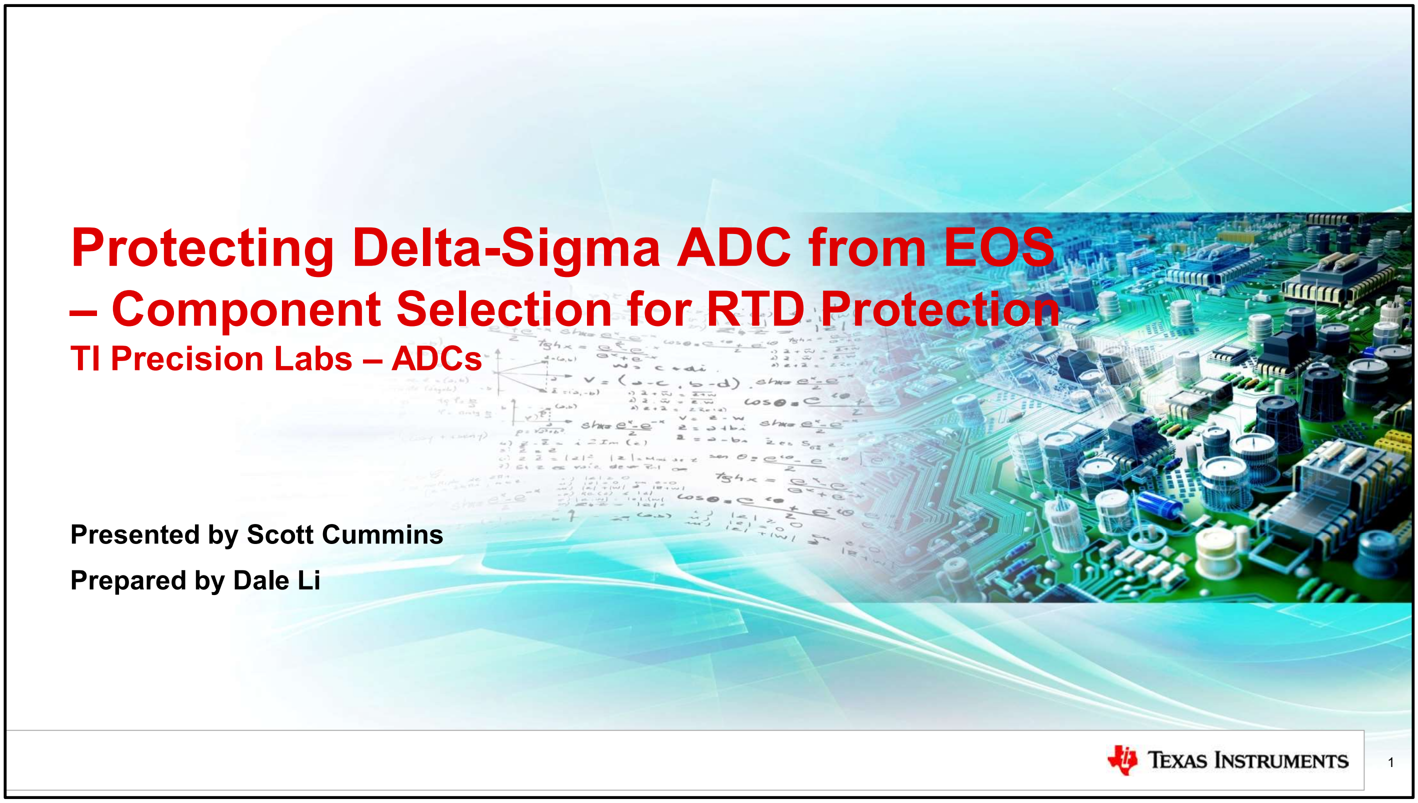
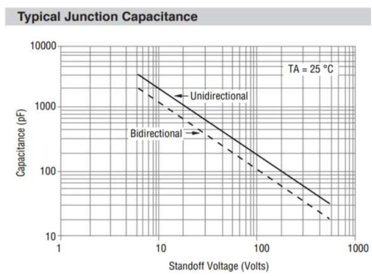


