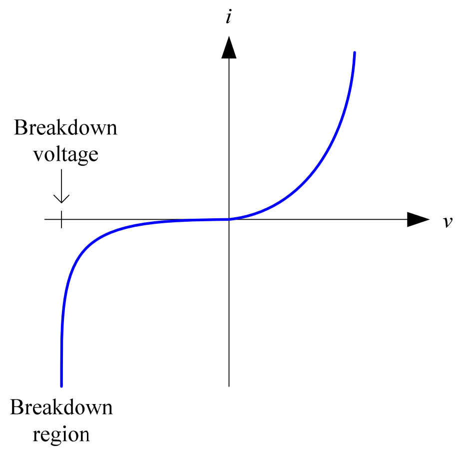
Lecture 6: Zener Diodes.

The very steep portion in the reverse biased *i*-*v* characteristic curve is called the breakdown region.



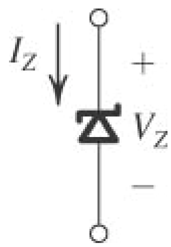
In this region the voltage across the diode remains nearly constant while the current varies (i.e., small internal resistance).

There are two physical mechanisms that can produce this behavior in the breakdown region. One is the Zener effect in which the large electric field in the depletion region causes electrons to be removed from the covalent bonds in the silicon.

The second mechanism is the avalanche effect in which charges that are accelerated to high speeds due to the large electric field in the depletion region collide with atoms in the silicon lattice causing charges to be dislodged. In turn, these dislodged charges have sufficient energy to liberate additional electrons. In other words, this avalanche effect is a cascading, ionization process.

Provided that the power dissipated in the diode is less than the maximum rated, the diode is not damaged when operating in the breakdown region. In fact, Zener diodes are designed to operate in this region.

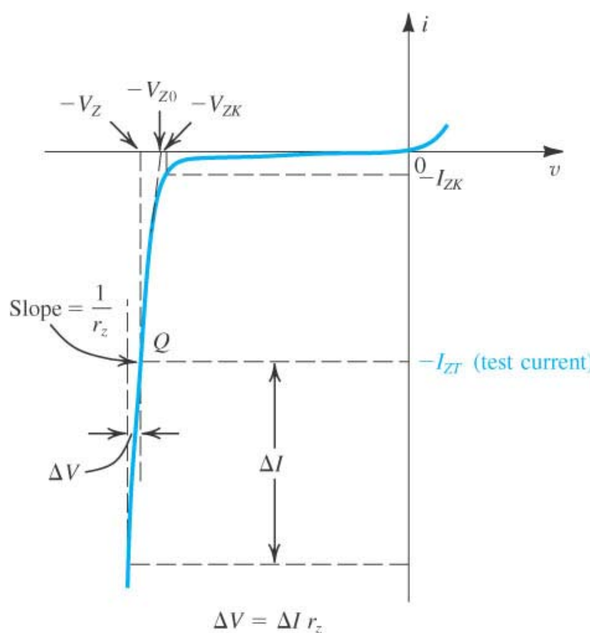
The circuit symbol for the Zener diode is



(Fig. 4.18)

These diodes are usually operated in the reverse bias regime (i.e., breakdown region) so that $I_Z > 0$ and $V_Z > 0$.

An enlargement of this breakdown region is shown in text Fig. 4.19:

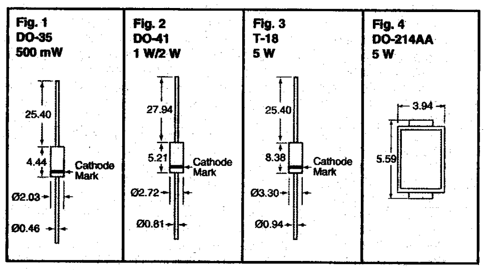


(Fig. 4.19)

The manufacturer specifies the $-V_{Z0}$ and test current I_{ZT}. One can design Zeners with a wide range of voltages.

The page below is from a Digikey catalog (www.digikey.com) and shows voltages from ranging from 3.6 V to 200 V, for example.

