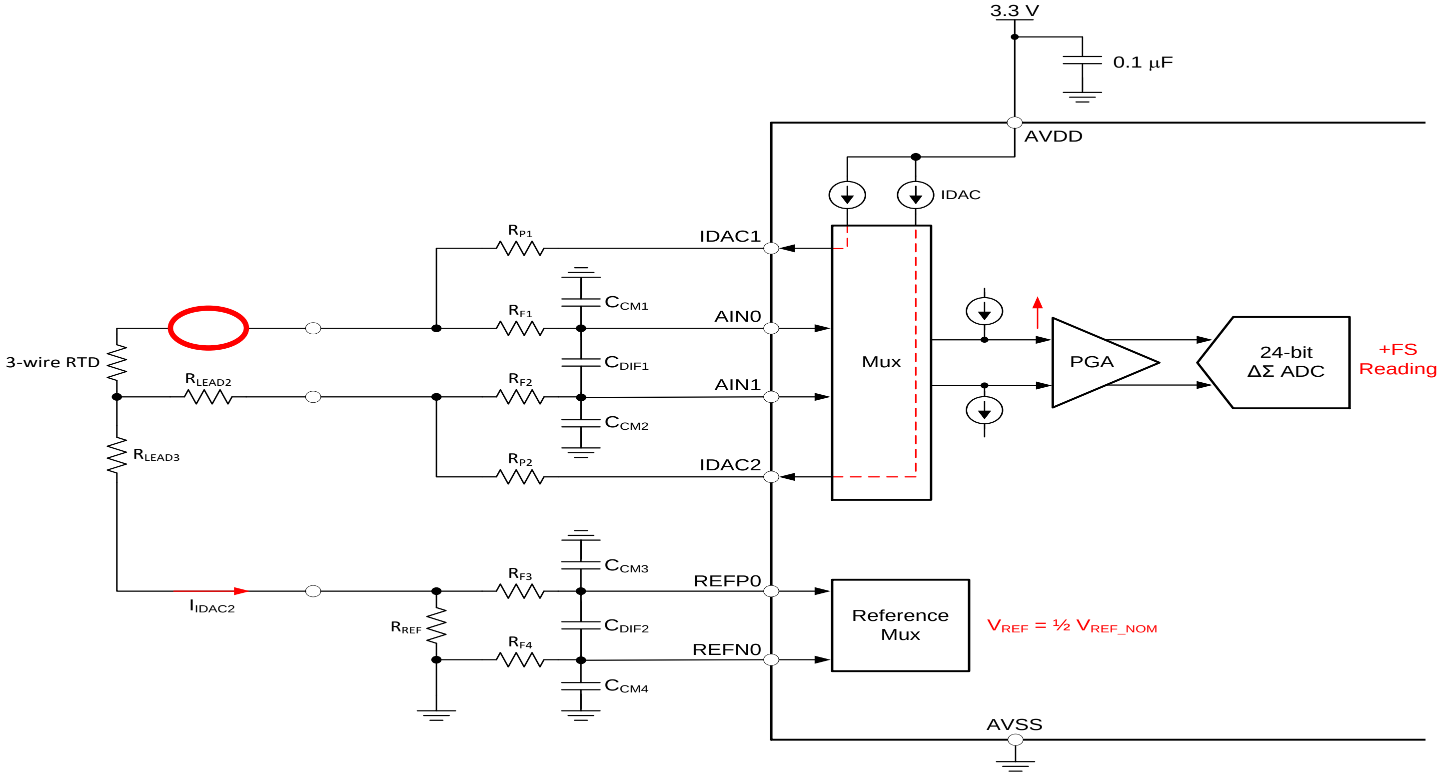
- ☑ Place bypass cap on VREFOUT pin.
- ☑ Turn internal V_{REF} ON, otherwise IDACs will not work.
- ☑ Check IDAC compliance is met.
- ☑ Check PGA common-mode voltage range is met.
  Single-ended measurements are NOT possible using a unipolar supply!
- ☑ Start a measurement only after the input signal has settled.
  Especially important when MUX'ing channels.