Hello, and welcome to the TI Precision Labs on protection of RTD measurement systems. In the last video we went over component selection for the RTD measurement system. In this video we will analyze the impact that the protection circuits have on performance. Specifically, leakage current and leakage drift will be calculated and measured. In general, a common shortcoming of TVS diode data sheets, is a lack of detail describing the statistical distribution of leakage current and leakage drift. As part of this investigation we measured a small sample of TVS diodes from different manufacturers to get a general sense of the statistical distribution of the leakage and the drift.

Capacitance and Leakage Current on TVS diode

- **Capacitance**
  - Changes with standoff voltage
  - Junction capacitance changes from hundreds pF up to 10-nF
  - Large power rating diode has higher capacitance and variation
  - Adds distortion to systems with AC inputs
- **Leakage Current**
  - Datasheet from most manufacturers only shows max leakage at room temperature.
  - Same PN from different manufacturers may have different leakage spec.
  - Leakage Variation with temperature.
  - Key impact to RTD measurement.



Manufacturers	PN	Leakage current(max at 25°C)
Bourns Inc.	SMBJ14CA	1uA
Littelfuse	SMBJ14CA	1uA
Vishay	SMBJ14CA	1uA
Diodes Inc.	SMBJ14CA	5uA
Taiwan Semi	SMBJ14CA	5uA

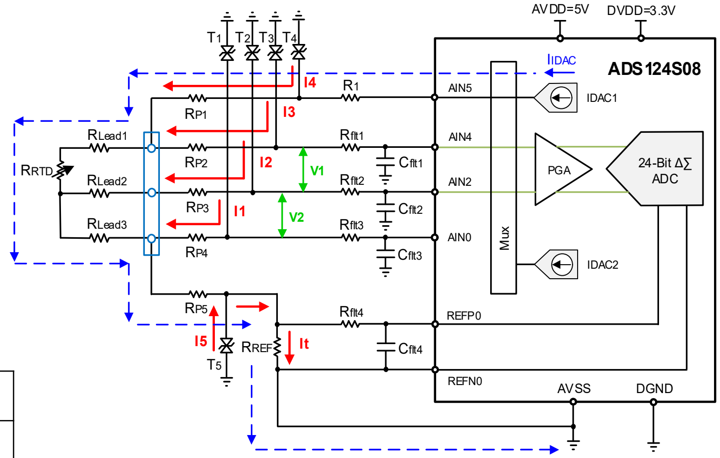
There are two main error sources introduced by TVS diodes: capacitance and leakage current. Capacitance of the TVS will vary according to the standoff voltage applied across the device. This change in capacitance will introduce non-linearity for systems with AC input. Since the RTD circuit has DC inputs, the parasitic capacitance doesn't really impact the performance here. In previous videos we covered examples with AC inputs that showed THD performance impacts from the parasitic capacitance. Leakage current is another important error source. Leakage will flow through the input impedance and introduce offset voltages. This error source can be minimized using calibration, but leakage drift over temperature is typically difficult to calibrate.

The table shown provides the maximum leakage current for some different commercially available TVS diodes. Unfortunately, diode manufacturers generally do not publish typical values for leakage or leakage over temperature. Later in this presentation we will show that if the leakage is equal to the specified maximum, then the offset error can be unacceptably large. For this reason we did an investigation where we measured large batches of different TVS diodes to get a better understanding of what to typically expect for leakage current. The results showed that typical performance is significantly better than the specified maximum. This video will cover the error analysis assuming worst case leakage and review typical results.

