VOL. 12, NO. 24, DECEMBER 2017 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

IMPLEMENTATION OF 32BIT SIGMA-DELTA (ΣΔ) A TO D CONVERSION FOR THERMAL DIODE ACQUISITION UNIT (TDAU)

Leo Bermudez Pestañas, Gajula Ramana Murthy and Ajay Kumar Singh
Faculty of Engineering and Technology, Multimedia University Malaysia
E-Mail: lpestanas@gmail.com

ABSTRACT

In the market today of temperature sensors, different methodologies of measurements were introduced such as Alcohol thermometer, Mercury thermometer, Temperature Dependent Resistor (RTD), Thermocouple that comes in different letters of calibration and temperature ranges and etc. However, there are some drawbacks using these temperature measurement technologies. And some of them must be operated with extreme caution. Like the Mercury Thermometer, usually it comes in the form of fragile glass tube packaging and has a certain temperature to operate. Operating this kind of thermometer will break instantly if exposed to temperatures out of range and releasing the highly toxic Mercury to the user or even contaminate the soil or ground water where it spilled. Thermocouples are efficient and durable in extremely high temperature measurement. But it does not produce a good reading result if the subject is vibrating or moving. Because it is dependent on the linear expansion of two different metallic elements. It may also get open circuited along the process. Temperature Dependent Resistor (RTD) is rugged and comes with different sizes where space constraint is an issue. It is linear in response, but sometimes relatively expensive with respect to the range of temperature that needs to be measured. In this paper, this will give the reader an idea how to construct a precision, vibration resistant and multipoint Thermal Diode Acquisition Unit (TDAU) which uses either PNP or NPN Silicon Transistor with low ideality factor as the temperature sensor itself. The output digitized resolution will be in 32bit Analog to Digital Conversion representation.

Keywords: temperature dependent resistor, thermocouple, linear expansion, ideality factor, thermal diode acquisition unit.

INTRODUCTION

A remote digital temperature sensor, also called a remote sensor or thermal diode sensor, measures the temperature of an external transistor - either a discrete transistor or one that is integrated on the die of another IC.

The conceptual circuit can use either NPN or PNP silicon transistor connected as a p-n junction equivalent to a real diode. to do this, the base and collector pin of the selected silicon transistor are tied together, which will represent the Anode teminal of such diode and same with the emitter as the cathode terminal of the diode for PNP transistor. This will be reversed in NPN as demonstrated in Figure-1.

Remote temperature sensors operate on a principle similar to the one shown in Figure-1, except that only one sensing transistor is used in Figure-2. Why is only one sensing transistor used? There are two reasons. First, two transistors would require one or two more pins on both the target IC and the sensor IC. Second, the use of two transistors would require the manufacturer of the target IC to very precisely match those transistors. Any differences between the two transistors would lead to measurement errors that would be out of the control of the remote sensor IC's manufacturer. Using a single sensing transistor requires fewer pins and allows the key error sources to be controlled (and compensated) by the manufacturer of the remote sensor IC in Figure-1(b) (Maxim integrated products, Inc., 2010).

For both cases, the accuracy of temperature measurement depends on the forcing current accuracy and relatively noise free signals (Linear technology(Now analog devices), 2012).

In this case, the forcing current is in the range valueof micrcoamperes where the diode voltage difference produced is extremely small and prone to noise contamination. interfacing this diode to an analog to digital converter will be a challenge when it comes to producing good resolution readout of the temperature with respect to the process.

This paper will introduce various techniques such as how to avoid the sources of the noise, increasing the wire distance without sacrificing the quality of temperature readout and many more.

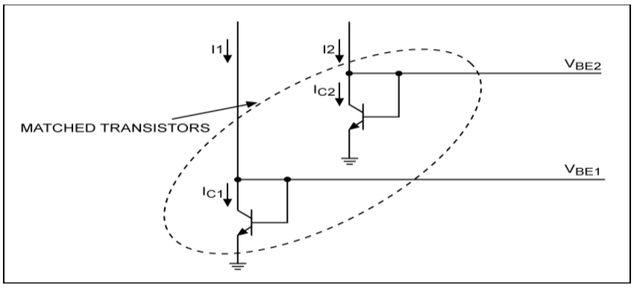

Figure-1. Conceptual circuit how two matched transistors can measure temperature (Maxim integrated products, Inc.,2010).

