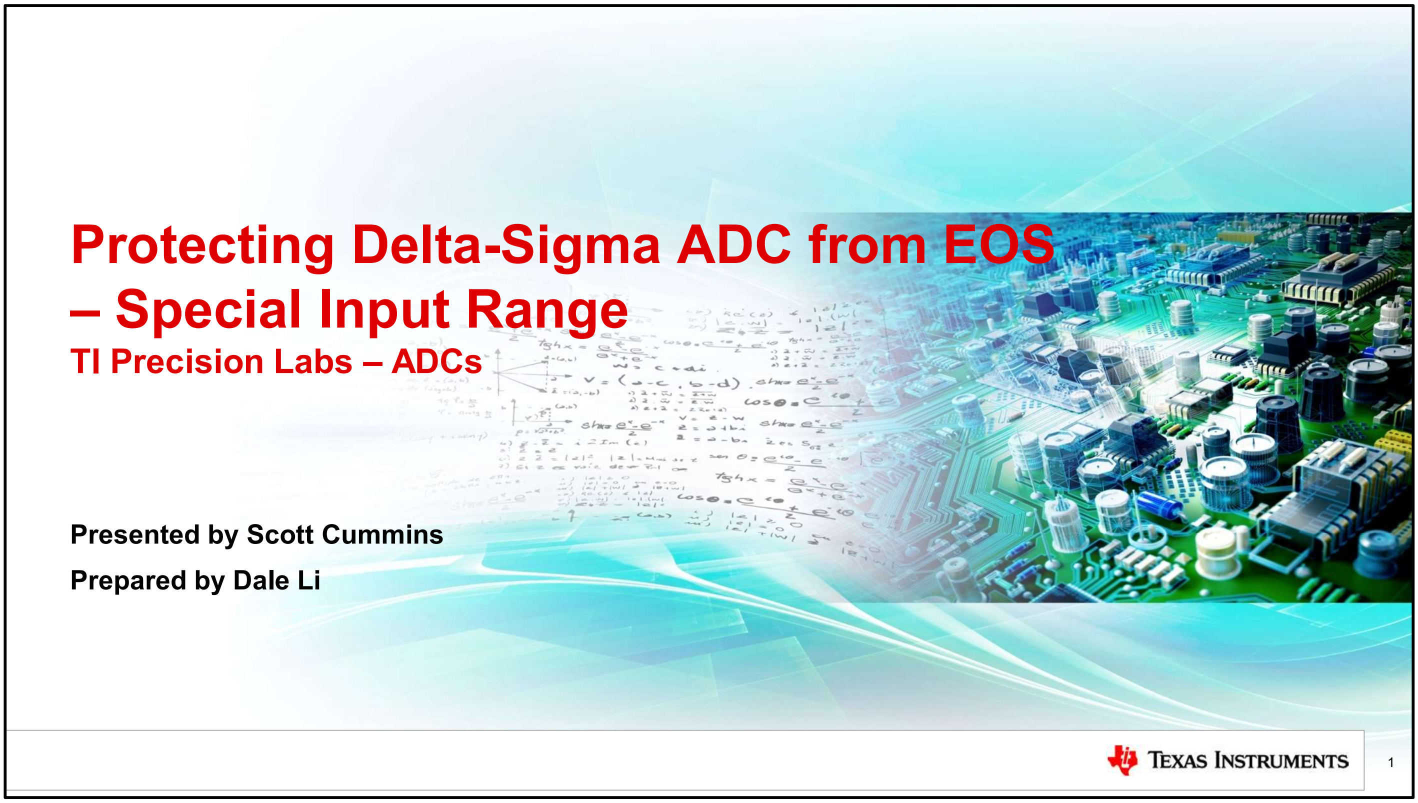