Calculated Error with SMBJ14CA diode

- **TVS leakage current are added:**
  - ➢ I3 and I4 through both RRTD and RREF.
  - ➢ I2 and I1 through RREF only.
- **Leakage current on SMBJ14CA from Bourns**: **Ileak = 1uA**

  (maximum at room temp, no spec over temp)



(*Common-mode capacitor not shown)

Additional error (maximum) at room temperature:

$\text{Ratio}_{\text{-Ideal}} = (I_{DAC} \cdot R_{RTD} \cdot \text{Gain})/(I_{DAC} \cdot R_{REF}) = 400\Omega \cdot 4/2k\Omega = 0.8$
$V_1 = (I_{DAC} + I_3 + I_4) \cdot (R_{RTD} + R_{lead1}) + I_3 \cdot R_{RP2} - I_2 \cdot (R_{P3} + R_{lead2})$
$V_2 = (I_{DAC} + I_2 + I_3 + I_4) \cdot R_{lead3} + I_2 \cdot (R_{RP3} + R_{lead2}) - I_1 \cdot R_{RP4}$
$\text{Ratio}_{\text{wLeak}} = (V_{\text{meas\_error}} \cdot \text{Gain})/V_{REF} = ((V_1 - V_2) \cdot \text{Gain})/(R_{REF} \cdot (I_{DAC} + I_1 + I_2 + I_3 + I_4 + I_5))$ $= (((I_{DAC} + 2I) \cdot R_{RTD} - 3I \cdot R_{lead}) \cdot \text{Gain})/(R_{REF} \cdot (I_{DAC} + 5I)) = 0.795$ *
$\text{Error} = (\text{Ratio}_{\text{-Ideal}} - \text{Ratio}_{\text{-Actual}})/\text{Ratio}_{\text{-Ideal}} \cdot 100\% = 0.625\%$

* *Note*: $I_1 = I_2 = I_3 = I_4 = I_5 = I$

⟵ **Accuracy desired: ±0.5%**

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Here we will calculate the error from TVS diode leakage..

Look at the circuit on the right side, the leakage current from T3 and T4 flows through both the RTD sensor and reference resistor Rref, as well as the lead resistances Rlead1 and Rlead3.

The leakage current (I2) from T2 flows through Rlead2, Rlead3, and the Rref reference resistor. The leakage current (I1) from the T1 TVS diode will flow through Rlead3 and the Rref resistor.

The leakage current of SMBJ14CA is 1uA maximum at room temperature.

The conversion result for this RTD circuit can be thought of as a ratio of the RTD resistance to the reference resistance with a gain factor. The ideal ratio can be calculated with the first equation, resulting in 0.8. This ratio doesn't include any leakage current error sources.

An expected ratio can be calculated by including all the leakage current sources in nodal calculations, and then substituting these nodal calculations into the ideal ratio relationship. In this example the expected ratio is 0.795. Note that this assumes that all the leakage currents are the same in each diode and equal to the worst case leakage. Furthermore, this analysis assumes that all the resistors in the circuit are equal to the stated value, so some error sources will cancel out completely. In a practical circuit the resistors and leakage currents will all have tolerance, but this simulation doesn't take that into account. For now, comparing the ideal ratio to the expected ratio, the calculated error is -0.625%. For this kind of circuit a common accuracy target is 0.1% or 0.5%. So, based on this initial calculation the diode solution will not be able to meet the design goal.

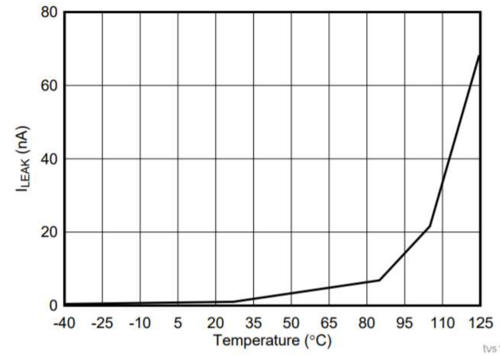
Error with Low Leakage Current of TVS diode