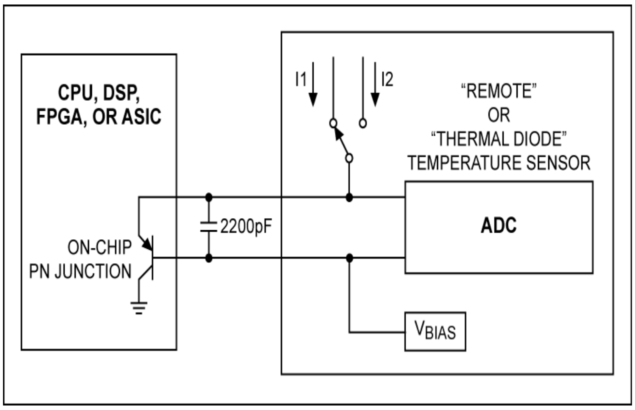

Figure-2. Single sensing transistor using two different forcing currents (Maxim integrated products, Inc., 2010).

Thermal diode sensor general equations

In order for us to determine the temperature reading from the P-N Junction of the matched Thermal Diode Sensors, the general equation in the voltage change of the two transistors with different forcing current is given below:

$$\Delta Vbe = Vbe1 - Vbe2 = n(\frac{kT}{q})(\ln(\frac{Ic2}{Ic1})) \quad (1)$$

Where:

n = the ideality factor (also called "nonideality factor") of the transistor junction; depends on process and device design and is generally very close to 1.01

k = Boltzmann's constant = 1.3806503 x $10^{-23}m^2$ kg $s^{-2}K^{-1}$

q = the electron charge = 1.60217646 x 10^{-19} coulombs

T = temperature in ˚K (temperature in ˚C + 273.15) (Maxim Integrated Products, Inc., 2010)

From this equation, the change in Base-Emitter Bias Voltage is ideally proportional to the temperature change. Because n, k, and Is (Ic2 and Ic1) are constants, the simplest way to measure the temperature is to force current and measure the voltage drop across the thermal diode to calculate the temperature. However, the accuracy will depend on n and Is, the ideality factor and reverse saturation current. These constants are process dependent and may vary from lot to lot.

To narrow down the confusion of solving the temperature, the equation must be rewritten in such a way the measurement will only depend on the ideality factor of the transistor as shown below.

$$T = \frac{(Vbe1 - Vbe2)}{\frac{nk}{q}\ln\frac{Ic1}{Ic2}} \quad (2)$$

Set the current such as:

$$Ic2 = N \cdot Ic1 \quad (3)$$

$$T = \frac{(Vbe1 - Vbe2)}{\frac{nk}{q}\ln\frac{1}{N}} \quad (4)$$

The main reason why the equation needs to rely on the ideality factor as shown in Equation 4 among all other variables from Equation 2, the ideality factor is relatively stable compared to the saturation current. Conceptually the delta measurement cancels the saturation current and all other non-ideal mechanisms not modeled by the equation (Linear technology (Now analog devices), 2012).

Temperature measurement error sources and reading stability techniques

In any kind of thermal diode acquisition unit measurement system, the sources of temperature measurement errors are taken care extensively to preserve the integrity of the temperature data. Even though this method of temperature measurement is not reliant on linear expansion like the thermocouple, care must be taken care from considering the printed circuit board (pcb) layout, environment noise sources, choosing the analog to digital converter architecture, the wire distance just in case the process is not possible to be monitored as close to the inputs of the analog to digital converter, the precision of the forcing current and power supply stability and etc.

If the sensing thermal diode is nearly located in a noisy signal source, the noise will couple via capacitance.

