AN90031

Zener diodes - physical basics, parameters and application examples

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Document information

Information	Content
Keywords	Zener voltage, voltage stabilizer, leakage current
Abstract	This application note explains the key parameters of Zener diodes and their testing methods. Application examples for these components are included.

1. Introduction

When biased in the forward direction Zener diodes have the same characteristic as a silicon p-n diode. Most important for Zener diode applications is the characteristic when biased in the reverse direction, where Zener diodes have a small leakage current below a specific breakdown voltage. Above the breakdown voltage, the I-V characteristic shows a steep increase of current. Zener diodes can operate constantly as voltage stabilizers at or above the breakdown voltage, V_Z. These components are produced for many different voltages with guaranteed small ranges for V_Z tested at a defined reverse current I_Z. Fig. 1 shows common symbols for a zener diode.

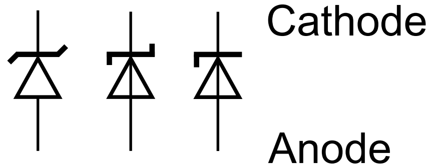


Fig. 1. Symbols for a Zener diode

Fig. 2 shows an example of the I-V curve of a Zener diode. For positive voltages the diode is in forward conduction. Current increases quite steeply if about 0.7 V is exceeded. In reverse direction an area is depicted where the diode is blocking. Once the breakdown voltage is reached, current increases significantly. The voltage drop across the diode is kept almost constant in this area. An ideal Zener diode would keep V_Z constant independent on the current. In practice however the curve is not perpendicular but there is a dynamic resistance $R_{dyn} = \Delta V_Z / \Delta I_Z$ larger than zero.

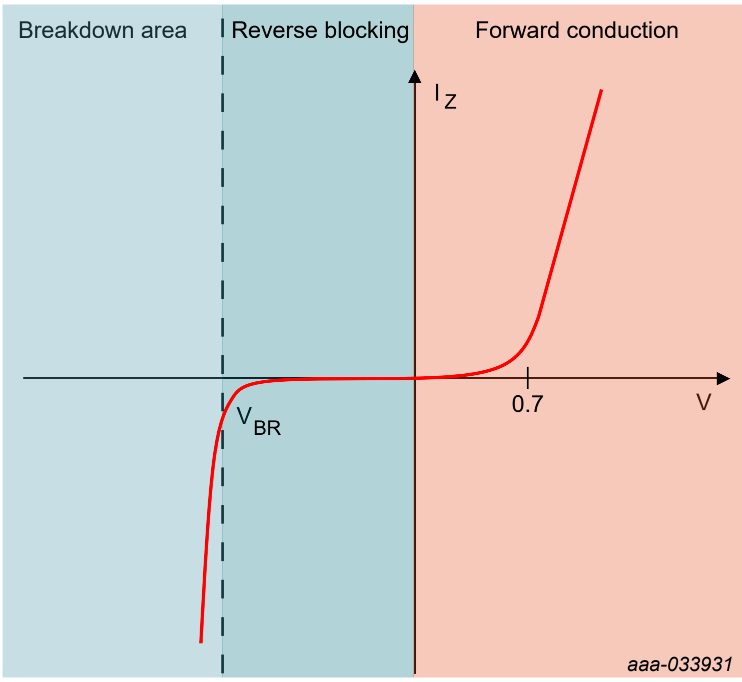


Fig. 2. I-V characteristic of a Zener diode

Zener diodes for voltages up to about 5 V are realized with highly doped substrates. For such p-n diodes an electrical breakdown occurs if electrons can tunnel from the valence band into the conduction band across the depletion area of the reverse biased junction. The free charge carriers create a sudden increase of the reverse current once the field strength is high enough.

Clarence Melvin Zener discovered the above described effect in 1934 and the diodes produced have been named after him. For Zener diodes with a breakdown voltage higher than 5 V, a different breakdown effect becomes dominant. This is the avalanche breakdown, which is different from the above discussed Zener effect. The electrical field across the p-n junction accelerates electrons in the transition area. These electrons create electron-hole pairs. Holes move to the negative electrode and get filled again, whereas the electrons move to the positive electrode. This motion of holes and electrons create a leakage current through a negative biased diode. With high field strength the mobile holes and electrons can generate more charge carriers by freeing up adjacent bound electrons. This process of generating more charge carries happens to the extent of an avalanche, so that a high current starts to flow if a specific reverse voltage is exceeded.

Both effects, the Zener effect and the avalanche effect, are not distinguished for the naming of Zener diodes. No matter which physical effect dominates the breakdown of the p-n junction, all voltage reference diodes are referred to as Zener diodes.

2. Data sheet parameters

Nexperia data sheets for Zener diodes generally cover a series of products, with each type number having a specified working voltage. These data sheets start with a section “General description” where the package type is given. The following section “Features and benefits” mentions the working voltage range. For Zener diodes that are offered with different tolerance selections of V_Z, which is the nominal working voltages, this information is provided as well.

The chapter “Quick reference data” contains a table with the maximum forward voltage V_F at a forward current I_F = 10 mA and ambient temperature T_{amb} = 25 °C. In order to avoid significant self-heating this parameter is tested in pulsed mode. The maximum total power dissipation P_{tot} is also given, together with the description of the related mounting condition. Table 1 below is an example from the data sheet of BZX884S[1].

Table 1. BZX884S Quick reference data

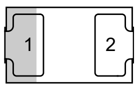
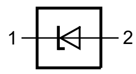
T_{amb} = 25 °C unless otherwise specified.

Symbol	Parameter	Conditions		Min	Typ	Max	Unit
V_F	forward voltage	I_F = 10 mA	[1]	-	-	0.9	V
P_{tot}	total power dissipation		[2]	-	-	365	mW

[1] Pulse test: tp ≤ 100 µs; δ ≤ 0.02
[2] Device mounted on a FR4 PCB, single-sided 70 µm copper, tin-plated and standard footprint.

Table 2 gives the pinning of the Zener diode. As for other diodes, the cathode is clearly marked with a bar in order to safeguard proper mounting in the desired direction. Table 3 is the ordering information with the type number, exact name, description and version of the package.

Table 2. BZX884S Pinning

Pin	Symbol	Description	Simplified outline	Graphic symbol
1	K	cathode[1]	 Transparent top view	 006aaa152
2	A	anode		

[1] The marking bar indicates the cathode.

Table 3. Ordering information

Type number	Package		
	Name	Description	Version
BZX884S series [1]	DFN1006BD-2	Leadless ultra small plastic package with side-wettable flanks (SWF); 2 terminals; 0.65 mm pitch; 1 mm x 0.6 mm x 0.47 mm body	SOD882BD

[1] The series includes 37 breakdown voltages with nominal working voltages from 2.4 V to 75 V and ±2 % and approximately ±5% tolerances.

The next data sheet chapter is named “Marking” and contains a Marking code table, (Table 4). All the available products with different working voltages in the two tolerance clusters are listed together with the marking code.