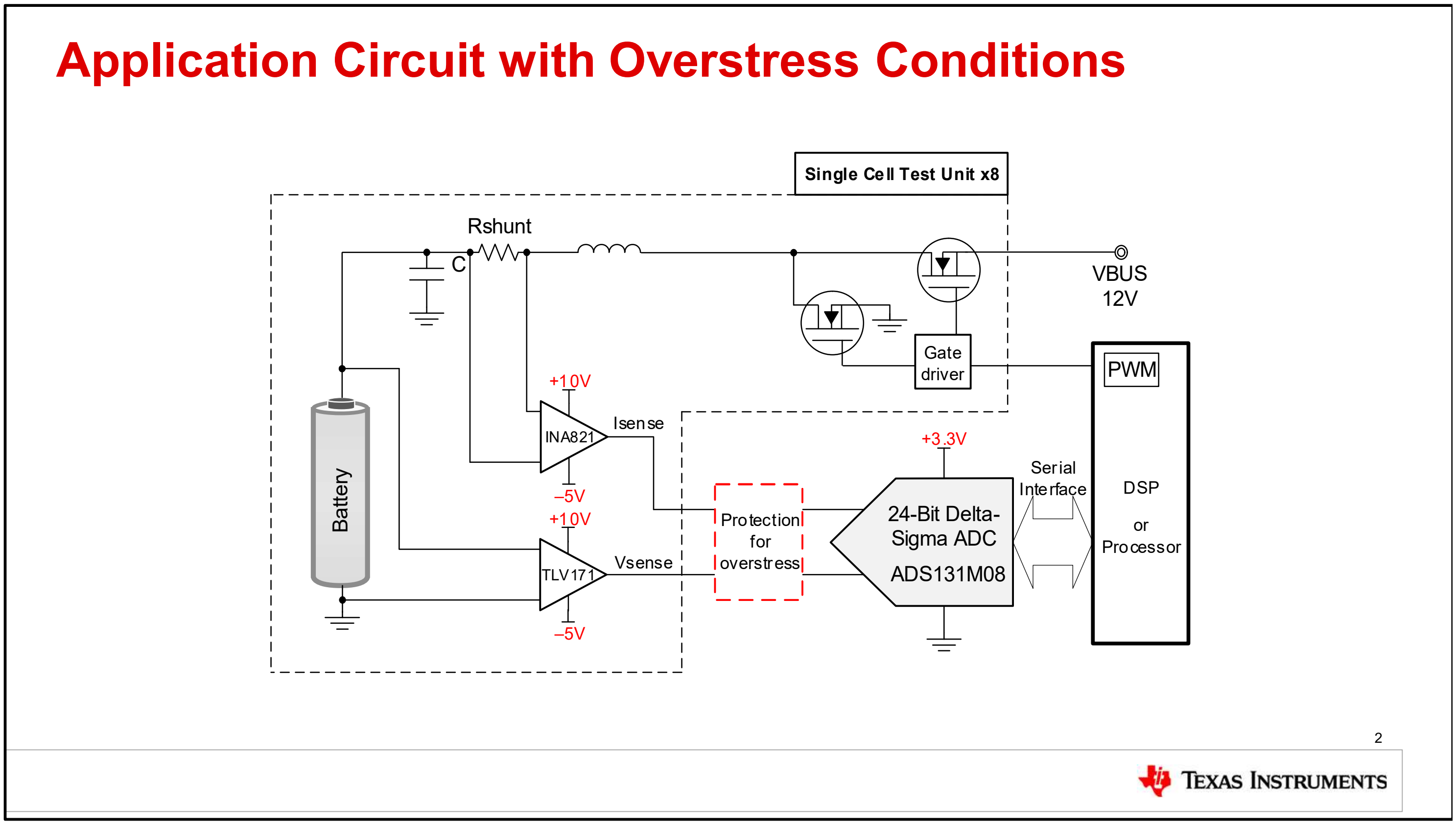