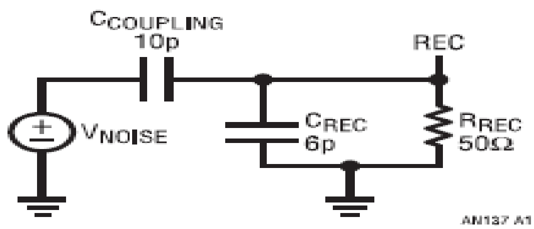

Figure-3. Capacitance coupled noise representation. (Linear technology(Now analog devices), 2012)

The analytical expression of coupling from Ott is:

$$V_{REC} = \frac{j\omega[\frac{C_{Coupling}}{C_{Coupling} + C_{Rec}}]}{\frac{1}{R_{REC}(C_{Coupling} + C_{REC})}} V_{Noise} \quad (5)$$

VOL. 12, NO. 24, DECEMBER 2017 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

In the case where R_{REC} is smaller than the impedance of the two capacitors, the equation can be simplified:

$$V_{REC} = j\omega R_{REC} C_{Coupling} V_{Noise} \tag{6}$$

If a shield is added, the equivalent circuit looks like this:

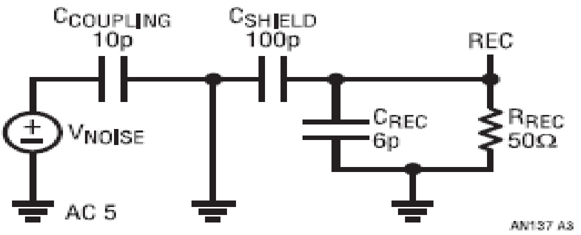

Figure-4. Noise shield representation.(Linear technology(Now analog devices), 2012).

In this case there is no coupling to the receiver at all; an example of shielding is given in the LTC2991 datasheet is shown on Figure-5:

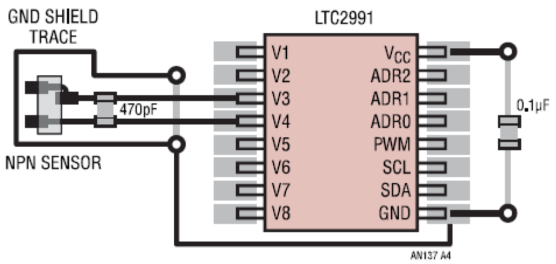

Figure-5. Ground trace shield or differential ground routing (linear technology(now analog devices), 2012).

Another way of differential ground routing was introduced by maxim integrated products incorporated. This can be seen in MAX6642 thermal diode sensor. routing the diode and ground traces in this manner will offer noise filtering as well. if the distance is less than 8 inches, it is required to put a non-polarized capacitor like 2200pf or reduced in value for filtering. This routing technique is necessary if High Voltage traces are unavoidable. Routing and filtering are futile if the noise sources are CRT's(Cathode ray tubes), clock generators, memory buses and ISA/PCI (Industry standard architecture/peripheral component interconnect) buses (maxim integrated products incorporated, 2009).

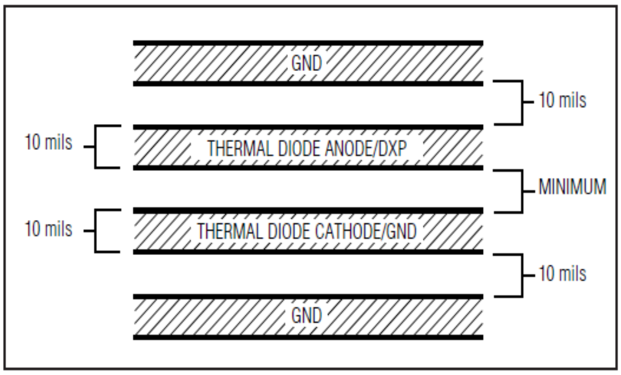

Figure-6. Recommended DXP PC traces(maxim integrated products incorporated, 2009).

The use of twisted pair cable for cable lengths 6 feet and 12 feet and shielded twisted pair for distances up to 100 feet is recommended for noisy environments. connect the diode anode terminal (DXP) and GND and the shield to GND. Leave the shield unconnected at the remote diode (Maxim integrated products incorporated, 2009).

Inductive coupling occurs when high current flows through a trace, creating a magnetic field, the field enters the current loop of the other circuit. The current loop will have a series voltage noise source from the external field.

$$V_{REC} = j\omega MI \tag{7}$$

Where:

MI = Mutual inductance

(Linear technology(now analog devices), 2012)

The received noise voltage is proportional to the mutual inductance and current (linear technology(now analog devices), 2012).