The naming of later generation Zener diodes is quite easy to interpret. At the beginning the Zener diode family name can be found. In the given example *BZX884S*. This is followed by a character for the tolerance. An indicator “B” stands for 2% tolerance, the character “C” for about 5%. Nexperia introduced a larger portfolio of Zener diodes with an “A” tolerance rating for the V_Z, which means 1% accuracy in order to address a growing demand for higher precision. Diodes in packages SOT23, SOD323 and SOD123F can be chosen. After the tolerance indicator, the working voltage is added, e.g. 2V4 for V_Z = 2.4 V. Integer voltage ratings show a number with no "V" as separator.

Table 4. Marking Codes

Type number	Mark. Code	Type number	Mark. Code	Type number	Mark. Code	Type number	Mark. Code
BZX884S-B2V4	2A	BZX884S-B15	2U	BZX884S-C2V4	4K	BZX884S-C15	4C
BZX884S-B2V7	2B	BZX884S-B16	2V	BZX884S-C2V7	4L	BZX884S-C16	4D
BZX884S-B3V0	2C	BZX884S-B18	2W	BZX884S-C3V0	4R	BZX884S-C18	4E
BZX884S-B3V3	2D	BZX884S-B20	2X	BZX884S-C3V3	4S	BZX884S-C20	4F
BZX884S-B3V6	2E	BZX884S-B22	2Y	BZX884S-C3V6	4T	BZX884S-C22	4G
BZX884S-B3V9	2F	BZX884S-B24	2Z	BZX884S-C3V9	4U	BZX884S-C24	4H
BZX884S-B4V3	2G	BZX884S-B27	3A	BZX884S-C4V3	4U	BZX884S-C27	4J
BZX884S-B4V7	2H	BZX884S-B30	3B	BZX884S-C4V7	4Y	BZX884S-C30	4M
BZX884S-B5V1	2J	BZX884S-B33	3C	BZX884S-C5V1	5B	BZX884S-C33	4N
BZX884S-B5V6	2K	BZX884S-B36	3D	BZX884S-C5V6	5C	BZX884S-C36	4P
BZX884S-B6V2	2L	BZX884S-B39	3E	BZX884S-C6V2	5F	BZX884S-C39	4Q
BZX884S-B6V8	N3	BZX884S-B43	3F	BZX884S-C6V8	5G	BZX884S-C43	4V
BZX884S-B7V5	2M	BZX884S-B47	3G	BZX884S-C7V5	5J	BZX884S-C47	4W
BZX884S-B8V2	2N	BZX884S-B51	3H	BZX884S-C8V2	5K	BZX884S-C51	4Z
BZX884S-B9V1	2P	BZX884S-B56	3J	BZX884S-C9V1	5L	BZX884S-C56	5A
BZX884S-B10	2Q	BZX884S-B62	3K	BZX884S-C10	3Y	BZX884S-C62	5D
BZX884S-B11	2R	BZX884S-B68	3L	BZX884S-C11	3Z	BZX884S-C68	5E
BZX884S-B12	2S	BZX884S-B75	3M	BZX884S-C12	4A	BZX884S-C75	5H
BZX884S-B13	2T	-	-	BZX884S-C13	4B	-	-

2.1. Limiting values

Table 5 contains the Limiting values. The maximum forward current I_F is defined as well as the maximum total power dissipation P_{tot}, followed by the maximum junction temperature T_j and the allowed temperature ranges for ambient T_{amb} and storage T_{stg}.

Table 5. BZX884S Limiting values

In accordance with the Absolute Maximum Rating System (IEC 60134).

Symbol	Parameter	Conditions		Min	Max	Unit
I_F	forward current			-	200	mA
P_{tot}	total power dissipation	T_{amb} = 25 °C	[1]	-	365	mW
T_j	junction temperature			-	150	°C
T_{amb}	ambient temperature			−55	+150	°C
T_{stg}	storage temperature			−65	+150	°C

[1] Device mounted on a FR4 PCB, single-sided 70 µm copper, tin-plated and standard footprint.

2.2. Thermal characteristics

Table 6 provides the $R_{th(j-a)}$ value for the device mounting on a standard footprint, single-sided PCB with 70 µm copper plating. This value could also be calculated with (150 K - 25 K)/0.365 W.

Table 6. BZX884S Thermal characteristics

Symbol	Parameter	Conditions		Min	Typ	Max	Unit
$R_{th(j-a)}$	thermal resistance from junction to ambient	in free air	[1]	-	-	340	K/W

[1] Device mounted on a FR4 PCB, single-sided 70 µm copper, tin-plated and standard footprint.

2.3. Characteristics

In Table 7 “Characteristics”, the maximum forward voltage drop at I_F of 10 mA is given, this is tested in pulsed mode.

Table 7. BZX884S Characteristics

T_j = 25 °C unless otherwise specified.

Symbol	Parameter	Conditions		Min	Typ	Max	Unit
V_F	forward voltage	I_F = 10 mA	[1]	-	-	0.9	V

[1] Pulse test: $t_p \leq 300$ µs; $\delta \leq 0.02$.

Table 8 and Table 9 list several very important parameters of the Zener diodes. The first column is the name extension, followed by a column for the accuracy ranges provided per diode. The 3rd column informs the minimum and maximum V_Z values at a reverse current of 5 mA for V_Z < 27 V. Above and equal V_Z = 27 V the testing current is reduced to 2 mA as otherwise the power dissipation would become quite high with $P = V_Z * I_Z$ in case of a high breakdown voltage. Additional operating cases are tested in mass production to ensure that the whole $V_Z – I_Z$ curve is correct in the reverse blocking area as well as in the forward conduction and the breakdown areas.

The differential resistance is defined as $r_{dif} = \Delta V_Z / \Delta I_Z$ and listed in the fourth column. This is the steepness of the $V_Z – I_Z$ curve. Ideal would be a dynamic resistance of 0 Ohm or a perpendicular curve. In this case V_Z would not change with reverse current and the breakdown voltage would stay stable, independent of the current applied.

The maximum reverse or leakage current is given in the next column, this is specified at about 2/3 of V_{BR}.

The next column contains the thermal coefficient S_Z in mV/K valid for an I_Z of 5 mA or . The breakdown voltage dependent on junction temperature can be calculated with the simple formula below:

$$V_Z = V_{Z(nominal)} + S_Z \times (T_j - 25\ °C) \tag{1}$$

For low voltage zener diodes S_Z is a negative coefficient, so V_Z decreases over temperature. The breakdown mechanism is the Zener effect. Above about 6 V the sign of S_Z changes and the avalanche effect becomes dominant.

Finally, there is a column for the diode capacitance C_d tested at V_R = 0 V and f = 1 MHz.

Table 8. Characteristics per type; BZX884S-B2V4 to BZX884S-C24

T_j = 25 °C unless otherwise specified.