Microsemi. Zener Diodes



500 mW Series DO-35 Silicon Zener Diodes, 1N5221 — 1N5281

(Value)	Nominal Zener Voltage Vz @ Izt (Volts)	Test Current Izt (mA)	(Value)	Nominal Zener Voltage Vz @ Izt (Volts)	Test Current Izt (mA)	(Value)	Nominal Zener Voltage Vz @ Izt (Volts)	Test Current Izt (mA)	(Value)	Nominal Zener Voltage Vz @ Izt (Volts)	Test Current Izt (mA)	(Value)	Nominal Zener Voltage Vz @ Izt (Volts)	Test Current Izt (mA)
21	2.4	20	35	6.8	20	46	16	7.8	60	43	3.0	71	100	1.3
23	2.7	20	36	7.5	20	47	17	7.4	61	47	2.7	72	110	1.1
24	2.8	20	37	8.2	20	48	18	7.0	62	51	2.5	73	120	1.0
26	3.3	20	38	8.7	20	49	19	6.6	63	56	2.2	74	130	0.95
27	3.6	20	39	9.1	20	50	20	6.2	64	60	2.1	75	140	0.90
28	3.9	20	40	10	20	51	22	5.6	65	62	2.0	76	150	0.85
29	4.3	20	41	11	20	52	24	5.2	66	68	1.8	77	160	0.80
30	4.7	20	42	12	20	53	25	5.0	67	75	1.7	78	170	0.74
31	5.1	20	43	13	9.5	54	27	4.6	68	82	1.5	79	180	0.68
33	6.0	20	44	14	9.0	55	28	4.5	69	87	1.4	81	200	0.65
34	6.2	20	45	15	8.5	58	36	3.4	70	91	1.4			

1W Series, DO-41 Glass Zener Diodes 1N4729A — 1N4763A

(Value)	Zener Voltage Vz (Volts)	Test Current Izt (mA)	(Value)	Zener Voltage Vz (Volts)	Test Current Izt (mA)
29	3.6	69	41	11	23
33	5.1	49	42	12	21
34	5.6	45	43	13	19
35	6.2	41	56	47	5.5
36	6.8	37	58	56	4.5
37	7.5	34	59	62	4.0
38	8.2	31	60	68	3.7
40	10	25	62	82	3.0
			63	91	2.8

2 W Series, DO-41 Silicon Zener Diodes 2EZ3.6D5 — 2EZ200D5

(Value)	Nominal Zener Voltage Vz (Volts)	Izt (mA)	(Value)	Nominal Zener Voltage Vz (Volts)	Izt (mA)	(Value)	Nominal Zener Voltage Vz (Volts)	Izt (mA)
3.6	3.6	139	17	17	29.4	62	62	8.1
3.9	3.9	128	18	18	27.8	75	75	6.7
4.3	4.3	116	19	19	26.3	82	82	6.1
5.1	5.1	98	20	20	25	91	91	5.5
6.2	6.2	80.5	22	22	22.8	110	110	4.5
6.8	6.8	73.5	27	27	18.5	120	120	4.2
7.5	7.5	66.5	33	33	15.1	130	130	3.8
8.2	8.2	61	39	39	12.8	140	140	3.6
12	12	41.5	43	43	11.6	170	170	2.9
13	13	38.5	47	47	10.6	180	180	2.8
14	14	35.7	51	51	9.8	190	190	2.6
15	15	33.4	56	56	9.0	200	200	2.5

5 W Series, T-18 Silicon Zener Diodes 1N5333B — 1N5388B

(Value)	Regulator Voltage Vz	Test Current Iz	(Value)	Regulator Voltage Vz	Test Current Iz
33	3.3	380	58	22	50
34	3.6	350	65	36	30
36	4.3	290	68	47	25
39	5.6	220	70	56	20
40	6.0	200	73	68	20
42	6.8	175	75	82	15
43	7.5	175	76	87	15
47	10	125	79	110	12
49	12	100	81	130	10
51	14	100	86	180	5.0
52	15	75	87	190	5.0
53	16	75	88	200	5.0

Fig.	DC Power Dissipation	Voltage Range (Code) See Chart	Digi-Key Part No.*	Cut Tape Pricing 1	10	100	Digi-Key Part No.*	Tape and Reel Pricing 2,500	3,000	4,000	6,000	8,000	10,000	Microsemi Part No.*
1	500 mW	2.4V — 200V	1N52(Value)DO35MSCT-ND	1.20	8.40	60.00	1N52(Value)DO35MSTR-ND	—	—	—	—	—	210.00/M	1N52(Value)DO35
2	1 W	3.6V — 91V	1N47(Value)AD041MSCT-ND	.25	1.65	13.20	1N47(Value)AD041MSTR-ND	—	—	74.00/M	—	59.00/M	—	1N47(Value)AD041
	2 W	3.6V — 200V	2EZ(Value)D5D041MSCT-ND	1.42	9.45	75.60	2EZ(Value)D5D041MSTR-ND	—	—	293.00/M	—	340.00/M	—	2EZ(Value)D5D041
3	5 W	3.3V — 200V	1N53(Value)BMSCT-ND	1.20	8.00	64.00	1N53(Value)BMSTR-ND	—	400.00/M	—	320.00/M	—	—	1N53(Value)B

* For complete part number, substitute corresponding value from chart for (Value).