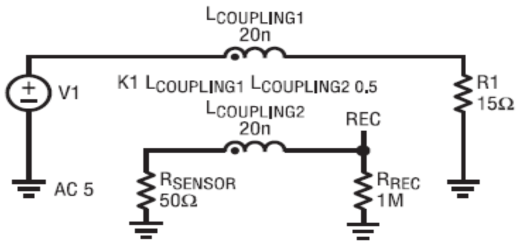

Figure-7. Inductance coupled noise (linear technology(now analog devices), 2012)

Ground coupling occurs when a sensor low sense is grounded at both ends, as is using a power block, a ground loop is formed. this loop can receive a magnetic field, hence inductive coupling, as shown in Figure-6.

VOL. 12, NO. 24, DECEMBER 2017 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

Not much can be done about this other than to make the shortest low sense route possible back to the receiver and keep the layers between the trace and ground place as thin as possible (Linear technology(now analog devices), 2012).

To overcome the ground coupling noise acquired by the thermal diode, by assigning the connection of the Anode of the diode-connected PNP or NPN transistor into one when implementing a multipoint temperature sensing. The D- or anode of the diode is forced to 0.7VDC by the VD- amplifier. The amplifier ensures that the D- or anode of the diode is a very low impedance node (National semiconductor(Now Texas instruments incorporated), 2011).

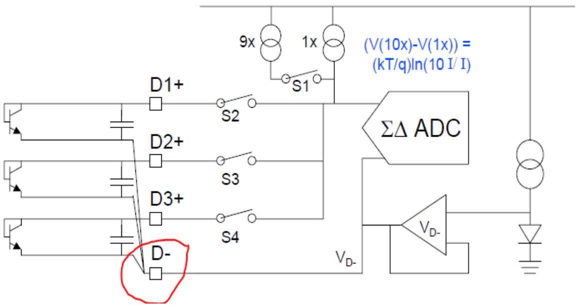

Figure-8. Unified D- connection from V_{D-} amplifier (National semiconductor(now Texas instruments incorporated), 2011)

The architecture of the analog to digital converter (ADC) will contribute also to eliminate the susceptibility of the temperature reading to noise. Since that temperature does not change so fast compared to other measurement parameters, the architecture Sigma-delta(ΣΔ) is chosen for this application.

The advantage of this analog to digital converter (ADC) architecture are superb linearity and inherent noise immunity. The linearity is directly attributable to the comparator in the ADC; the noise immunity is due to the digital averaging filter (Microchip technology incorporated, 2014).

The Sigma-delta (ΣΔ) ADC used in National's temp sensors is a special architecture designed for DC andvery low frequency inputs. While some traditional Sigma-delta (ΣΔ) ADC architectures have problems with DC inputs due to the generation of tone at certain frequencies (the tone frequency depends on sampling frequency and the input DC level), this special architecture easily handles DC inputs:

Very high oversampling ratio (OSR): For our Sigma-Delta (ΣΔ) ADC, OSR > 10000x. Typical Sigma-Delta(ΣΔ) ADC's have OSRs on the order of ~256x. (A new project at Berkeley has had a Sigma-Delta(ΣΔ) ADC with OSR = 40000x).

To maximize DC accuracy, the integrators are reset after every conversion. Normal Sigma-Delta (ΣΔ) ADC's will not do this.

A first-order Sinc filter is used as the decimating filter. This allows offset trimming and auto-zeroing for DC applications.

Sigma-delta (ΣΔ) ADC's are very accurate, but slow compared to SAR architecture. Sigma-delta (ΣΔ) ADC's can achieve >20 bits of accuracy, where successive approximation register (SAR) ADC's is only practical up to about 12-bits, since they are limited by their digital to analog converter (DAC) linearity. The successive approximation register (SAR) is a faster architecture, but speed is unnecessary for slowly changing signals like temperature.

This particular Sigma-Delta (ΣΔ) ADC inherently averages the input, giving better noise rejection (National semiconductor(Now Texas instruments incorporated), 2011).

From the figure below of analog to digital converter architecture types, the Sigma-delta (ΣΔ) ADC has the greatest performance when it comes to representing the original analog signal due to its high effective number of Bits (ENOB) and simplified anti-aliasing capability. This can be operated with lesser external signal filtering components. Although the slowest among the four types, this is applicable where high resolution readout is required for a slow changing measurement parameter such as temperature. 1 is the highest among the rating and asterisk means capability (Black, 1999).