- ☑ Configure SPI interface for SPI Mode 1.
- ☑ Convert twos-complement correctly.
- ☑ Don't use absolute IDAC value to calculate R_{RTD}.
  Otherwise measurement is not ratiometric anymore.

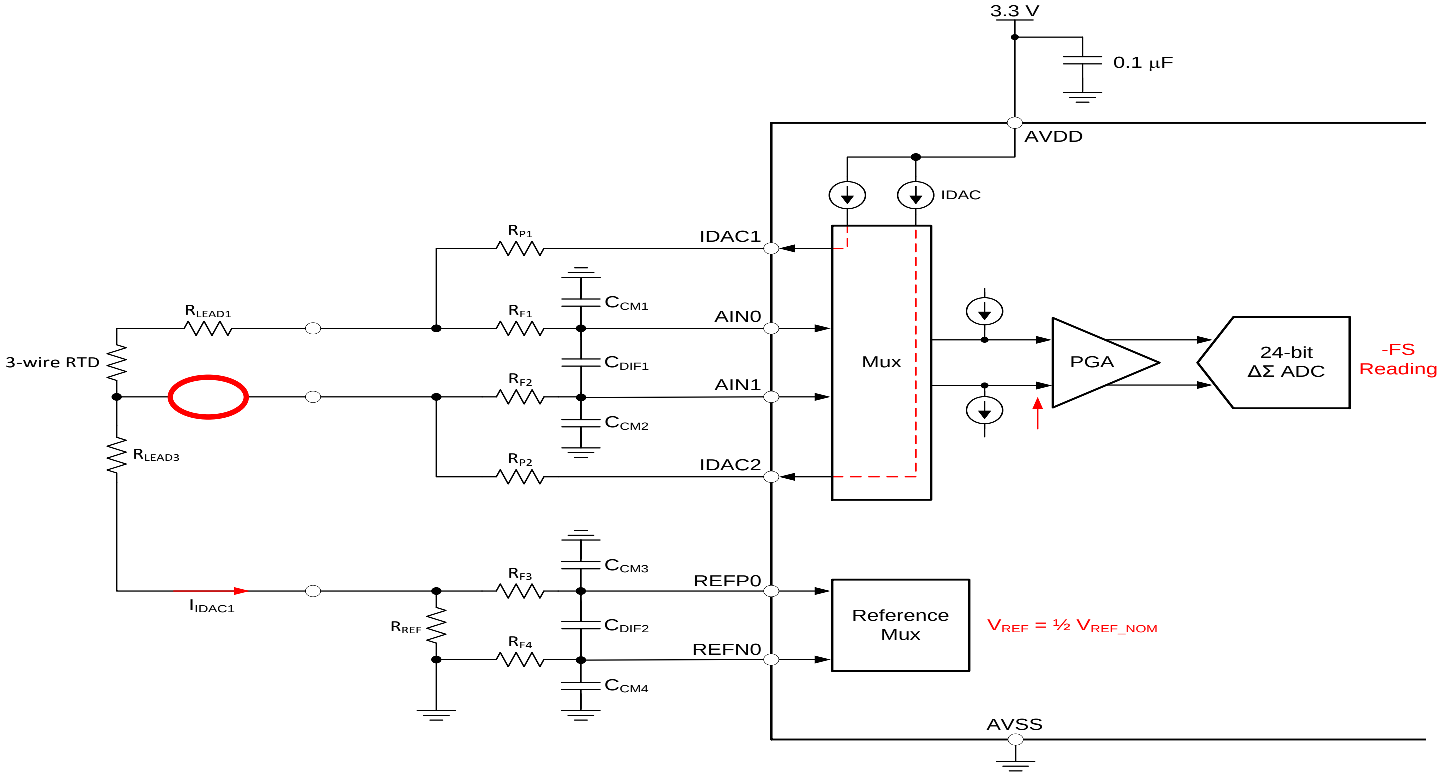
$$R_{RTD} = \frac{Code}{2^n} \times \frac{4 \times R_{REF}}{Gain}$$