BZX884S	Sel	Working voltage V_Z (V)		Differential resistance r_{dif} (Ω)				Reverse current I_R (µA)		Temperature coefficient S_Z (mV/K)		Diode capacitance C_d (pF) [1]
		I_Z = 5 mA		I_Z = 1 mA		I_Z = 5 mA				I_Z = 5 mA		
		Min	Max	Typ	Max	Typ	Max	Max	V_R (V)	Min	Max	Max
2V4	B	2.35	2.45	275	600	70	100	50	1.0	-3.5	0.0	450
	C	2.20	2.60									
2V7	B	2.65	2.75	300	600	75	100	20	1.0	-3.5	0.0	450
	C	2.50	2.90									
3V0	B	2.94	3.06	325	600	80	95	10	1.0	-3.5	0.0	450
	C	2.80	3.20									
3V3	B	3.23	3.37	350	600	85	95	5	1.0	-3.5	0.0	450
	C	3.10	3.50									
3V6	B	3.53	3.67	375	600	85	90	5	1.0	-3.5	0.0	450
	C	3.40	3.80									
3V9	B	3.82	3.98	400	600	85	90	3	1.0	-3.5	0.0	450
	C	3.70	4.10									
4V3	B	4.21	4.39	410	600	80	90	3	1.0	-3.5	0.0	450
	C	4.00	4.60									
4V7	B	4.61	4.79	425	500	50	80	3	2.0	-3.5	0.2	300
	C	4.40	5.00									
5V1	B	5.00	5.20	400	480	40	60	2	2.0	-2.7	1.2	300
	C	4.80	5.40									
5V6	B	5.49	5.71	80	400	15	40	1	2.0	-2.0	2.5	300
	C	5.20	6.00									
6V2	B	6.08	6.32	40	150	6	10	3	4.0	0.4	3.7	200
	C	5.80	6.60									
6V8	B	6.66	6.94	30	80	6	15	2	4.0	1.2	4.5	200
	C	6.40	7.20									
7V5	B	7.35	7.65	30	80	6	15	1	5.0	2.5	5.3	150

BZX884S	Sel	Working voltage V_Z (V)		Differential resistance r_{dif} (Ω)				Reverse current I_R (μA)		Temperature coefficient S_Z (mV/K)		Diode capacitance C_d (pF) [1]
		I_Z = 5 mA		I_Z = 1 mA		I_Z = 5 mA				I_Z = 5 mA		
		Min	Max	Typ	Max	Typ	Max	Max	V_R (V)	Min	Max	Max
	C	7.00	7.90									
8V2	B	8.04	8.36	40	80	6	15	0.7	5.0	3.2	6.2	150
	C	7.70	8.70									
9V1	B	8.92	9.28	40	100	6	15	0.5	6.0	3.8	7.0	150
	C	8.50	9.60									
10	B	9.80	10.20	50	150	8	20	0.2	7.0	4.5	8.0	90
	C	9.40	10.60									
11	B	10.80	11.20	50	150	10	20	0.1	8.0	5.4	9.0	85
	C	10.40	11.60									
12	B	11.80	12.20	50	150	10	25	0.1	8.0	6.0	10.0	85
	C	11.40	12.70									
13	B	12.70	13.30	50	170	10	30	0.1	8.0	7.0	11.0	80
	C	12.40	14.10									
15	B	14.70	15.30	50	200	10	30	0.05	10.5	9.2	13.0	75
	C	13.80	15.60									
16	B	15.70	16.30	50	200	10	40	0.05	11.2	10.4	14.0	75
	C	15.30	17.10									
18	B	17.60	18.40	50	225	10	45	0.05	12.6	12.4	16.0	70
	C	16.80	19.10									
20	B	19.60	20.40	60	225	15	55	0.05	14.0	14.4	18.0	60
	C	18.80	21.20									
22	B	21.60	22.40	60	250	20	55	0.05	15.4	16.4	20.0	60
	C	20.80	23.30									
24	B	23.50	24.50	60	250	25	70	0.05	16.8	18.4	22.0	55
	C	22.80	25.60									

[1] f = 1 MHz; V_R = 0 V

Table 9. Characteristics per type; BZX884S-B27 to BZX884S-C75

T_j = 25 °C unless otherwise specified.

BZX884S	Sel	Working voltage V_Z (V)		Differential resistance r_{dif} (Ω)				Reverse current I_R (μA)		Temperature coefficient S_Z (mV/K)		Diode capacitance C_d (pF) [1]
		I_Z = 2 mA		I_Z = 0.5 mA		I_Z = 2 mA				I_Z = 2 mA		
		Min	Max	Typ	Max	Typ	Max	Max	V_R (V)	Min	Max	Max
27	B	26.50	27.50	65	300	25	80	0.05	18.9	21.4	25.3	50
	C	25.10	28.90									
30	B	29.40	30.60	70	300	30	80	0.05	21.0	24.4	29.4	50
	C	28.00	32.00									

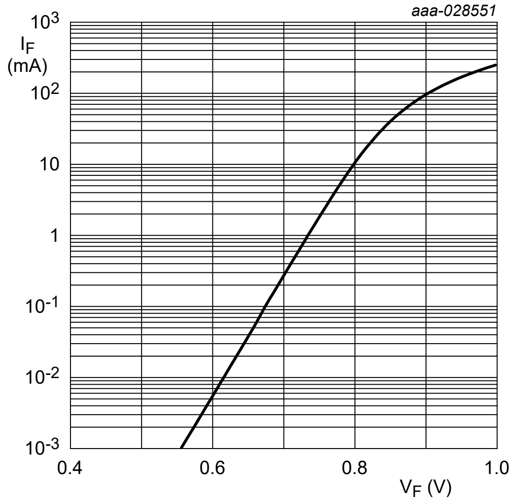
BZX884S	Sel	Working voltage V_Z (V)		Differential resistance r_{dif} (Ω)				Reverse current I_R (μA)		Temperature coefficient S_Z (mV/K)		Diode capacitance C_d (pF) [1]
		I_Z = 2 mA		I_Z = 0.5 mA		I_Z = 2 mA				I_Z = 2 mA		
		Min	Max	Typ	Max	Typ	Max	Max	V_R (V)	Min	Max	Max
33	B	32.30	33.70	75	325	35	80	0.05	23.1	27.4	33.4	45
	C	31.00	35.00									
36	B	35.30	36.70	80	350	35	90	0.05	25.2	30.4	37.4	45
	C	34.00	38.00									
39	B	38.20	39.80	80	350	40	130	0.05	27.3	33.4	41.2	45
	C	37.00	41.00									
43	B	42.10	43.90	85	375	45	150	0.05	30.1	37.6	46.6	40
	C	40.00	46.00									
47	B	46.10	47.90	85	375	50	170	0.05	32.9	42	51.8	40
	C	44.00	50.00									
51	B	50.00	52.00	90	400	60	180	0.05	35.7	46.6	57.2	40
	C	48.00	54.00									
56	B	54.90	57.10	100	425	70	200	0.05	39.2	52.2	63.8	40
	C	52.00	60.00									
62	B	60.80	63.20	120	450	80	215	0.05	43.4	58.8	71.6	35
	C	58.00	66.00									
68	B	66.60	69.40	150	475	90	240	0.05	47.6	65.6	79.8	35
	C	64.00	72.00									
75	B	73.50	76.50	170	500	95	255	0.05	52.5	73.4	88.6	35
	C	70.00	79.00									

[1] f = 1 MHz; V_R = 0 V

Data sheet graphs

Following the characteristic tables a number of graphs are included.