Characteristic	Flash	Pipelined	SAR	Sigma-Delta
Throughput	1	2	3	4
Resolution (ENOB)	4	3	2	1
Latency	1	3	2	4
Suitability for converting multiple signals per ADC	1	2	1	3
Capability to convert non-periodic multiplexed signals	1	2	1	3
Simplified anti-aliasing				*
Can undersample	*	*	*	
Can increase resolution through averaging (with dither noise)	*	*	*	

Figure-9. Comparison of analog to digital converter architectures (Black, 1999).

METHODOLOGY

Along the market of Thermal diode sensor available, the measurement ranges will come from -55 ˚C to +125 ˚C, -40 ˚C to +125 ˚C or 0 ˚C to +150 ˚C available in different resolutions, accuracy and features. In this paper, it will introduce a design in which it can cater the -55 ˚C to +150 ˚C to cover most of the frequently used temperature measurement ranges.

When it comes to resolution, the usual thermal diode sensor on the market usually offers 14bit, 16bit and 24bit resolution to be the highest. this paper will also provide a conceptual data of temperature measurement predicted results in different analog to digital conversion resolutions for comparison.

First, determine the thermal diode measurement temperature range, diode voltage difference and the ideality factor of the transistor and its type, whether to use PNP or NPN as the remote diode sensing element and the forcing current values to be used. Remember that the temperature should be expressed in Absolute Scale (in Kelvin). The forcing current should come from a precision constant current source and connected with Kelvin method (4-Wire) to avoid any losses due to the distance from the analog to digital converter (ADC) to the thermal diode area.

Next, determine the analog to digital converter (ADC) architecture that will be used to quantize the analog voltage coming from the diode-connected transistor. in this case, for measuring temperature, sigma-delta (σΔ) analog to digital conversion is the best choice for this application.

Finally, apply all possible filtering, printed circuit board (PCB) design rules in layout and noise mitigation schemes for reliable temperature data collection.

In Table 1, the desired parameters were tabulated for the proposed temperature range design.

Table-1. Delta measurement parameters

Temperature -55 ˚C	**218.15K = -55 ˚C+ 273.15**
Temperature +150 ˚C	423.15K = +150 ˚C + 273.15
Ic1 (Force Current Low)	10μA
Ic2(Force Current High)	100μA
Ideality Factor	1.008-1.010
ADC Reference Voltage	2.5 Volts DC

In Table-2, the possible thermal diode voltages are pre-calculated with respect to different ideality factors that a diode-connected transistor can exhibit. the figures are less than 1 volt indicating that the movement of temperature readings is very close to each other and very hard to differentiate the temperature change with respect to the voltage.

Since that the Ideality factor and the temperature range were given, the theoretical value of the thermal diode voltage is going to be simulated with different analog to digital conversion resolutions. The resolutions are 14bit, 24bit and 32bit. The test condition will be using a 2.5 volts dc reference voltage among the three different types of analog to digital converter resolutions.

almost all graphs succeeded to give a linear graph, but the 32bit analog to digital conversion results exhibits more linearity and precision given in the figures considering that the graphical figures exposes the -1 °C, 0 °C and +1 °C temperature data.

CONCLUSIONS

The thermal diode or remote diode temperature reading performance can be planned and enhanced by relying on the Ideality factor of the diode-connected transistor chosen to be the sensing element of the thermal diode acquisiton unit to be designed.

The use of Sigma-delta (ΣΔ) analog to digital converter architecture exhibits more accuracy on slow varying measurements that requires high resolution readout. Oversampling and decimation feature that are the main capability of the sigma-delta (ΣΔ) analog to digital converter will work efficiently when noise is present on the system. Reduction of external anti-aliasing filters is now possible to achieve in such system. The use of successive approximation register (SAR) analog to digital converter architecture is not encouraged since some measurements are not changing rapidly with respect to time. The cost of high sampling rate successive approximation register (SAR) analog to digital converter is more expensive than a high resolution Sigma-delta (ΣΔ) analog to digital converter.

Any kind of filtering and sampling is useless for protecting the thermal diode readout from the sources of noises such as CRT's, clock generators, memory buses and industry standard architecture/peripheral component interconnect(ISA/PCI) slots present on computing devices such as personal computers. These noise sources should be considered and avoided at all times.