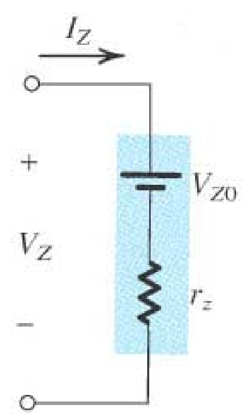
The rated V_Z at the specified I_{ZT} is listed for these Zener diodes. The circled component, for example, has $V_Z = 8.2$ V at $I_{ZT} = 31$ mA. The maximum rated power is 1 W for this device.

As the current deviates from the specified value I_{ZT}, the voltage V_Z also changes, though perhaps only by a small amount. The change in voltage ΔV_Z is related to the change in the current ΔI_Z as

$$\boxed{\Delta V_Z = r_z \Delta I_Z} \quad (1)$$

where r_z is the incremental or dynamic resistance at the Q point and is usually a few Ohms to tens of Ohms. See the datasheet for the particular device you are working with.

Because of the nearly linear relationships in the breakdown region, the reverse bias model of the Zener diode is



(Fig. 4.20)

where

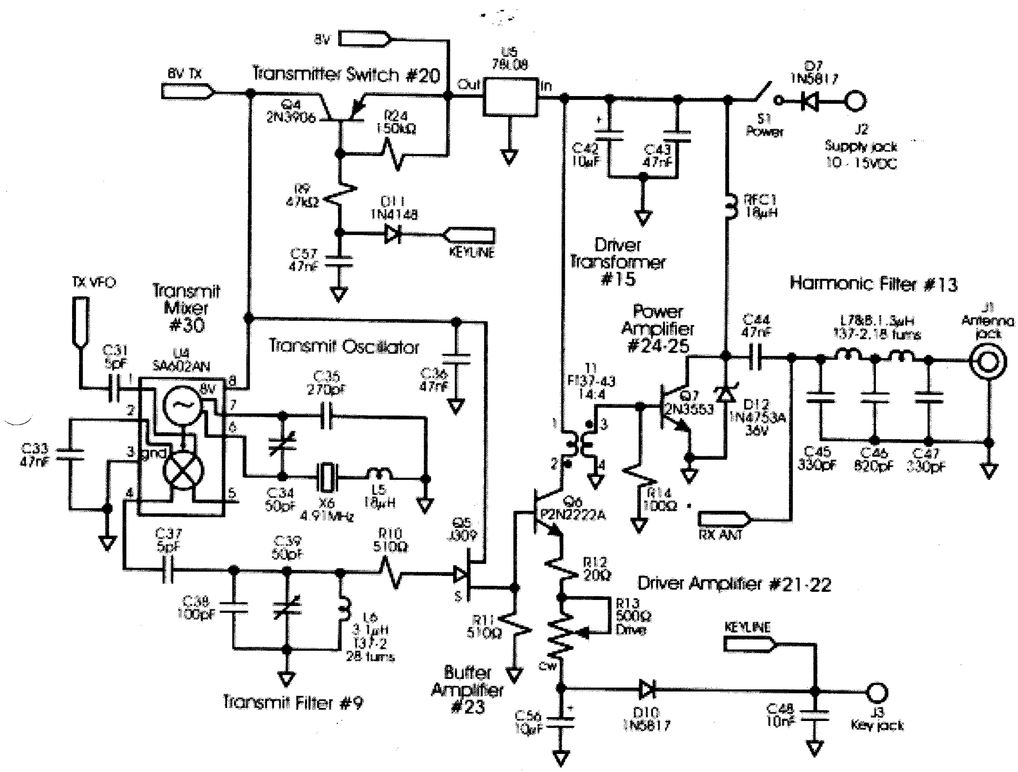
$$\boxed{V_Z = V_{Z0} + r_z I_Z} \quad (4.20),(2)$$

as is apparent from Fig. 4.19.