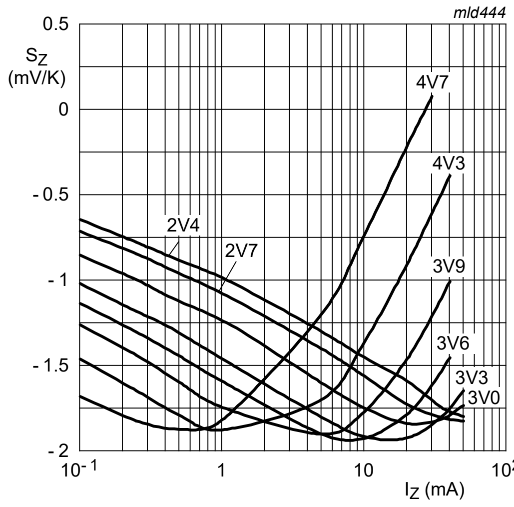
Fig. 3 shows the I–V curve of BZX884S-B/C6V8 for forward direction with a logarithmic scale for I_F



T_j = 25 °C

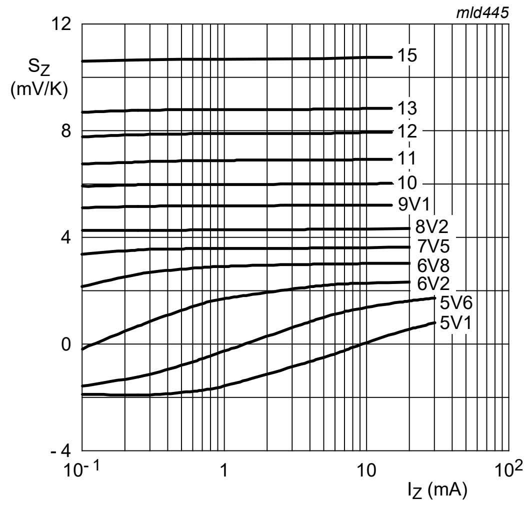
Fig. 3. Forward current as a function of forward voltage, typical values BZX884S-B/C6V8

Fig. 4 depicts how the temperature coefficient S_Z varies over the working current I_Z. For lower working voltages there is a quite significant influence on this coefficient. From Fig. 5 it can be concluded that S_Z becomes almost constant over I_Z for working voltages above 7.5 V.



T_j = 25 °C to 150 °C

Fig. 4. Temperature coefficient as a function of working current; typical values BZX884S-B/C2V4 to B/C4V7

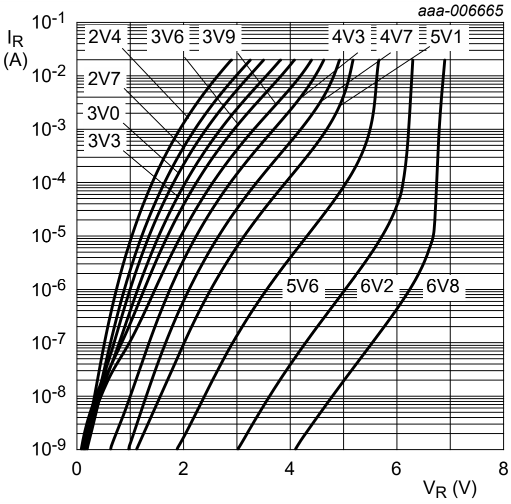


T_j = 25 °C to 150 °C

Fig. 5. Temperature coefficient as a function of working current; typical values BZX884S-B/C5V1 to B/C15

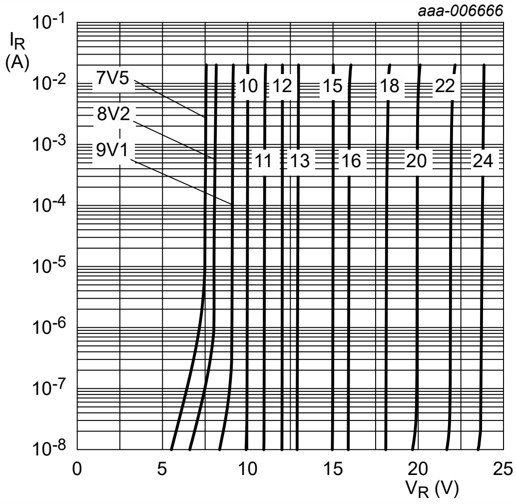
For Zener diodes the I–V characteristic in reverse direction shows how effectively the component can be used to stabilize a voltage. For low Zener voltages, the breakdown voltage increases significantly versus reverse current as Fig. 6 shows. In this diagram the reverse direction I–V curves from 2.4 V up to 6.8 V are depicted.

Fig. 7 and Fig. 8 show the reverse direction characteristics for higher voltage Zener diodes from the BZX884S series. These devices get quite close to an ideal Zener diode which would have a perpendicular I–V characteristic at the nominal V_Z voltage, so reverse current I_Z would not have an impact on the breakdown voltage.



T_j = 25 °C

Fig. 6. Reverse current as a function reverse voltage; typical values (BZX884S-B/C7V5 to B/C24)



T_j = 25 °C

Fig. 7. Reverse current as a function reverse voltage; typical values (BZX884S-B/C27 to B/C75)

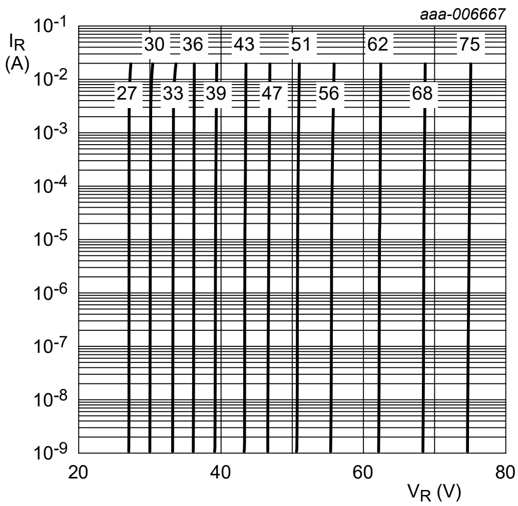


Fig. 8. Reverse current as a function reverse voltage; typical values (BZX884S-B/C7V5 to B/C24)

3. Zener diode application examples

Zener diodes are often used to generate a stabilized voltage. In Fig. 9 a Zener diode ZD1 is connected to a voltage source via a series resistor. The load resistor R_{LOAD} is connected in parallel to the Zener diode. This load could also be a sophisticated electronic circuit requiring a stable supply voltage. The value of series resistor R1 has to be chosen that residual current also flows through the Zener diode with the highest expected load current. The minimum current through the Zener diode should safeguard that the diode operates in the steep region of reverse conduction. The current used for the measurement of V_Z in the data sheet is a good value, this means about 5 mA up to V_Z = 17 V and 2 mA for Zener diodes with high Zener voltages.