The theoretical simulation also shows that the range of -55 °C to +150 °C is still possible since that the quantization values are still in range of the analog to digital converter resolutions.

Table-2. Predicted thermal diode voltage on different ideality factors.

Temperature	Absolute temperature	Voltage (Ideality factor = 1.008)	Voltage (Ideality factor = 1.009)	Voltage (Ideality factor = 1.010)
-55	218.15	0.043631966	0.043675252	0.043718537
-50	223.15	0.044632011	0.044676289	0.044720567
-45	228.15	0.045632056	0.045677326	0.045722596
-40	233.15	0.046632101	0.046678363	0.046724625
-35	238.15	0.047632146	0.0476794	0.047726655
-30	243.15	0.048632191	0.048680438	0.048728684
-25	248.15	0.049632236	0.049681475	0.049730713
-20	253.15	0.050632282	0.050682512	0.050732742
-15	258.15	0.051632327	0.051683549	0.051734772
-10	263.15	0.052632372	0.052684586	0.052736801
-5	268.15	0.053632417	0.053685623	0.05373883
-1	272.15	0.054432453	0.054486453	0.054540454
0	273.15	0.054632462	0.054686661	0.05474086
1	274.15	0.054832471	0.054886868	0.054941265
5	278.15	0.055632507	0.055687698	0.055742889
10	283.15	0.056632552	0.056688735	0.056744918
15	288.15	0.057632597	0.057689772	0.057746947
20	293.15	0.058632642	0.058690809	0.058748977
25	298.15	0.059632687	0.059691847	0.059751006
30	303.15	0.060632732	0.060692884	0.060753035
35	308.15	0.061632777	0.061693921	0.061755064
40	313.15	0.062632822	0.062694958	0.062757094
45	318.15	0.063632867	0.063695995	0.063759123
50	323.15	0.064632912	0.064697032	0.064761152
55	328.15	0.065632957	0.06569807	0.065763182
60	333.15	0.066633003	0.066699107	0.066765211
65	338.15	0.067633048	0.067700144	0.06776724
70	343.15	0.068633093	0.068701181	0.068769269
75	348.15	0.069633138	0.069702218	0.069771299
80	353.15	0.070633183	0.070703255	0.070773328
85	358.15	0.071633228	0.071704293	0.071775357
90	363.15	0.072633273	0.07270533	0.072777387
95	368.15	0.073633318	0.073706367	0.073779416
100	373.15	0.074633363	0.074707404	0.074781445
105	378.15	0.075633408	0.075708441	0.075783474
110	383.15	0.076633453	0.076709478	0.076785504
115	388.15	0.077633498	0.077710516	0.077787533
120	393.15	0.078633543	0.078711553	0.078789562
125	398.15	0.079633588	0.07971259	0.079791592
130	403.15	0.080633633	0.080713627	0.080793621
135	408.15	0.081633678	0.081714664	0.08179565
140	413.15	0.082633724	0.082715701	0.082797679
145	418.15	0.083633769	0.083716739	0.083799709
150	423.15	0.084633814	0.084717776	0.084801738

VOL. 12, NO. 24, DECEMBER 2017 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