Part Number	MFG	Reverse Standoff Voltage (V_R)	Breakdown Voltage (V_{BR})		Clamping Voltage Max (V_C@I_{PP})	Reverse Leakage (I_R@V_R)			Peak Power Dissipation W (P_{PP})	
			Min	Typ		Typ at 27°C	**Max** at 27°C	**Max** at **85°C**	8/20us	1ms
TVS1401	TI	14V	17.1	17.6	22.2	1.1nA	30nA	**260nA**	600	120
SMBJ14CA	Bourns	14V	15.6	17.2	23.2		**1uA**			600

RTD system error calculated from leakage current:

PN	MFG	Error	Temperature
TVS1401	TI	**0.159%**	**85°C**
SMBJ14CA	Bourns	**0.625%**	**25°C**

Accuracy desired: ±0.5%



Leakage Current vs Temperature at ±14V on TVS1401.

Note: The error with TVS1401 at room temp is much smaller.

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Now, let's check the error with a TI TVS diode solution, TVS1401. Most TVS diode manufacturers only show a maximum leakage current at room temperature in their datasheet, for example SMBJ14CA, this makes it difficult to evaluate the error contributed by the TVS diode over temperature. The TI device is specified over temperature, and also provides a typical specification at room temperature.

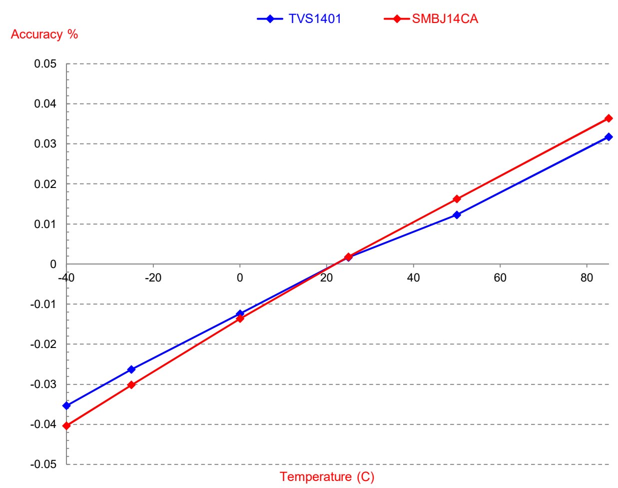
The TVS1401 has a very low leakage current of 30nA maximum at room temperature, compared to 1uA of leakage current from the SMBJ14CA. The TI TVS diode datasheet specifies maximum leakage current at high temperature which is 260nA, also the leakage current vs. temperature graph is shown in the datasheet which is very helpful to estimate the error for the designers.

Using the same equations for error calculations, the TVS1401 error is only 0.16% at 85°C which is much lower than the SMBJ14CA even at room temperature. Based on the calculation, the TI TVS diode solution can meet the design goal of ±0.5%

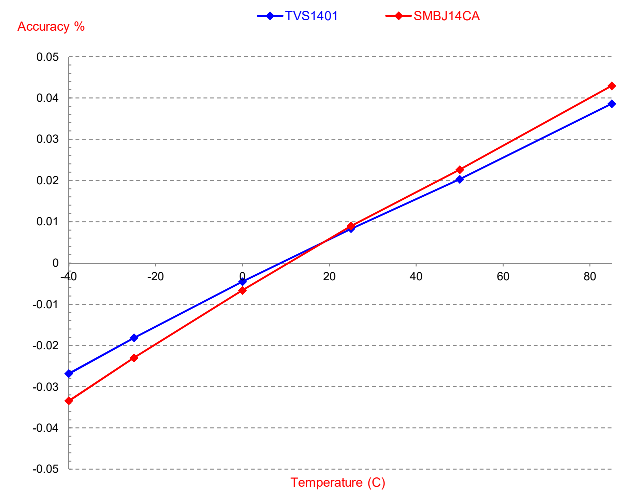
across the full temperature range.