The power dissipated in R1 is:

$$\text{R1} = \frac{V_{IN} - V_Z}{I_{Z(min)} + I_{LOAD(max)}} \tag{2}$$

The power dissipated in R1 is:

$$P_{\text{R1}} = \frac{(V_{IN} - V_Z)^2}{\text{R1}} \tag{3}$$

The Zener diode has the maximum power dissipation, if no load is connected. In this case all the current via R1 flows through the diode:

$$P_{\text{ZD1}} = V_Z \times I_Z = V_Z \times \frac{V_{IN} - V_Z}{\text{R1}} \tag{4}$$

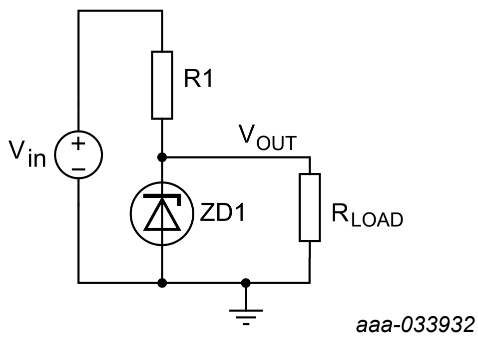


Fig. 9. Voltage Stabilizer with a Zener diode

The basic voltage stabilizer circuit shown in Fig. 9 is used for rather low power requirements. For higher power requirements of a load circuit it is not efficient that the full current through R1 heats up the Zener diode in case that the load is turned off or that much heat is generated if load current consumption drops for a use case. The circuit in Fig. 10 improves this significantly. The Zener diode ZD1 is driven in breakdown via R1. The base of the bipolar transistor Q1 is connected to the stabilized voltage across ZD1.

The output voltage at R_{LOAD} is according to the equation:

$$V_{OUT} = V_Z - V_{BE} \tag{5}$$

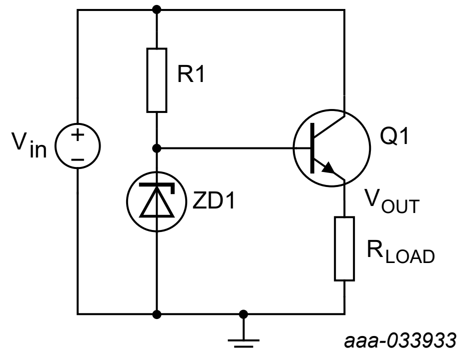


Fig. 10. Voltage Stabilizer with a bipolar transistor and Zener diode voltage reference

Power dissipation in the Zener diode is almost independent from load current if it is assumed that the base current is a small part of the current through R1 only. For output voltages of about 5 V the circuit has a quite good thermal stability because a thermal coefficient of about - 2.0 mV/K is compensated by a decrease of V_{BE} with a very similar coefficient.

Another important application area for Zener diodes is clamping of undesired over-voltages. In Fig. 11 a simple load switch is depicted. The gate oxide of MOSFETs is sensitive to over-voltages. Internal ESD diodes of FETs should not be used for clamping in an application because the gate-source voltage V_{GS} is above data sheet limits in this case. The breakdown voltage of the ESD diode is higher than the specified V_{GS} rating. In the application example a P-channel FET switches the load current. The FET turns on once the gate gets negative voltage against the source. If switch S1 is turned on, the voltage divider of R2 and R1 with ZD1 in parallel define the gate voltage higher than $V_{GS(th)}$. The voltage at the gate is limited by ZD1 to a level which is within the V_{GS} rating of the FET with some safety margin. Gate voltage can be adjusted by a resistor divider without a Zener diode. But in this case the circuit is not safe if V_{IN} sees over-voltage events. The resistor R1 has to be applied for discharge of the gate once the load switch is turned off. S1 is realized with an N-channel control FET or a BJT normally.

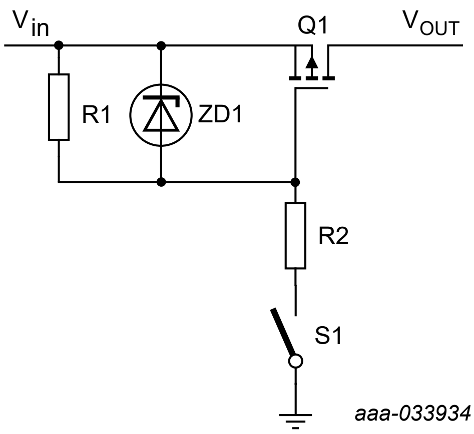


Fig. 11. Load switch with P-Channel FET and Zener diode for gate voltage clamping

Fig. 11 is another solution for protecting a MOSFET. The FET Q1 is switching an inductive load. The inductance has no free-wheeling diode. Once the switch turns off, the current continues to flow. L1 creates a voltage which is high enough to break through the drain-source path of the FET. However, with the zener diode applied between the drain and gate of the FET, the FET can get gate drive so that the V_{DS} rating is not exceeded. The FET runs in linear mode for a short duration and the energy stored in the inductor is dissipated in the FET in a comparably short time. Compared to a simple free-wheeling diode parallel to L1 a higher voltage loss across the drain-source path leads to higher power and faster decay of the stored energy in the inductor.

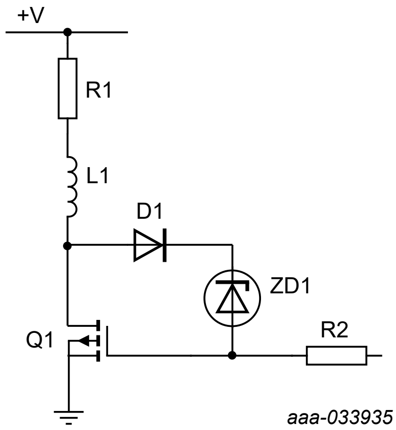


Fig. 12. Protection of a switch for an inductive load with a Zener diode

Zener diodes can be used for all kind of applications where voltage levels have to be clamped or kept below a limit. Fig. 13 shows a level limiter for an AC source. For a sine wave source the maxima and minima are symmetrically clipped to $V_Z + V_F$.

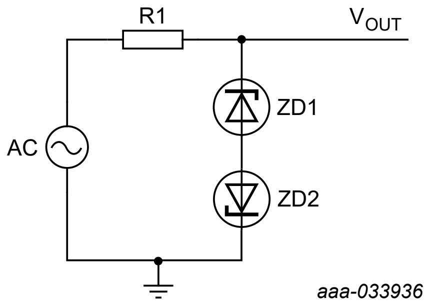


Fig. 13. Example for level clipping of an AC voltage by Zener diodes

Fig. 14 shows a SPICE simulation result of a 1 kHz sine wave voltage source supplied via 220 Ohm to Zener diodes with a V_Z of 5.6 V in a serial structure with connected anodes. It can be seen that the clipping levels are about 0.6 V higher than V_Z as to be expected. In a similar approach Zener diodes are often implemented as ESD and surge pulse protection for signal lines. With the voltage clipping function they avoid excessive over-voltages that could endanger a damage of electronic circuits.