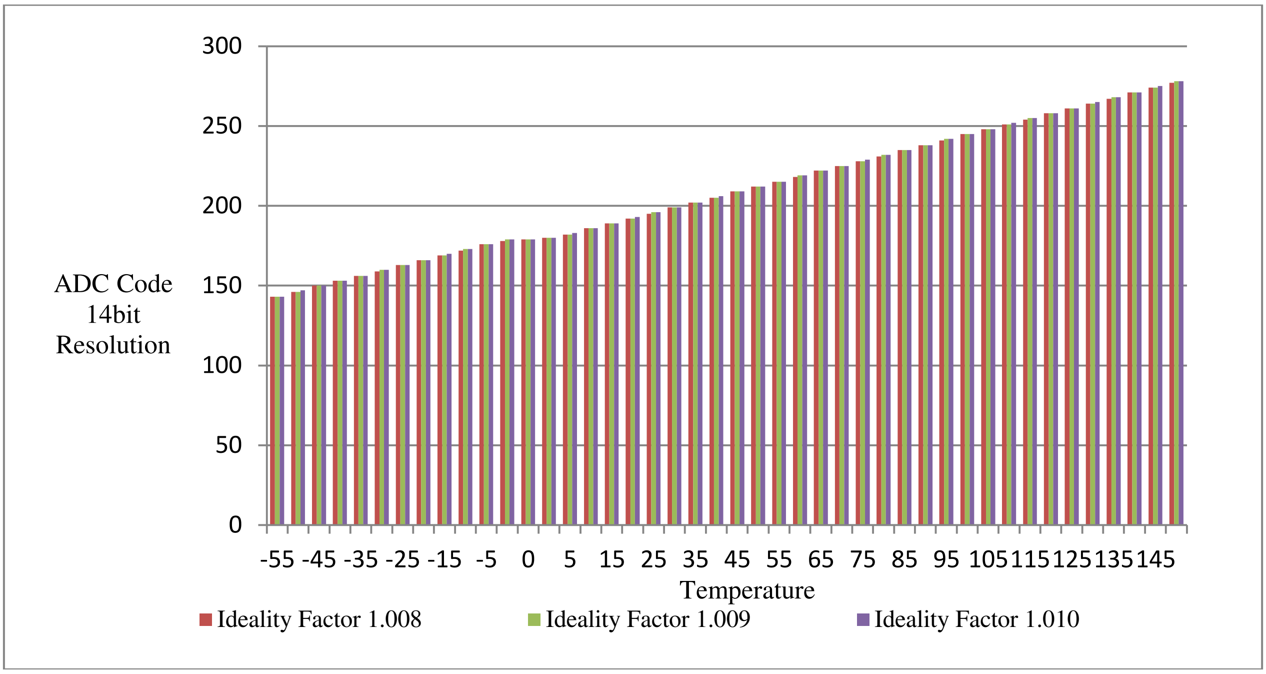

Figure-10. 14bit analog to digital converter resolution vs. temperature.

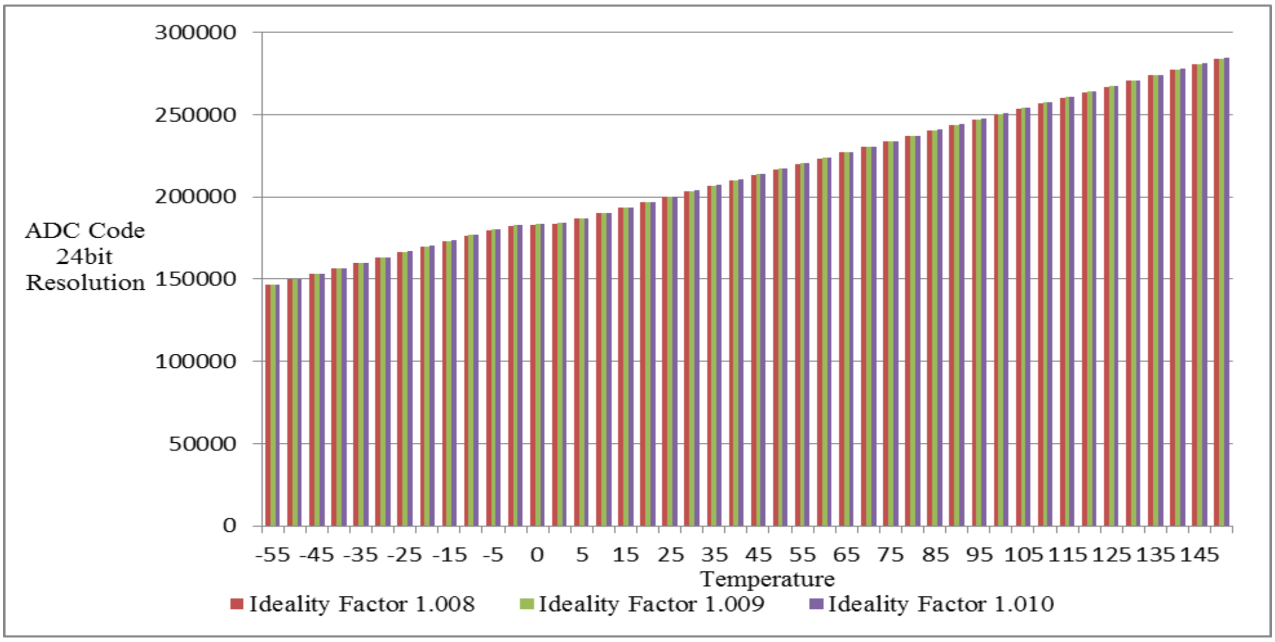

Figure-11. 24bit analog to digital converter resolution vs. temperature.