Hello, and welcome to the TI Precision Labs on protection of RTD measurement systems. In the last several videos we covered the protection of a delta-sigma converter used in RTD measurements. In this video we cover another example where a delta-sigma converter is used in battery monitoring solutions. The objective here is to provide additional case study examples. The general techniques covered in these case studies can be adapted to many different topologies.



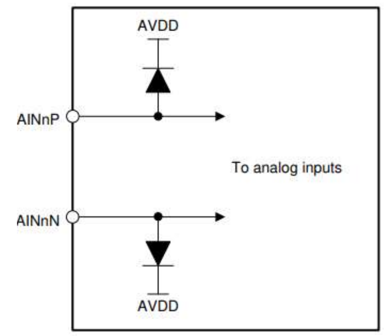
This slide shows the block diagram for the general battery monitoring system that we need to protect. In summary this circuit measures the current and voltage across the battery using an instrumentation amplifier and an op amp. The goal of this presentation is to design the protection circuit represented as a box at the input of the ADS131M08 analog to digital converter.

Abs Max Ratings and Recommended Operating Conditions

ADS131M08/M06/M04/M02:

Abs Maximum Ratings	MIN	MAX	UNIT
Analog Input - AINP/AINN	**AGND - 1.6**	**AVDD + 0.3**	**V**
AVDD/DVDD to AGND/DGND	- 0.3	3.9	V
Reference Input Voltage	AGND - 0.3	AVDD + 0.3	V
Digital Input Voltage	DGND - 0.3	DVDD + 0.3	V
Input Current	- 10	+ 10	mA

Recommended Operating	MIN	MAX	UNIT
Absolute Input Voltage - AINP/AINN	**AGND - 1.3**	**AVDD**	**V**
AVDD/DVDD to AGND/DGND	2.7	3.6	V
Reference Input Voltage	1.1	1.3	V



Input ESD Protection Circuity

(1) Operation outside the *Absolute Maximum Ratings* may cause permanent device damage. *Absolute Maximum Ratings* do not imply functional operation of the device at these or any other conditions beyond those listed under *Recommended Operating Conditions*. If used outside the *Recommended Operating Conditions* but within the *Absolute Maximum Ratings*, the device may not be fully functional, and this may affect device reliability, functionality, performance, and shorten the device lifetime.

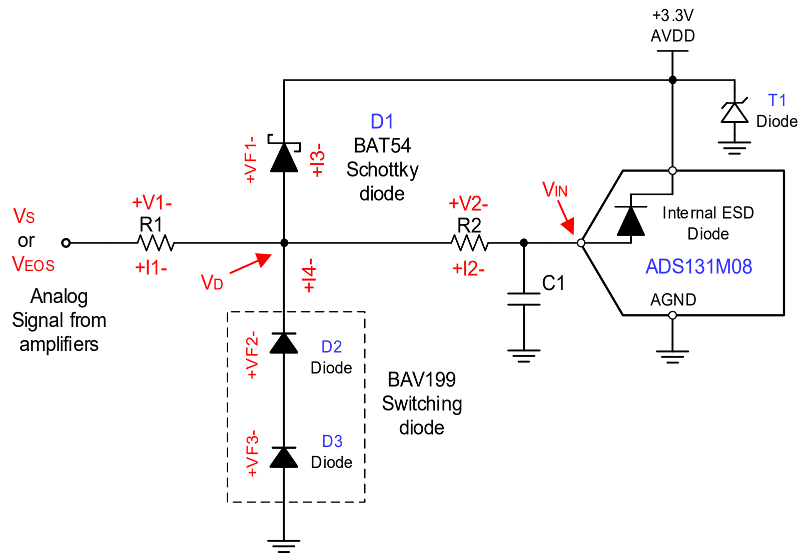
Note: The same protection technique on following slides can be used for ADS131B04-Q1, ADS131A02, ADS131A04 because they have same or similar input ESD structure and input ranges.

Here are the absolute maximum ratings and recommended operating conditions of the ADS131M08. Notice that this device has somewhat unusual ESD input protection. It uses a single diode to AVDD, but does not have a diode to GND. The reason the negative supply does not have a diode is that the input can actually go 1.3V below GND. A traditional diode clamp would not allow for this range. The device does have an ESD structure for negative going ESD pulses but this structure cannot be used for in-circuit EOS protection. For this device, the ability to allow input signals below the negative supply is an important feature which is used in many of its target applications.

To protect this circuit we will need to consider the recommended and absolute maximum analog input range. In this case the recommended range can measure 1.3V below ground and the absolute maximum cannot be lower than 1.6V below GND. Ideally, we would build an input clamp that will turn on between -1.3V and -1.6V. Let’s take a look at one possible solution.