Applications of Zener Diodes

What are Zener diodes used for? Applications include:

1. Voltage overload protection. This circuit is from the NorCal 40A radio that is built in EE 322 *Electronics II – Wireless Communication Electronics*:



2. Voltage regulation. See the figure below. An example of such a regulator circuit will be considered next.

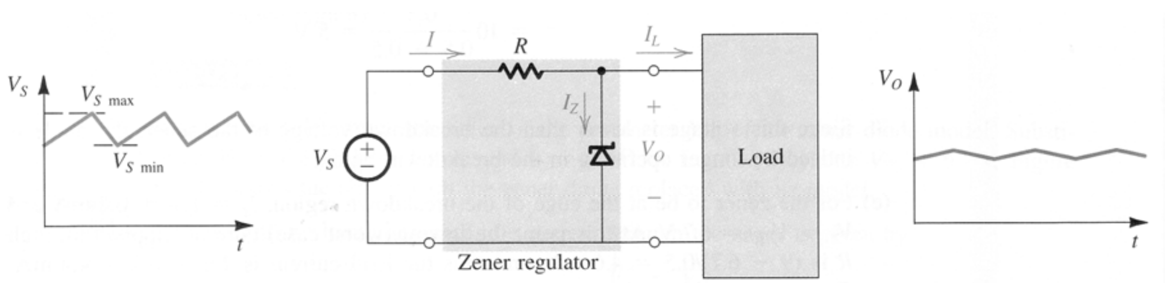
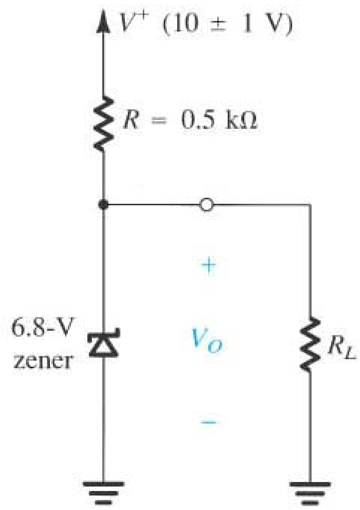


Fig. 3.34 A zener shunt regulator. Observe that while the raw supply V_S has a large ripple component, the regulated voltage V_O has a very small ripple.

(Source: Sedra and Smith, fourth ed.)

Example N6.1 (similar to text example 4.7). The Zener diode in the circuit below has the following characteristics: 6.8-V rating at 5 mA, $r_z = 20\ \Omega$, and $I_{ZK} = 0.2$ mA.



(Fig. 4.21a)

With these ratings

$$V_Z = V_{Z0} + r_z I_Z \quad \Rightarrow \quad V_{Z0} = V_Z - r_z I_Z$$

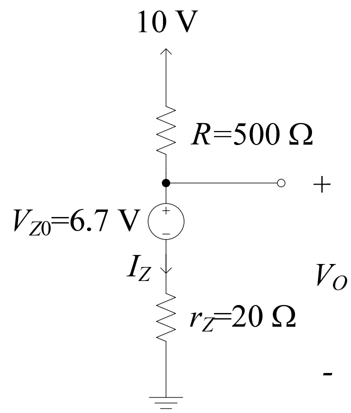
or

$$V_{Z0} = 6.8 - 20 \cdot 5 \times 10^{-3} = 6.7 \text{ V}$$

Note that the supply voltage can fluctuate by ± 1 V. Imagine this fluctuation is a random process rather than a time periodic variation.

Determine the following quantities:

(b) Find V_O with no load and V^+ at the nominal value. The equivalent circuit for the reverse bias operation of the Zener diode is



From this circuit we calculate

$$I_Z = \frac{10-6.7}{500+20} = 6.35 \text{ mA}$$

Therefore,

$$V_O = 10 - I_Z \cdot 500 = 10 - 6.35\times10^{-3} \cdot 500 = 6.83 \text{ V}$$

(c) Find the change in V_O resulting from a ± 1 V change in V^+. Using the circuit above the $V^+ = 11$ V:

$$V_O = 11 - \frac{11-6.7}{500+20} \cdot 500 = 6.865 \text{ V}$$

Similarly, with V^+=9 V:

$$V_O = 9 - \frac{9-6.7}{500+20} \cdot 500 = 6.788 \text{ V}$$

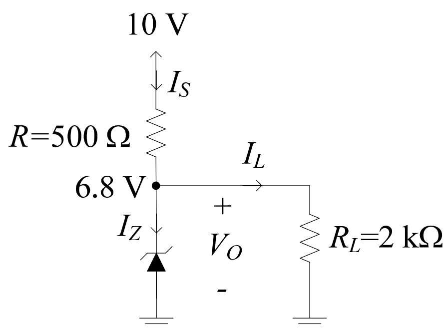
Consequently, $\Delta V_O = 6.865 - 6.788 = 0.077$ V or $\Delta V_O = \pm 38.5$ mV.