Zener diodes are often used as voltage references. Fig. 15 shows an example where an OP-Amp is used as non-inverting buffer to provide the reference voltage created by the zener diode ZD1 as output voltage with low impedance towards connected electronic loads. The current through the Zener diode can be chosen small compared to the circuit shown in Fig. 9. In order to support such applications with a narrow spread of V_Z at low Zener currents, dedicated low current zener diode families are offered. Instead of 5 mA that are used for standard Zener diodes, these components are selected for 50 µA. If standard Zener diodes are used for low current applications, the parts should be tested upfront, if clamping works as desired.

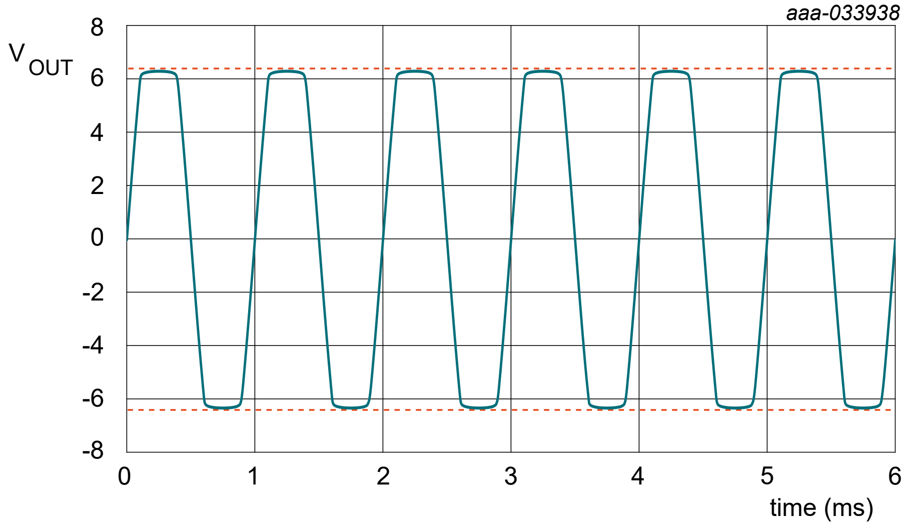


Fig. 14. Symmetrical clipping of 1 kHz sine wave with BZT52H-B5V6

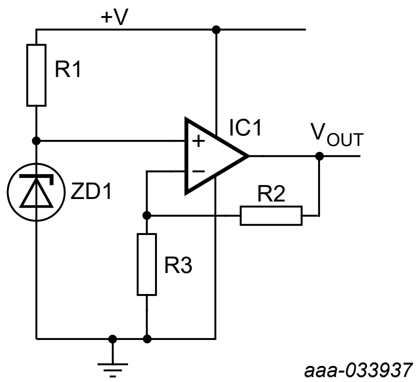


Fig. 15. Zener diode as voltage reference with an OP-Amp buffer

4. Avalanche breakdown considerations

The major application for Zener diodes is to operate them in reverse polarity. If the reverse bias voltage is below the breakdown voltage the diode can be considered as a capacitor. The capacitance depends on the size of the active areas and the distance of the depletion zone in the reverse mode. The depletion zone in a silicon crystal is not a perfect electrical insulator. A few electrons can get into the depletion zone or some electrons in the depletion zone can lose their bounds. These free electrons get accelerated to the positive voltage side which is the cathode of the Zener diode. If the field strength is high enough a free electron can pick up enough kinetic energy in the electric field to punch free another bond electron. This mechanism leads to a chain reaction of creating more and more free electrons which is the so-called avalanche breakdown.

From the description of the avalanche mechanism, it is obvious that leakage current is a major precondition beside providing an electrical field strength high enough for an avalanche breakdown. The more free electrons are present the bigger is the probability to start an impact ionization and because of this an avalanche breakdown.

With a very simple test circuit a Zener diode can be operated at different operating points with regards to the Zener current I_Z. The diode under test is put in series with a resistor R1 and a DC voltage higher than V_Z is connected. The voltage at the diode is investigated with an oscilloscope, see Fig. 16.

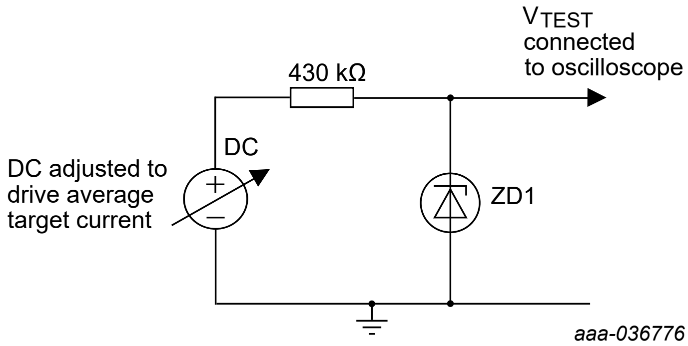


Fig. 16. Zener diode noise test circuit

I_Z can be adjusted according $I_Z = (V_{in} – V_Z) / R1$. If the current is chosen smaller than 500 µA the voltage at the Zener diode will show an overlay of “noise”. For low currents the avalanche condition stops if not enough impact ionizations happen statistically to keep the desired Zener current stable at the value according to the above formula. If conduction stops the voltage at the diode rises and the diode capacitance gets charged via R1. Due to the higher field strength an avalanche breakdown gets started again. Because the start of an avalanche breakdown has a statistical spread, a random noise of triangle-shaped overswings can be observed. The signal even falls below V_Z after the steep falling edges where the breakdown has started again so that the diode stops conducting and needs to get re-triggered with a rising ramp signal again.

In Fig. 17 an example of a 27 V Zener diode is shown. 470 kΩ had been used as series resistor. If the maximum overswing shall be found it is important to adapt the series resistor such that the overshoot waveforms look like triangles. If the resistance of the series resistor is chosen too low, the waveforms show the typical flat run-in of a capacitor charging voltage curve, because the overshoot cannot get bigger than V_{in} - V_Z.