Input Protection Solution

- **D_1 Selection – BAT54 (Selected):**
  - Lower forward voltage, leakage current and capacitance.
- **T_1 – TVS diode:**
  - Recommended for power supply clamp as the power supply may not be able to sink the fault current.
- **D_2 and D_3 Selection – BAV199:**
  - BAV199: typical 0.9V forward voltage, a dual diode with 2 diodes.



Vs: normal operation signal.
VEOS: electrical overstress signal.

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Here is the protection circuit for the ADS131M08. D1 is a traditional positive clamp which will turn on when the input is above 3.3V. A Schottky BAT54 was used as it has a low forward voltage and relatively low leakage. T1 is a TVS diode that will absorb transients directed through D1 to the positive supply. Keep in mind that the LDO that is supplying the 3.3V cannot sink large transient currents. D2 and D3 are placed in series to create a clamp that typically drops 0.9V. Thus this will allow the input voltage to swing about 0.9V below ground before turning on. On the previous slide we saw that the recommended input range should allow for signals to go 1.3V below ground, so it seems that it would be better to choose a device with a higher forward drop. But we will see in the next few slides that it is very difficult to find a diode that will remain fully off inside the normal operating range but turn on before the absolute maximum voltage.

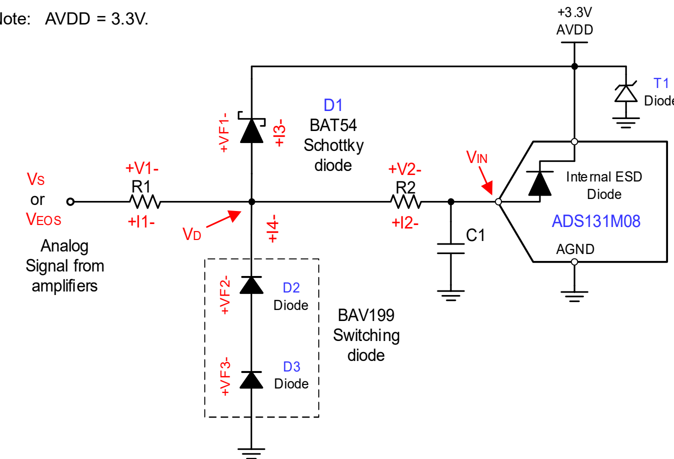
Understanding the Protection Scheme

INA821 Maximum Output Ratings:	
Output voltage range (Vo)	$-5V \le V_O \le +10V$
Short-circuit current (I_{SC})	$-20mA \le V_O \le +20mA$
TLV171 Maximum Output Ratings:	
Output voltage range (Vo)	$-5V \le V_O \le +10V$
Short-circuit current (I_{SC})	$-35mA \le V_O \le +25mA$

ADS131M08 Absolute Maximum Ratings:			
	Min	Max	Unit
Analog Input	- 1.6	+ 3.6	V
Input Current	- 10	+ 10	mA

Note: AVDD = 3.3V.

- **Normal Operation:**
  - Reverse-Biased on D_1, D_2 and D_3.
- **Positive EOS: $V_D > +3.3V$**
  - Forward-Biased on D_1.
  - Reverse-Biased state on D_2 and D_3.
- **Negative EOS: $V_D < 0V$**
  - Forward-Biased on D_2 and D_3.
  - Reverse-Biased state on D_1.



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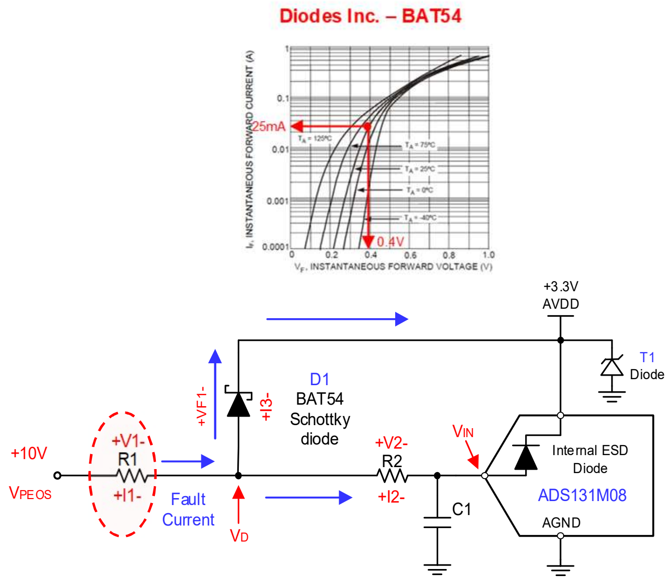
Recall from the first slide that the ADC inputs are driven by two different amplifiers: the INA821 and the TLV171. The output range of the amplifiers corresponds to the worst case fault signals that the ADC will see. For both amplifiers the output voltage range is from -5V to +10V, and the maximum output currents are at most 35mA. The amplifier specification “short circuit current” is always the maximum output current that an amplifier can supply. These currents and voltage ranges will be used in the next few slides to select the resistor values for R1 and R2. Note that under normal operation all the diodes are reverse biased. For positive EOS D1 will turn on and direct the EOS event to T1. For negative EOS events D2 and D3 will turn on and limit the input voltage to about -0.9V.