RTD Measurement: Accuracy vs. Temperature

RTD - 100ohm (0°C)



RTD - 400ohm (850°C)



Conditions: 0.1% 10ppm/°C resistors for Rp and R1, 0.01%, 5ppm/°C resistor for Rref. No calibration on ADC.

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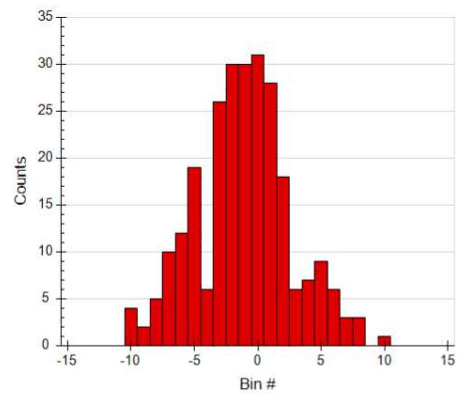
This slide shows measured accuracy on hardware with the TI TVS diode TVS1401 solution in blue, and the conventional TVS diode, SMBJ14CA, solution in red across the full temperature range from -40°C to 85°C. For this measurement, a low drift and 0.01% high precision resistors are used for the reference resistor for the highest accuracy. The RP and R1 resistors are also low drift precision resistors as the matching of these resistors can have some impact on leakage current cancelation.

The RTD in this example is substituted with two different precision resistors to emulate an RTD at 0C and at 850C. The objective of this test is to illustrate how the leakage current and leakage over temperature impacts circuit performance. Both TVS diodes performed better than the calculated error based on their specification. The SMBJ14CA device's calculated error was expected to be 0.625% but the worst error measured was 0.042%. The TVS1401 device's calculated error was expected to be 0.159% over temperature and its worst error was 0.038%.

You might be surprised by the small measured error of the SMBJ14CA as compared to the calculated error. Based on our characterization of some common commercially available TVS diodes this is not unusual. It seems that most manufacturers of TVS diodes only provide a maximum room temperature leakage current specification, and generally this specification seems to be substantially greater then the typical expected leakage. We will look at the measured diode leakage on a set of SMBJ14CA diodes more closely later.

RTD Measurement: Resolution with TI TVS1401 diode

Measured Result:		
	ENOB (bits)	**Noise-Free Resolution** (bits)
High Temp (+85°C)	21.2	18.8
Room Temp (+25°C)	21.3	19.0
Cold Temp (-40°C)	21.5	19.1



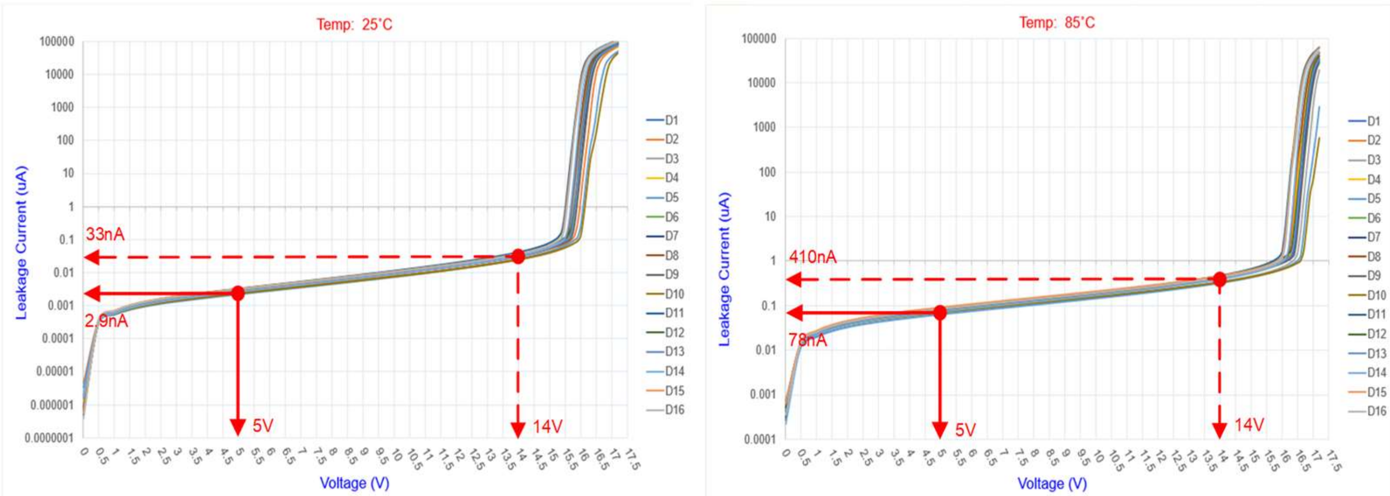
Channel	Samples	Mean	Std Dev	Pk-to-Pk	ENOB	NFB
ADC0	256	1679321.4	6.9	38	21.2	18.8