OPEN SENSOR DETECTION

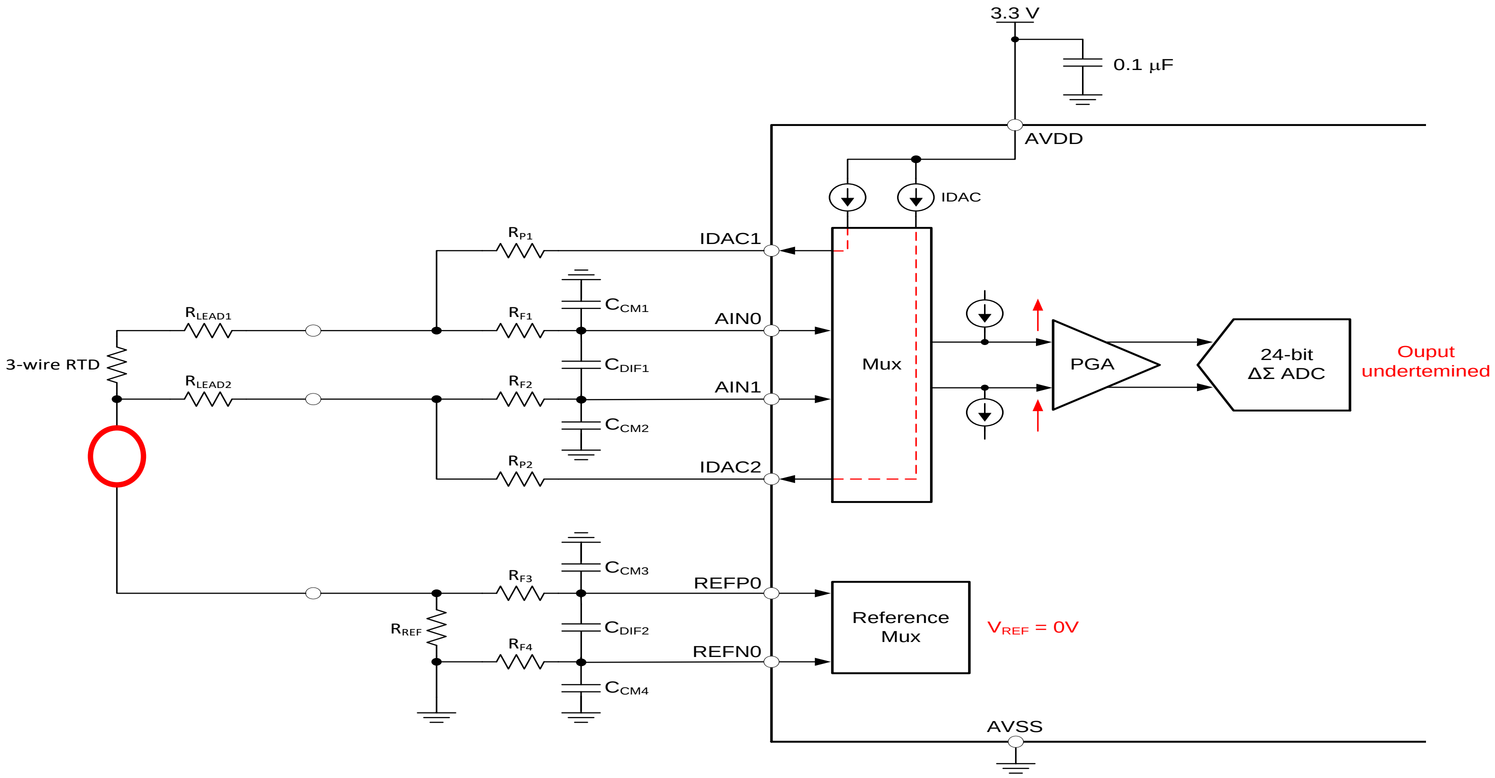
Open Sensor Detection, Lead 1



Open Sensor Detection, Lead 2

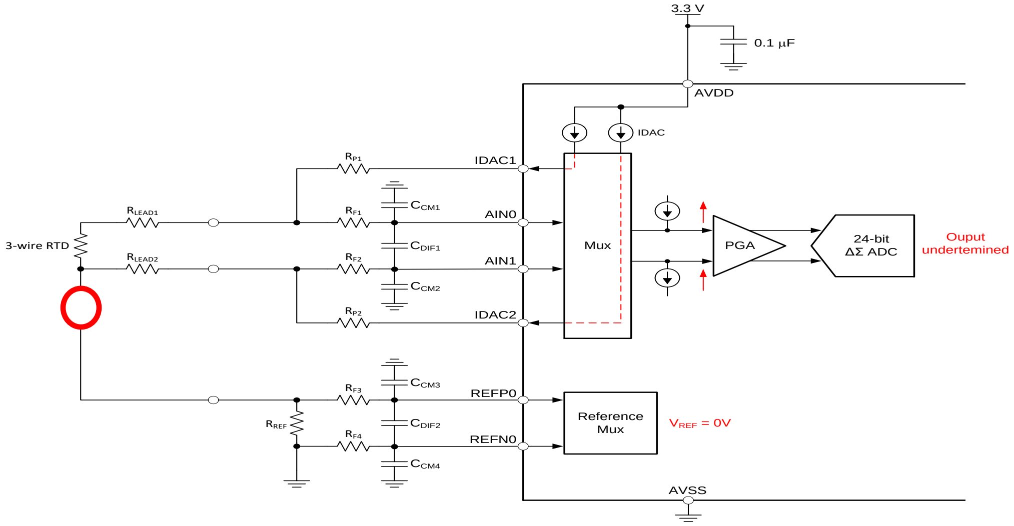


Open Sensor Detection, Lead 3 (I)



Open Sensor Detection, Lead 3 (II)

- Option1: Measure V_{REF}
  - Reconfigure MUX1 [2:0] to measure V_{REF}
  - Detect that V_{REF} is below certain threshold.



- Option 2: REFP0 as GPIO
  - Diagnostic cycle – stop conversions, set REFP0 as GPIO
  - If = high, reference is present
  - If = low, reference is absent