Select R_1 for Positive EOS



Parameters known:		
1	I_1 (TLV171)	$-35mA \sim +25mA$ (I_{SC})
2	V_{EOS} (TLV171)	$-5V \sim +10V$ (V_O)
3	I_2 (ADC Input)	$\pm 10mA$ ($I_{ADC\_IN\_ABS}$)
4	V_{IN} (ADC Input)	$-1.6V \sim +3.6V$ (V_{ADC_IN})
Select R_1 for Positive EOS:		
1	I_1	$I_{1\_POS} = I_{SC\_MAX} = 25mA$
2	V_F (BAT54)	$V_{F1} = 0.4V$ (Selected at 25mA)
3	R_1 (Minimum)	$R_{1\_P} = \frac{V_{EOS\_MAX} - V_{F1} - AVDD}{I_{1\_POS}} = \frac{10V - 0.4V - 3.3V}{25mA} = 252\Omega$

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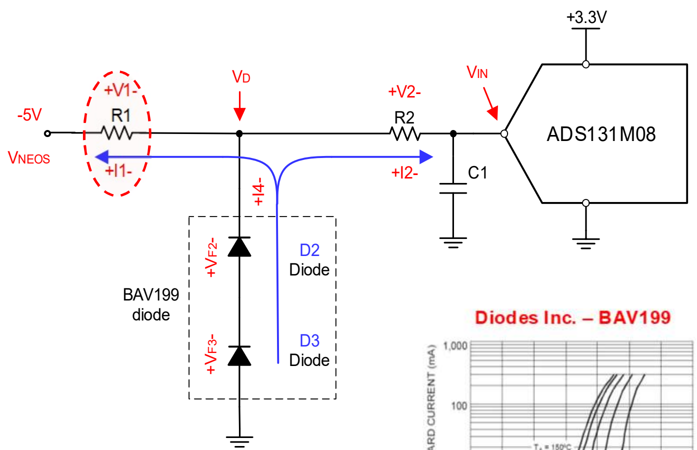
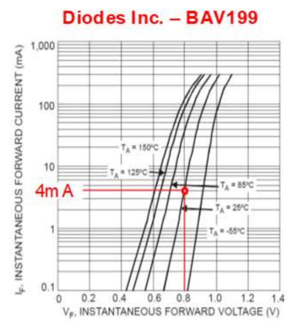
In this slide we will select a value for R1 for positive EOS events. Before finding R1 we collect all the important overstress parameters. First we determine the worst case fault currents that R1 will see. These currents are taken from the amplifier short circuit current specifications. Next we consider the worst case voltages that will be applied in an EOS condition. In this case it is the amplifier maximum output range. Finally we get the absolute maximum ADC input specifications.

To find the value for R1 we need an accurate diode voltage drop. The drop depends on the current flow in the diode. The curves for the BAT54 are used with the maximum current to determine the maximum diode drop of 0.4V. The voltage across R1 is calculated by subtracting the diode and supply voltage from the input fault voltage. The resistor voltage is then divided by the fault current to find a minimum value for the series limiting resistor. Increasing this resistor will make the circuit more robust but will add noise and increase leakage current errors.