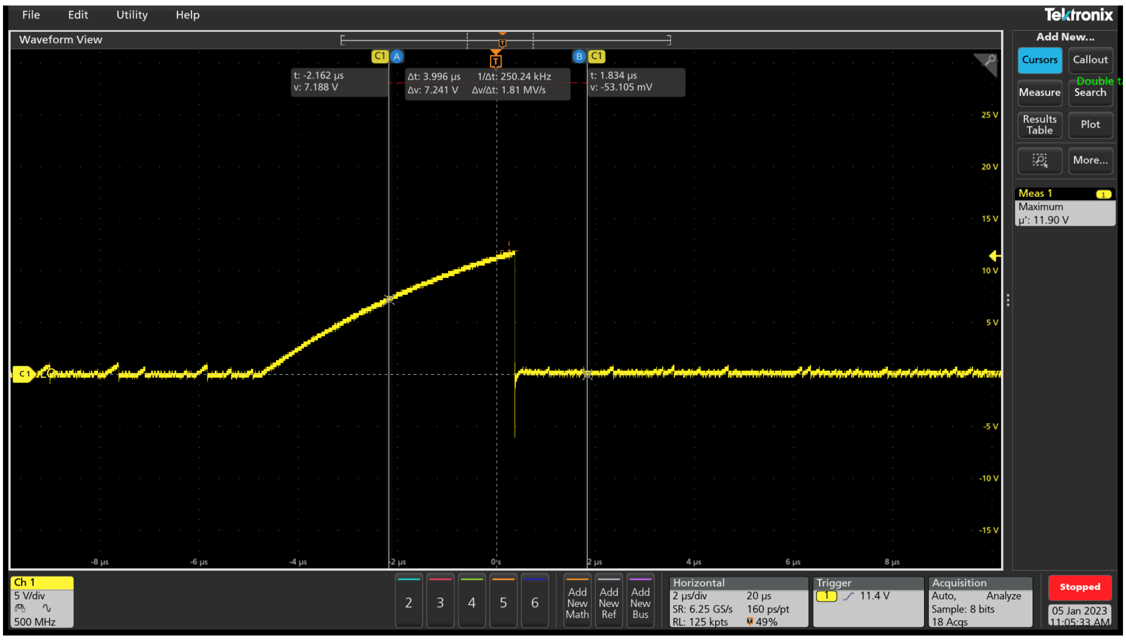


Fig. 17. Avalanche noise for a 27 V Zener diode operated with 50 µA with 470 kΩ in series

Fig. 18 shows a test with 50 µA current applied via 43 kΩ. With a low series resistance, a comparably low voltage V_{in} is required to achieve a desired average current for the test circuit and the overswing voltage can get clipped. The clipped pulses show then a statistical variation of the breakdown delay. These delays can get bigger compared to a test with same current where the voltage at the Zener diode can ramp up to a higher voltage without clipping effects. The highest overswing can be captured by adjusting the trigger level of an oscilloscope to higher values step by step until no bigger trigger events can be found anymore. Because of the statistical nature of the avalanche breakdown the oscilloscope should get enough time to wait for a trigger event which can be seen as maximum overswing.

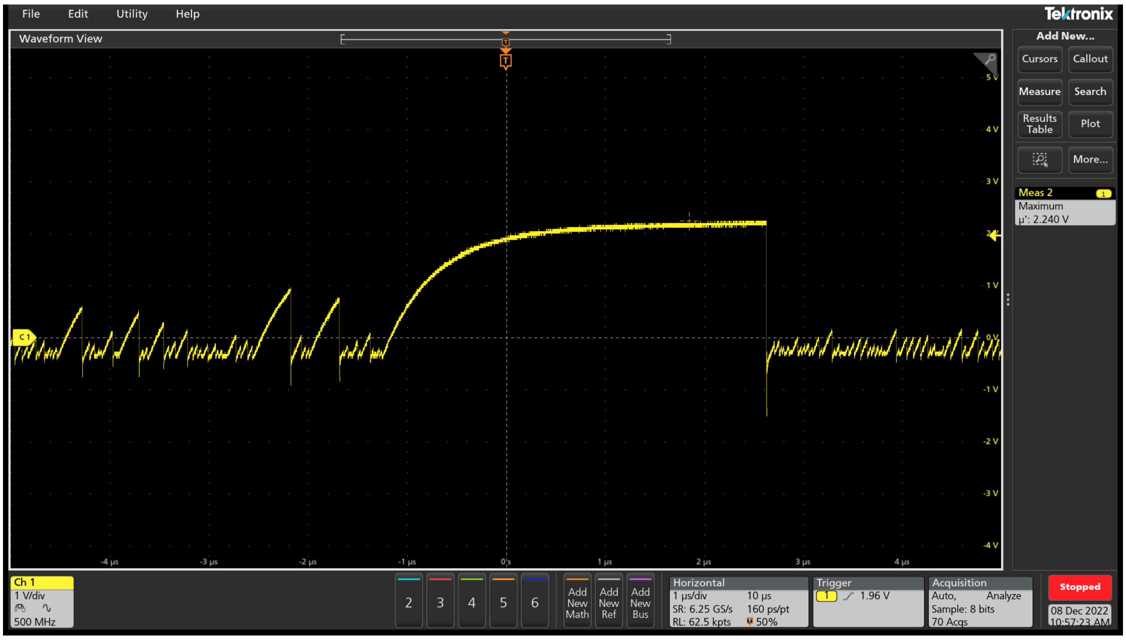


Fig. 18. Avalanche noise for a 33 V Zener diode operated with 50 μA with 43 kΩ in series

The diagram in Fig. 19 shows the maximum noise levels found for a 24 V Zener diode in dependence on the current tested with 1.5 MΩ series resistance. Maximum noise is seen with I_Z = 20 μA to 40 μA. For currents larger than about 0.3 mA the noise almost disappears. For currents lower than about 20 μA the noise pulses decrease in voltage. This is because the rise times become larger and the charge time for the diode capacitance increases. Then there is more time for a start of an avalanche breakdown while the voltage rises, the breakdown delay is not big enough for seeing the maximum values for these very small currents.

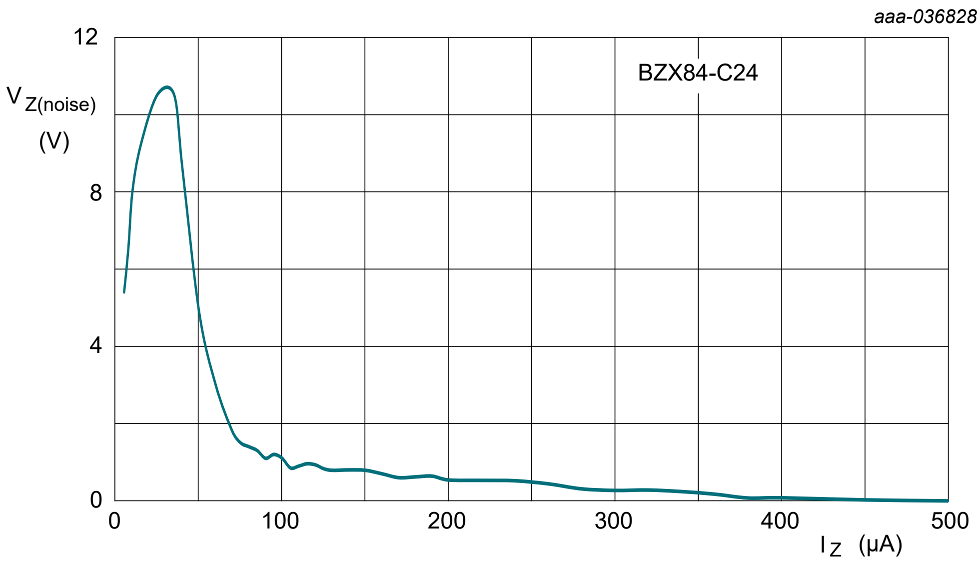


Fig. 19. Maximum noise level for BZX84-C24 as a function of I_Z

In the described test set-up, the Zener diodes are exposed to a constant bias voltage via a series resistor. Alternatively, turn-on tests can be performed where a test pulse is applied to the device under test (DUT) while the waveform is captured. Nexperia performs tests where 100 V or 150 V pulses are provided with a low frequency (~ 1 Hz) to a DUT which is connected via 10 kΩ to the generator. The series resistor and the diode capacitance C_d define the rise rate of the test pulse. In

Fig. 20 a 'scope trace of such test is shown. The clamping of the input voltage shows a statistical spread. Fig. 20 shows a worst case captured with a significant overswing voltage. In area 1 the signal ramps up according to the time constant 10 kΩ × C_d. Then the Zener diode becomes conductive and a short undershoot can be seen in area 2. After this the Zener diode shows the desired nominal clamping voltage in area 3.