The ratio of the change in output voltage to the change in the source voltage ($\Delta V_O / \Delta V^+$) is called the line regulation of the regulator circuit. It's often expressed in units of mV/V. For this example and no load attached,

$$\text{Line Regulation} \equiv \frac{\Delta V_O}{\Delta V^+} = \frac{77}{11-9}\frac{\text{mV}}{\text{V}} = 38.5\frac{\text{mV}}{\text{V}}$$

(d) Find the change in V_O resulting from connecting a load of $R_L = 2$ kΩ with a nominal $V^+ = 10$ V.

Assuming that the diode is operating in the breakdown region:



then $$I_L = \frac{6.8}{2000} = 3.4 \text{ mA.}$$

Is this a reasonable value? Calculate I_S:

$$I_S = \frac{10-6.8}{500} = 6.4 \text{ mA.}$$

So, yes, this is a reasonable value because $I_L < I_S$, as it must.

From (1), $\Delta V_O = r_z \Delta I_Z$ and since $\Delta I_Z = -3.4$ mA then

$$\Delta V_O = 20\left(-3.4\times 10^{-3}\right) = -68 \text{ mV}$$

The ratio of the change in output voltage to the change in the load current ($\Delta V_O/\Delta I_L$) is called the load regulation of the regulator circuit. It's often expressed in units of mV/mA. For this example,

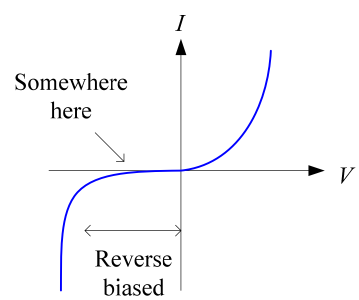
$$\text{Load Regulation} \equiv \frac{\Delta V_O}{\Delta I_L} = \frac{77}{-3.4}\frac{\text{mV}}{\text{mA}} = -22.6\frac{\text{mV}}{\text{mA}}$$

(e) What is V_O when R_L = 0.5 kΩ? Assume the diode is in breakdown. In this case,

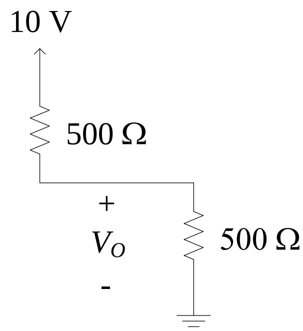
$$I_L \approx \frac{6.8}{500} = 13.6 \text{ mA.}$$

Is this a reasonable value? No, because this value is greater than I_S = 6.4 mA.

Therefore, in this case the Zener diode is not operating in the breakdown region. Also, the diode can't be forward biased. Consequently, we conclude the diode must be operating in the reverse bias region.



The equivalent circuit in this case is



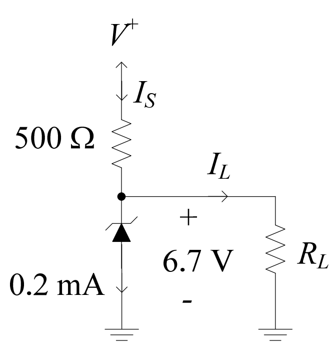
From this circuit we calculate

$$V_O = \frac{500}{500+500}\cdot 10 = 5 \text{ V}.$$

This voltage is less than the breakdown voltage V_{ZK}, which is consistent with the reverse biased assumption.

(f) Determine the minimum R_L for which the diode still remains in breakdown for all V^+. (We know from the results in parts (c) and (d) of this example that R_L must lie between 500 Ω and 2 kΩ when $V^+ = 10$ V.)

Referring to Fig. 3.21, at the "knee" $I_Z = I_{ZK} = 0.2$ mA and $V_Z = V_{ZK} \approx V_{Z0} = 6.7$ V.



- If $V^+ = 9$ V:

$$I_S = \frac{9-6.7}{500} = 4.6 \text{ mA.}$$

Therefore, I_L = 4.6 mA-0.2 mA = 4.4 mA, so that

$$R_L = \frac{V_L}{I_L} = \frac{6.7}{4.4\times 10^{-3}} = 1{,}522\ \Omega$$

- If $V^+ = 11$ V:

$$I_S = \frac{11-6.7}{500} = 8.6 \text{ mA.}$$

Therefore, I_L = 8.6 mA-0.2 mA = 8.4 mA, so that

$$R_L = \frac{V_L}{I_L} = \frac{6.7}{8.4\times 10^{-3}} = 798\ \Omega$$

The smallest load resistance that can be attached to this circuit and have the diode remain in breakdown is R_L = 1,522 Ω. The reason is that for any smaller value when V^+ = 9 V results in the diode leaving breakdown and entering the reverse bias mode.