Select R_1 for Negative EOS





Parameters known:		
1	I_1 (TLV171)	$-35mA \sim +25mA$ (I_{SC})
2	V_{EOS} (TLV171)	$-5V \sim +10V$ (V_O)
3	I_2 (ADC Input)	$\pm 10mA$ ($I_{ADC\_IN\_ABS}$)
4	V_{IN} (ADC Input)	$-1.6V \sim +3.6V$ (V_{ADC_IN})
Select R_1 for Negative EOS:		
1	V_F (BAV199)	$V_{F2} = V_{F3} = 0.8V$ (Selected as half of $V_{ADC\_IN\_MIN}$)
2	I_1	$I_{1\_NEG} = -I_{SC\_MAX} = -4mA$ (Check BAV199's curve)
3	R_1 (Minimum)	$R_{1\_N} = \frac{V_{EOS\_MIN} - (-V_{F2} - V_{F3})}{I_{1\_NEG}} = \frac{-5V - (-0.8V - 0.8V)}{-4mA} = 850\Omega$
4	**Select R_1 = 1kΩ**	
Resistor Power Rating Check:		
6	$P_{R1} = \frac{(V_{EOS\_MAX} - V_{F1} - AVDD)^2}{R_1} = \frac{(10V - 0.4V - 3.3V)^2}{1k\Omega} = 39.69mW$	

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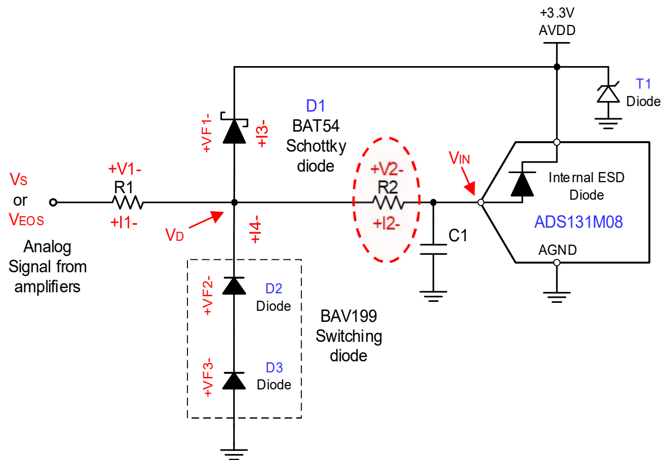
Here we perform the same calculation as in the previous slide but for negative EOS events. For a negative fault the diodes D2 and D3 will turn on. This procedure yields a slightly different minimum value for R1. For the positive fault R1 was 252 ohms and for the negative fault the resistor is 850 ohms. Choose the largest of the two resistors and round up for margin. In this case we selected 1kohm for the limiting resistor.

Select R_2



Parameters known:		
1	I_1 (TLV171)	$-35mA \sim +25mA$ (I_{SC})
2	V_{EOS} (TLV171)	$-5V \sim +10V$ (V_O)
3	I_2 (ADC Input)	$\pm 10mA$ ($I_{ADC\_IN\_ABS}$)
4	V_{IN} (ADC Input)	$-1.6V \sim +3.6V$ (V_{ADC_IN})
Select R_2 for Positive EOS:		
1	I_2 (Target)	$I_{2\_POS} = \pm 1mA < I_{ADC\_IN\_ABS}$
2	R_2 (Minimum)	$R_{2\_P} = \frac{(V_{F1} + AVDD) - V_{IN\_MAX}}{I_{2\_POS}} = \frac{(0.4V + 3.3V) - 3.6V}{1mA} = 100\Omega$
Select R_2 for Negative EOS:		
3	It's not critical because V_D is designed to be equal to the $V_{ADC\_IN\_MIN}$ (-1.6V) for a negative EOS, so I_{2_NEG} = 0mA.	
4	**Select R_2 = 100Ω**	
Resistor Power Rating Check:		
6	$P_{R2} = \frac{(V_{F1} + AVDD - V_{IN\_MAX})^2}{R_2} = \frac{(0.4V + 3.3V - 3.6V)^2}{100\Omega} = 0.1mW$	