Condition:

- TVS1401 Protection Solution,
- Low side Reference, 3-wire RTD,
- High precision 100Ω resistor instead of PT100.

This slide shows measured resolution at different temperatures. The objective is to show that the noise and signal integrity is not impacted by the protection circuit. The Effective Number of Bits, or ENOB, is greater than 21-bits across temperature. Also, the Noise-Free resolution is higher than 18-bits across temperature. These measurements both meet typical design goals for this kind of system and it is clear that the addition of the protection components had minimal impact on noise performance.

Why SMBJ14CA Solution doesn‘t show worse accuracy?



Note: 14V is the standoff voltage of SMBJ14CA .

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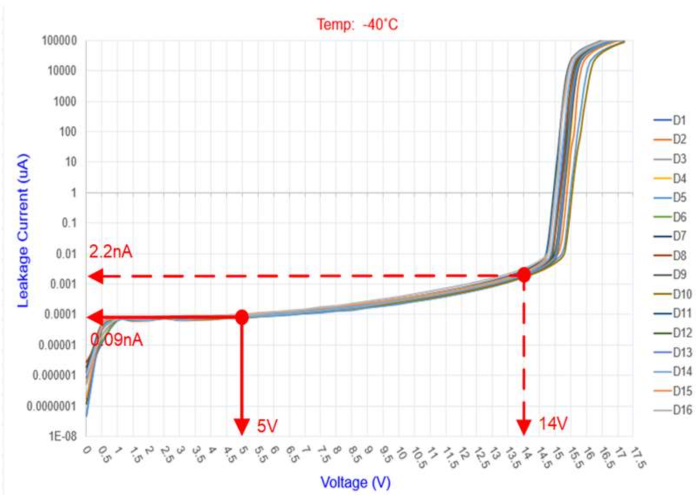
This slide shows the diode reverse leakage current characteristics across voltage. This diode is rated to have a reverse standoff voltage of 14V and is expected to breakdown between 15.6V and 17.2V. For this measured group of diodes there is a clear breakdown between 15V and 17V as expected. At 14V the specified maximum current is 1uA, but you can see that for this group the highest leakage is 410nA at 85C. In the next slide we will show the curve for -40C. Diode leakage will increase with temperature as is shown here. However, in real world cases condensation at cold temperatures can cause additional leakage. The measurements made here were done in a nitrogen purged environment so that condensation isn’t a factor.

Why SMBJ14CA Solution doesn‘t show worse accuracy?



SMBJ14CA Measured Leakage Current:

Temperature	Forced Voltage		
	3.5V	5V	14V
High Temp (+85°C)	59 nA	78 nA	410 nA
Room Temp (+25°C)	2.0 nA	2.9 nA	33 nA
Cold Temp (-40°C)	0.075 nA	0.09 nA	2.2 nA

Note 1: Specified room temperature maximum leakage for the SMBJ14CA is 1μA at the 14V standoff voltage. Measured leakage room temperature leakage at 14V is 33nA .