**Make sure GPIO theshold is met

IDAC CHOPPING

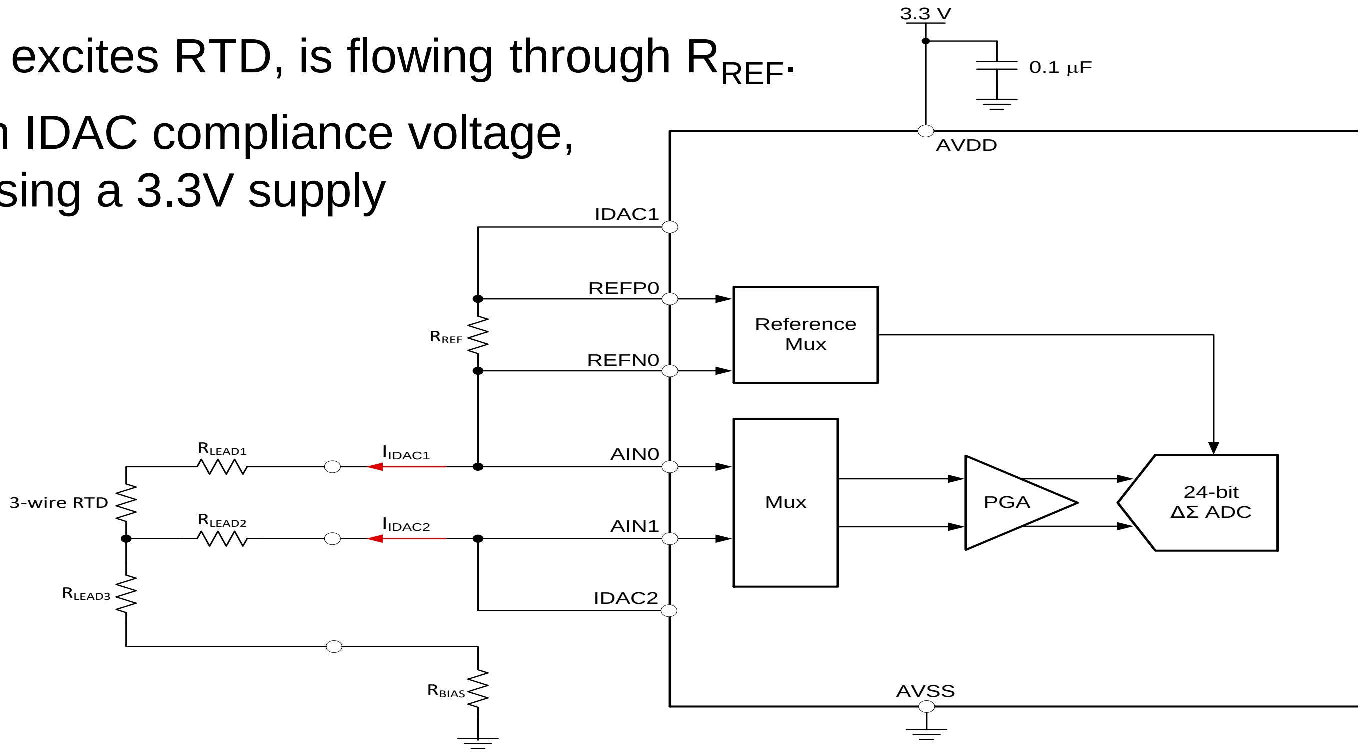
Errors due to IDAC Mismatch

PARAMETER	CONDITIONS	ADS1246, ADS1247, ADS1248			UNIT
		MIN	TYP	MAX	
CURRENT SOURCES (IDACS)					
Output current		50, 100, 250, 500, 750, 1000, 1500			μA
Voltage compliance	All currents	AVDD – 0.7			V
Initial error	All currents, each IDAC	–6	±1	6	% of FS
Initial mismatch	All currents, between IDACs		±0.15		% of FS
Temperature drift	Each IDAC		100		ppm/°C
Temperature drift matching	Between IDACs		10		ppm/°C

- IDACs exhibit initial mismatch and drift mismatch
- Two potential errors:
  - Gain Error
    Only one IDAC is flowing through RTD but both IDACs flow through $R_{REF.}$
    Calculation assumes both IDACs are equal.
  - No 100% R_{LEAD} cancellation

Improved Implementation

- Eliminates gain error due to IDAC mismatch.
- Same current that excites RTD, is flowing through R_{REF}.
- Harder to maintain IDAC compliance voltage, especially when using a 3.3V supply



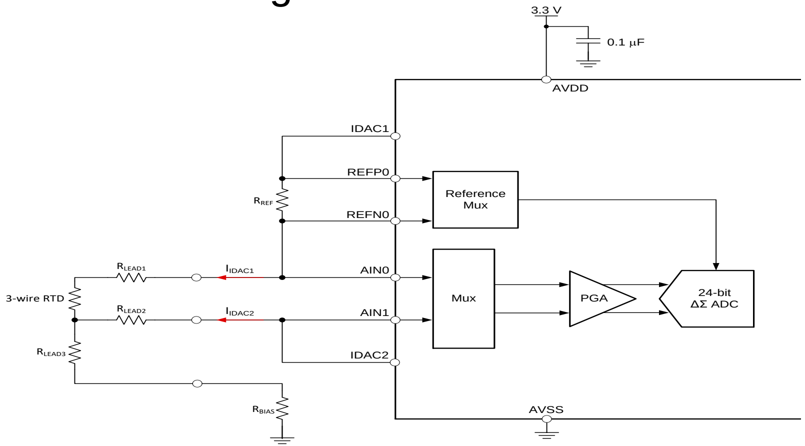
IDAC Chopping

- IDAC "Chopping"
  - Two measurements with IDACs swapped are taken and averaged
  - Improves R_{LEAD} compensation