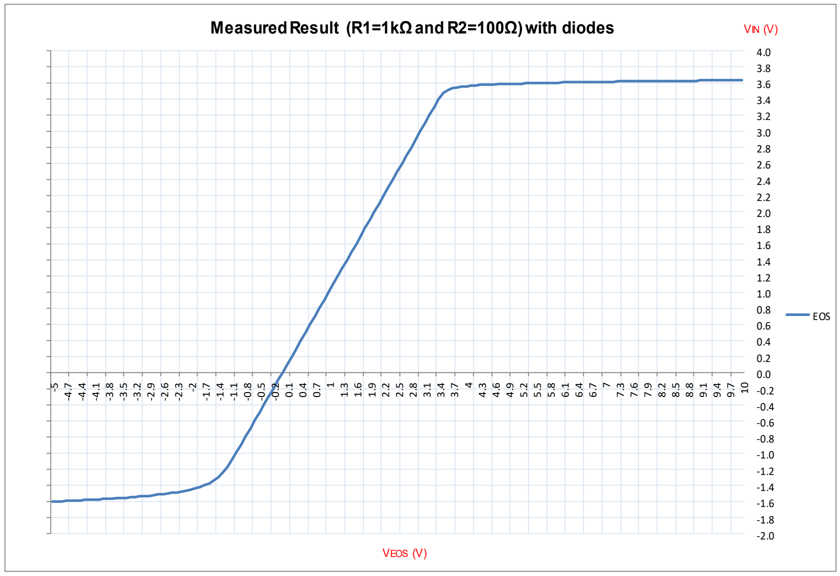
Texas Instruments

The last step is to select a value for R2. This resistor limits the input current to the ADC to +/-1mA. A similar calculation is used for R2 and the value is determined to be 100 ohms.

Overstress Signal Clamp Check on ADC Input

ADS131M08 Absolute Maximum Ratings:			
	Min	Max	Unit
Analog Input	- 1.6	+ 3.6	V
Input Current	- 10	+ 10	mA

Recommended Operating			
	MIN	MAX	UNIT
Analog Input	- 1.3	3.3	V



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This slide shows measured results for the diode clamp circuit. The circuit works well for protection as the clamp limits the input voltage to less than the absolute maximum rating for the ADC. On the other hand, recall that the operating range of the ADC extends to -1.3V. This circuit will begin to turn on at approximately -0.9V so some error will be introduced below -0.9V input signal.

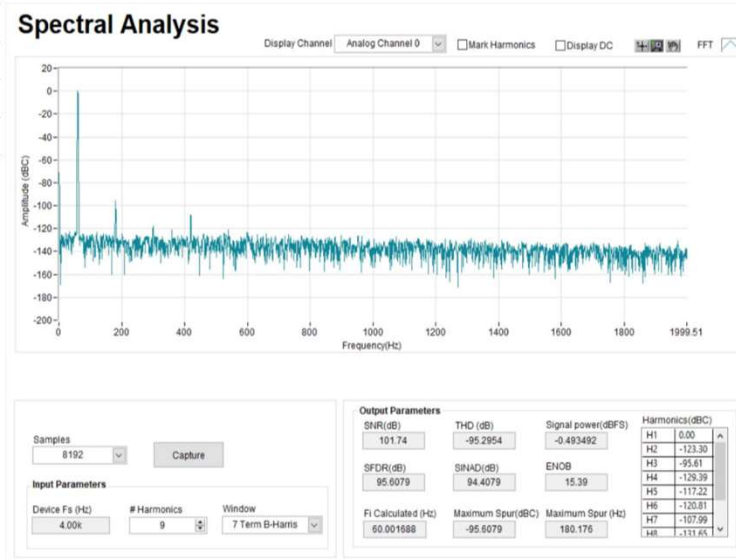
SNR & THD Performance Check

ADS131M08 AC Performance Measured on Hardware:			
	Test 1	Test 2	Unit
SNR	**101.7**	**101.9**	dB
THD	**- 95.3**	**- 95.2**	dB

Test condition:

Test 1: R1 = 1kΩ, R2 = 100Ω with BAT54 (D1) and BAV199 (D2 and D3).

Test 2: R1 = 1kΩ, R2 = 100Ω without BAT54(D1) and BAV199 (D2 and D3).



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Here we test the input protection to show that the input diodes have minimal impact on performance. Test 1 illustrates performance with the protection diodes and test 2 illustrates performance without the diodes. You can see that some distortion is introduced by the diodes but it is minimal.