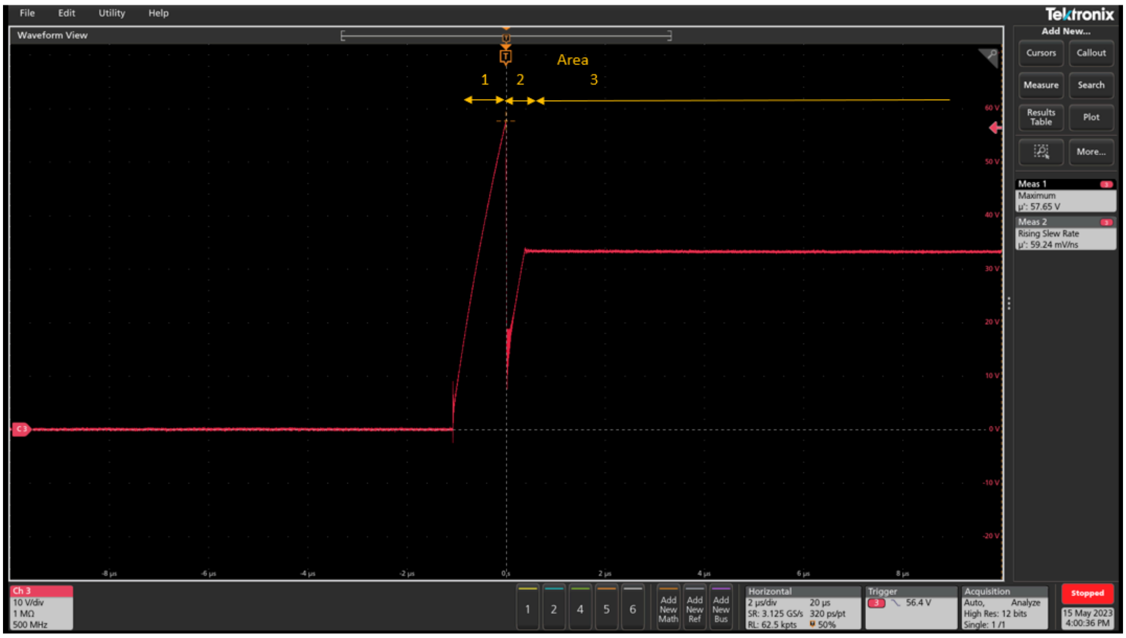


Fig. 20. BZX84-C33 pulse test with 100 V via 10 kΩ

Zener diodes with a low breakdown voltage are based on the name-giving Zener effect as described in the introduction section of this application note. If the Zener effect is dominating the breakdown, the leakage current of the Zener is comparably high like the I-V curves in Fig. 6 and Fig. 7. With enough leakage current and therefore a high number of impact ionizations, the noise issue for low I_Z cannot be observed.

Above about V_Z = 6 V both breakdown effects, the Zener tunnel effect, and the avalanche breakdown, start to play a role and at about 10 V the avalanche breakdown becomes dominant. This fact can be seen in the I-V diagrams in Fig. 7 as well. From 10 V onwards, the I-V curves are almost perpendicular even for a very small current once V_Z is reached. For voltage types bigger than 10 V, the avalanche breakdown is dominating, and the slope of the I-V curve is very steep.

Nexperia offers two kinds of Zener series to address the noise topic:

The standard series BZ*, TDZ, NZH, and HPZR are optimized for an extremely low leakage current. The leakage current is in the region of only a few pA. While this is an advantage for some applications, this can cause noise or overswing for other applications. The corresponding series are:

- BZX884S
- BZX884
- BZX585
- BZX384
- BZX84J
- TDZxJ
- BZT52
- NZH
- BZT52H
- BZB84
- BZX84
- BZB784
- BZX84W
- BZV90
- BZV49
- HPZR

and if applicable their ‘Q’-version (* = under development).

The PZU, PDZ, and 50 µA Zener series have a moderately increased leakage current (I_R > 1 nA before the breakdown). The probability of an impact ionization is clearly increased and the noise and overswing is reduced accordingly. The corresponding series are:

- BZX8850*
- PZU884*
- PZUxBL
- BZX58550*
- PZUxBA
- BZX38450*
- PDZ-B
- PZUxB
- BZX8450*
- BZX845*

and if applicable their ‘Q’-version (* = under development).

For the usage of Zener diodes in applications the low leakage parts should be run with an I_Z of more than 0.5 mA. Then there is no noise issue to be expected anymore. For V_Z < 10 V also the low league current series work stable at low currents. Selecting components with a moderately higher leakage current that use a gold-kill process reduce the noise level also for Zener voltages above 10 V significantly.

The low leakage types can become problematic if voltages shall be clipped exactly without overshoots or turn-on delays when it is not possible to apply a sufficiently high bias current. In these cases, the above listed Zener diodes should be selected.

5. Zener diodes package overview

Nexperia offers zener diodes in a wide range of packages. Section 5 shows all options from the small DFN1006 packages up to the bigger variants such as SOT223 with high power capability. The values in column 3 apply for mounting the devices on an FR4 Printed-Circuit Board with a standard footprint. The board uses single-sided copper with tin-plating.

Table 10. Nexperia’s packages for Zener diodes, configuration and P_{tot} ratings

Package name	Configuration	P_{tot} (mW)
DFN1006BD-2 (SOD882BD)	single	365
DFN1006(D)-2 (SOD882)	single	250
SOD523	single	300
SOD323	single	300/400/490
SOD323F	single	310
SOT23	single, dual	250/300
SOT323	Single, dual	250/275/300/350
SOD123	single	365/590
SOD123F	single	500/830
SOT89	single	1000
SOT223	single	1500
SOD80C (MiniMelf)	single	500
SOD27 (DO-35)	single	500
SOD66 (DO-41)	single	1000/1300

6. References

1. BZX884S series data sheet.

7. Revision history

Table 11. Revision history

Revision number	Date	Description
3.0	2023-06-07	Section 4 added.
2.0	2022-06-27	Fig. 12 updated.
1.0	2021-10-01	Initial version.

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