Note 2: averaged result for 16 diodes.

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TEXAS INSTRUMENTS

This slide shows the -40C graph of leakage vs reverse voltage, and the table summarizes the average result for all the diodes measured. The highest leakage measured at the 14V standoff voltage is 410nA at 85C. As expected the leakage when a lower reverse voltage is applied is much smaller. For a 5V reverse voltage the maximum leakage is 78nA. This is an important finding as our design uses a TVS diode with a 14V standoff voltage but normally applies only 5V across it. This is an important benefit of using a TVS diode with a standoff that is greater than the normal operating voltage.

Why SMBJ14CA Solution doesn‘t show worse accuracy?

RTD system error calculated from leakage current:

PN	MFG	Calculated Error		Temperature	Note
		14V	3.5V		
SMBJ14CA	Bourns	0.251%	0.036%	85°C	Calculation based on average current measured for 16 devices
		0.020%	0.001%	25°C	Calculation based on average current measured for 16 devices
TVS1401	TI	0.159%	*	85°C	Calculation based on data sheet maximum
		0.018%	*	25°C	Calculation based on data sheet maximum

* No specification data for leakage current at 3.5V voltage.

The diodes works on lower voltage under normal condition

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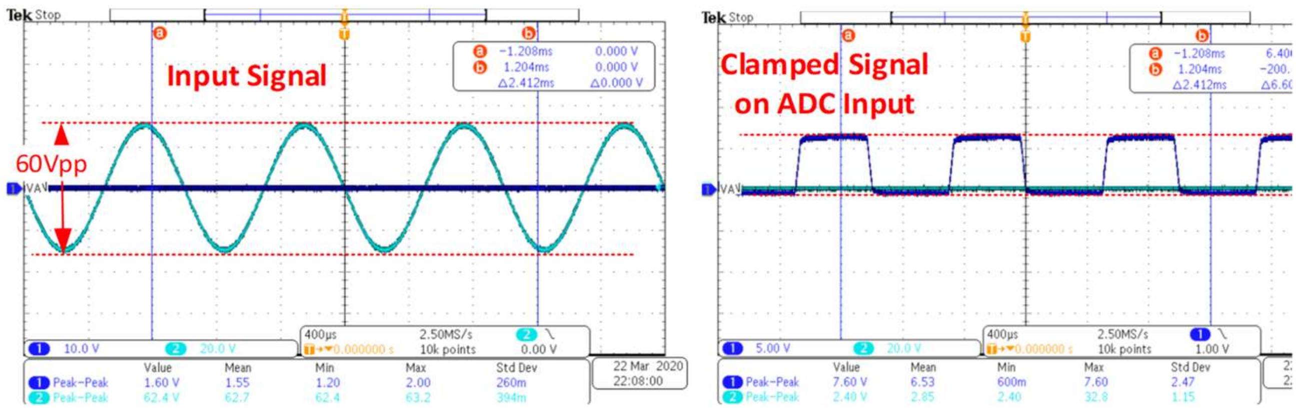
TEXAS INSTRUMENTS

Here we summarize and compare the accuracy of the Bourns and TI TVS diodes. In this table the TI diode is based on maximum specifications and the bourns diode is based on average leakage measurements. One important point to understand here is that reducing the applied voltage to about 3.5V substantially reduces leakage and consequently reduces error. Unfortunately, most diode manufacturers do not provide detail on typical leakage distributions, how leakage behaves over temperature, and how leakage changes with applied reverse voltage. This can make it difficult to estimate error based on data sheet specifications alone. Often, using the data sheet specifications for diode leakage can lead to an overestimate of expected leakage, and this error may be unacceptable from a product specification perspective.