Accuracy Performance Check

Measurements at Room Temperature (25°C)

Vs (V)	Measured Vs (V)	Conversion Code	Uncalibrated Vs (V)	Voltage Error without Calibration (%)	Voltage Error with Calibration (%)
1.14	1.139898	7913462	1.132030	0.690	0.000
1.0	0.999916	6941921	0.993050	0.687	0.002
0.8	0.799941	5553901	0.794492	0.681	0.003
0.5	0.499973	3471737	0.496636	0.667	0.004
0.05	0.050034	348389	0.049837	0.393	0.000
0	0.000043	1068	0.000153	–	–
–0.05	–0.049958	–345711	–0.049454	1.008	0.000
–0.5	–0.499903	–3469100	–0.496259	0.729	0.003
–0.8	–0.799879	–5551380	–0.794131	0.719	0.004
–1.0	–0.999867	–6939513	–0.992705	0.716	0.003
–1.14	–1.139845	–7910985	–1.131675	0.717	0.000

Note: the calibration is two point calibration.

Finally, this slide shows the results of a DC linearity sweep. The circuit has some inherent gain error, but when an end point calibration is performed the overall error is very low as a percentage. Note that the input range is limited to about
-1.14V as driving the input signal lower will begin to turn on the external protection diodes D2 and D3.

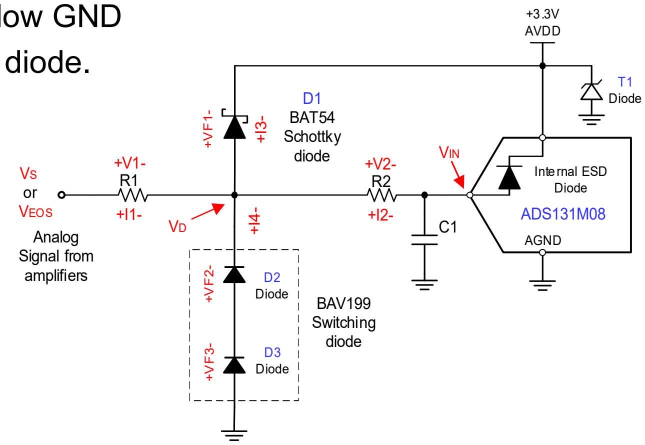
Thanks for your time!
Please try the quiz.

TEXAS INSTRUMENTS 12

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. For the circuit below, why is a series diode circuit used to protect negative faults?
   a. To increase the current rating of the diode.
   b. To allow a small negative swing below GND
   c. To increase the power rating of the diode.
   d. For lower noise.



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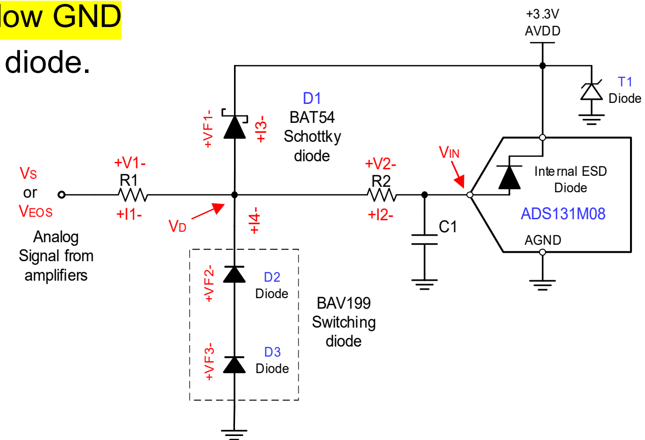
Question 1, For the circuit below, why is a series diode circuit used to protect against negative faults?

Questions: Protecting Low Voltage ADC

1. For the circuit below, why is a series diode circuit used to protect negative faults?
   a. To increase the current rating of the diode.
   b. To allow a small negative swing below GND
   c. To increase the power rating of the diode.
   d. For lower noise.



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The correct answer is “b To allow a small negative swing below GND”. This particular ADC allows input swing below GND so it does not have a traditional internal ESD diode.

Thanks for your time!

TEXAS INSTRUMENTS