$$V_{IN(1)} = I_{IDAC1} \times (R_{LEAD1} + R_{RTD}) - I_{IDAC2} \times R_{LEAD2}$$

$$V_{IN(2)} = I_{IDAC2} \times (R_{LEAD1} + R_{RTD}) - I_{IDAC1} \times R_{LEAD2}$$

$$R_{LEAD1} = R_{LEAD2} = R_{LEAD}$$



$$V_{IN} = \frac{V_{IN(1)} + V_{IN(2)}}{2} = \frac{I_{IDAC1} \times R_{RTD}}{2} + \frac{I_{IDAC2} \times R_{RTD}}{2}$$

$$\frac{V_{IN} \times Gain}{2 \times V_{REF}} = \frac{\frac{I_{IDAC1} \times R_{RTD}}{2} \times Gain}{2 \times I_{IDAC1} \times R_{REF}} + \frac{\frac{I_{IDAC2} \times R_{RTD}}{2} \times Gain}{2 \times I_{IDAC2} \times R_{REF}} = \frac{R_{RTD} \times Gain}{2 \times R_{REF}}$$

- Note: Input filters need to settle before beginning a new conversion

Achievable Resolution with ADS1248

Table 1. Noise in μV_{RMS} and (μV_{PP})
at AVDD = 5V, AVSS = 0V, and External Reference = 2.5V

DATA RATE (SPS)	PGA SETTING							
	1	2	4	8	16	32	64	128
5	1.1 (4.99)	0.68 (3.8)	0.37 (1.9)	0.19 (0.98)	0.1 (0.44)	0.07 (0.31)	0.05 (0.27)	0.05 (0.21)
10	1.53 (8.82)	0.82 (3.71)	0.5 (2.69)	0.27 (1.33)	0.15 (0.67)	0.08 (0.5)	0.06 (0.36)	0.07 (0.34)
20	2.32 (13.37)	1.23 (6.69)	0.71 (3.83)	0.34 (1.9)	0.18 (1.01)	0.12 (0.71)	0.10 (0.51)	0.09 (0.54)

- LSB size:

$$\frac{2 \times V_{REF}}{2^{24} \times Gain} = \frac{2 \times 1.65V}{2^{24} \times 4} = 49.2nV$$

- Input referrerd Noise: $3.83uV_{pp}$
- Pt100 Sensitivity: 1mA x 0.385Ω/°C = 0.385mV/°C
- Temperature Resolution per Code: 49.2nV / 0.385mV/°C = 0.0001°C
- Noise Free Temperature Resolution: $3.83uV_{pp}$ / 0.385mV/°C = 0.01°C

Supporting Collateral

- TI Precision Designs
  - TIPD109:Simple Thermocouple Measurement Solution Reference Design, <1°C Accurate
  - TIPD120: 3-wire RTD Acquisition System Accurately Measures Temperature From -200°C - 850°C
  - TIPD152: 0°C – 100°C, Hardware-Compensated Ratiometric 3-Wire RTD System Reference Design
  - TIPD164: Analog Input Module for Industrial Outputs and Temperature Sensors Reference Design
  - TIPD193:RTD to Voltage Reference Design Using Instrumentation Amplifier and Current Reference
  - TIDA-00018:Temperature Sensor Interface Module for Programmable Logic Controllers (PLC)
  - TIDA-00168:Thermocouple AFE Using RTD or Integrated Temperature Sensor for Cold Junction Compensation (CJC)

- Application note
  - SBAA274:A Basic Guide to Thermocouple Measurements– Joseph Wu
  - SBAA275:A Basic Guide to RTD Measurements– Joseph Wu
  - TC and RTD Measurement Step-by-step Design Procedure October 2014 – Joachim Wurker