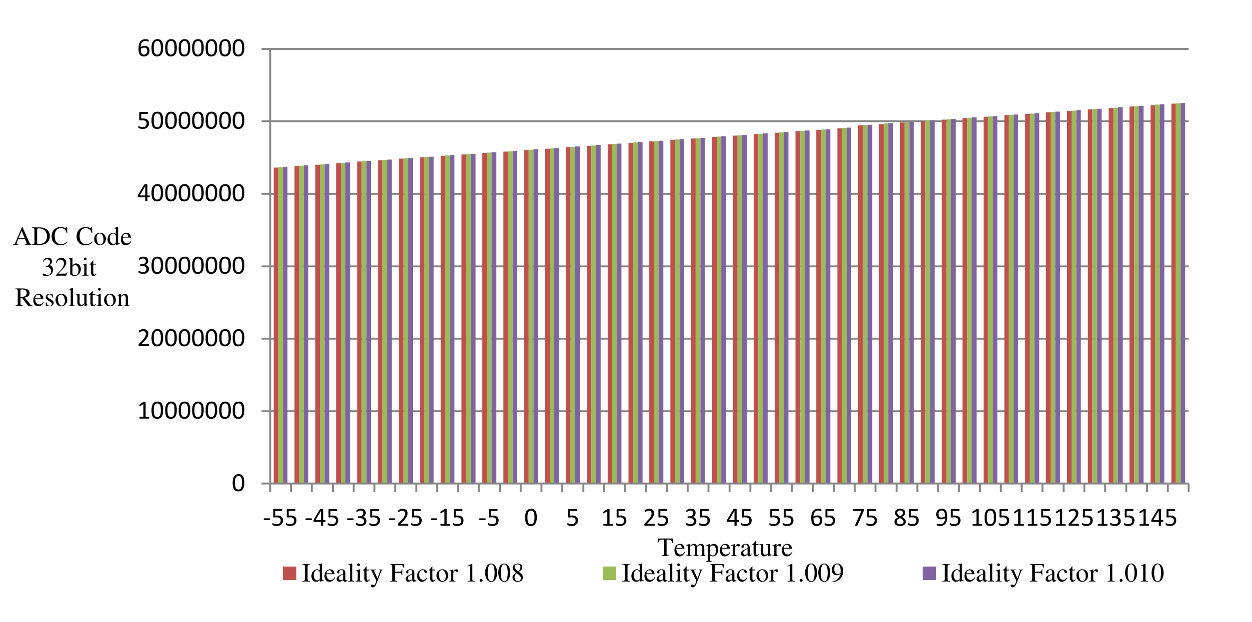

Figure-12. 32bit analog to digital converter resolution vs. temperature.

REFERENCES

Black B. 1999. September. Analog-to-Digital Converter Architectures and Choices for System Design. Retrieved June 13, 2017, from AnalogDialogue: http://www.analog.com/en/analog-dialogue/articles/analog-to-digital-converter-architectures-and-choices.html

Linear Technology(Now Analog Devices). 2012, May. Accurate Temperature Sensing with an External P-N Junction. California, Milpitas, United States of America.

Maxim Integrated Products Incorporated. 2009. MAX6642 ±1 °C, SMBus-Compatible Remote/Local Temperature Sensor with Overtemperature Alarm. California, Sunnyvale, United States of America.

Maxim Integrated Products, Inc. 2010. Thermal Management Handbook. California, Sunnyvale, United States of America.

Microchip Technology Incorporated. 2014, March 25. Using Temperature Sensing Diodes with Remote Thermal Sensors. Chandler, Arizona, United States of America.

National Semiconductor(Now Texas Instruments Incorporated). 2011. LM82, LM83, LM84, LM87 Multiple Remote Diode Temperature Sensing. Dallas, Texas, United States of America.