When including a TVS protection scheme in your product to prevent against damage from electrical overstress, it may be necessary to characterize the diodes to better understand any undefined leakage characteristics. It may also be necessary to confirm product accuracy with a production test if the TVS diode leakage specifications lead to unacceptable errors. The main point of this presentation is to show that it is possible to use TVS diodes to protect the ADC inputs and still meet accuracy targets, but it can be challenging to do this based on published specifications alone.

EOS Protection Verification on ADC Input



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The final slide in this presentation shows a sinusoidal fault signal of 60Vpp applied to the input. This is just one example to show the clamping action of the TVS diode, but any other transients can be applied to the input. The circuit was designed to withstand a ±40V DC fault. DC faults are very challenging as they will dissipate significant continuous power in the TVS diode and series limiting resistors. The circuit will be able to withstand short transients much greater than 40V.

For this example sinusoidal fault signal you may notice that the clamped signal is bit higher than absolute maximum rating of a voltage input, however the ADC is protected as long as the input current is limited to less than the absolute maximum current rating of ±10mA. Therefore, this circuit is an effective input protection for the sinusoidal waveform.

Thanks for your time!
Please try the quiz.

TEXAS INSTRUMENTS 11

That concludes this video – thank you for watching! Please try the quiz to check your understanding of this video's content.

Questions: Protecting Low Voltage ADC

1. (T/F) TVS diode leakage will decrease at high temperatures?
   a. True.
   b. False.

2. If a TVS diode is specified to have 1µA maximum leakage at the standoff voltage (14V), what leakage will be below the standoff voltage (5V)?
   a. Leakage at 5V will be higher
   b. Leakage at 5V will be lower
   c. Leakage does not depend on reverse voltage.

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Question 1, true or false: TVS diode leakage will decrease at high temperatures?

Questions: Protecting RTD input Delta-Sigma

1. (T/F) TVS diode leakage will decrease at high temperatures?
   a. True.
   b. False.

2. If a TVS diode is specified to have 1μA maximum leakage at the standoff voltage (14V), what leakage will be below the standoff voltage (5V)?
   a. Leakage at 5V will be higher
   b. Leakage at 5V will be lower
   c. Leakage does not depend on reverse voltage.

The correct answer is "b. False". Leakage for all diodes will increase with temperature.

Question 2, If a TVS diode is specified to have 1μA maximum leakage at the standoff voltage (14V), what leakage will be below the standoff voltage (5V)?

Questions: Protecting RTD input Delta-Sigma

1. (T/F) TVS diode leakage will decrease at high temperatures?
   a. True.
   b. False.

2. If a TVS diode is specified to have 1µA maximum leakage at the standoff voltage (14V), what leakage will be below the standoff voltage (5V)?
   a. Leakage at 5V will be higher
   b. Leakage at 5V will be lower
   c. Leakage does not depend on reverse voltage.

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The correct answer is "b. Leakage at 5V will be lower". Leakage will always increase when the reverse voltage is decreased.

Questions: Protecting RTD input Delta-Sigma

3. (T/F) TVS diode data sheets typically do not provide information on how leakage changes over temperature, what typical leakages are, and how changing the reverse voltage impacts leakage. Based on the limited specifications it may be difficult to accurately predict error.

   a. True.

   b. False.

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Question 3, true of false. TVS diode data sheets typically do not provide information on how leakage changes over temperature, what typical leakages are, and how changing the reverse voltage impacts leakage. Based on the limited specifications it may be difficult to accurately predict error.

Questions: Protecting RTD input Delta-Sigma

3. (T/F) TVS diode data sheets typically do not provide information on how leakage changes over temperature, what typical leakages are, and how changing the reverse voltage impacts leakage. Based on the limited specifications it may be difficult to accurately predict error.

   a. True.

   b. False.

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The correct answer is "a. True". TVS data sheets typically provide information on maximum room temperature leakage at the standoff voltage, and this may not be sufficient information to accurately predict error.

Thanks for your time!