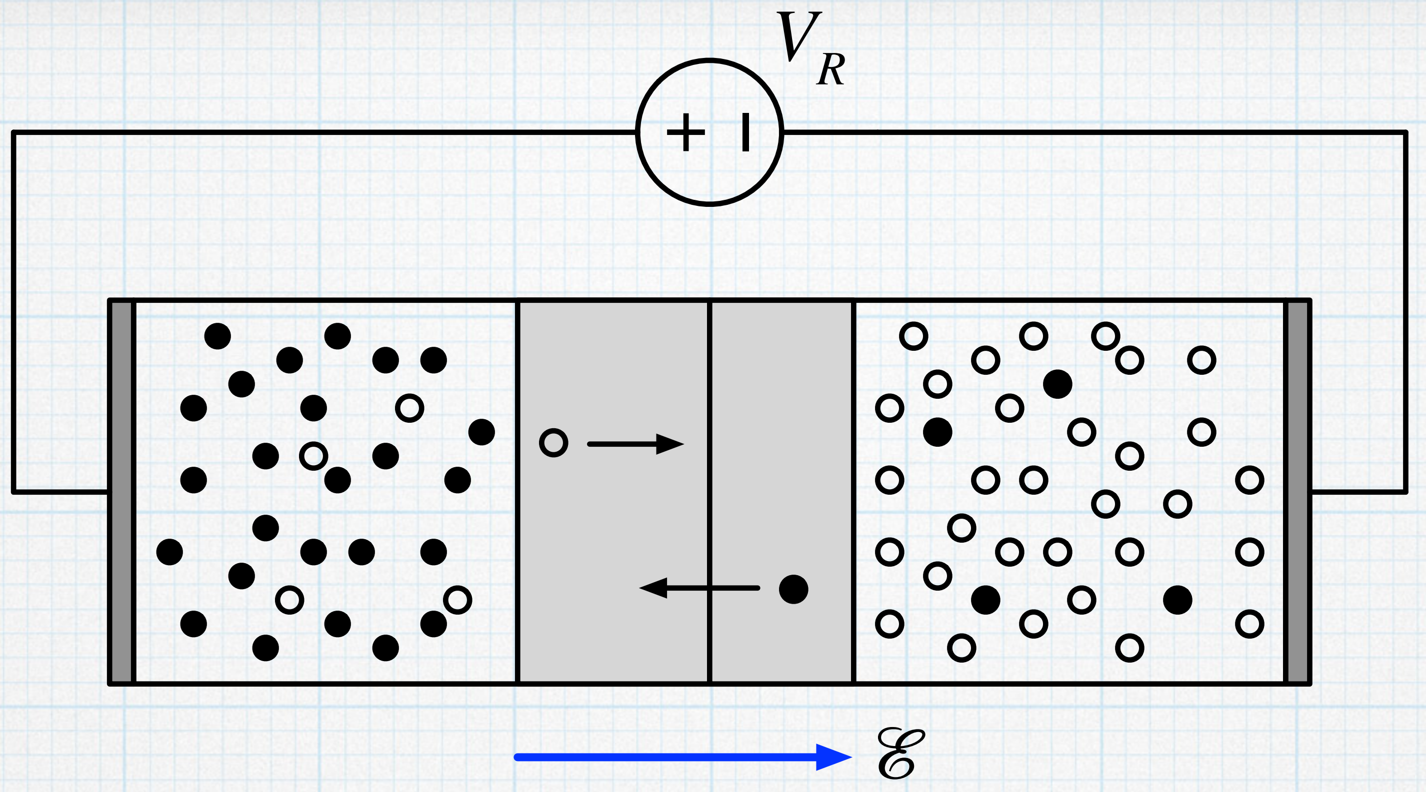
Zener diodes (avalanche multiplication)

In reverse-bias, we have been viewing the diode as behaving essentially like an open circuit. (Actually, a capacitor is a more accurate depiction.)

For the ideal diode, we assume that we can apply any reverse voltage and the reverse current will stay at the same tiny trickle, $-I_S$.

But for any diode, if the reverse voltage is increased enough, there will be a sudden and dramatic increase in reverse current. This happens at a very specific voltage and the i-v curve goes from being essentially horizontal (open-circuit) to essentially vertical (like a short-circuit, but with a specific voltage across it.)

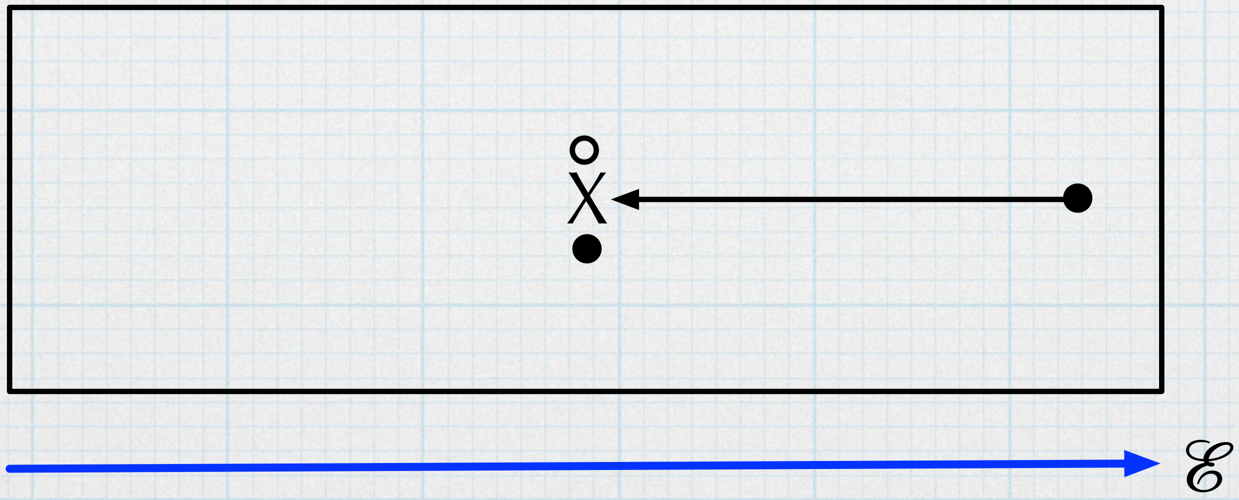
It is almost as if a huge current is being created out of nothing. (Doesn't Kirchhoff have something to say about this?) In essence, that is exactly what is happening.



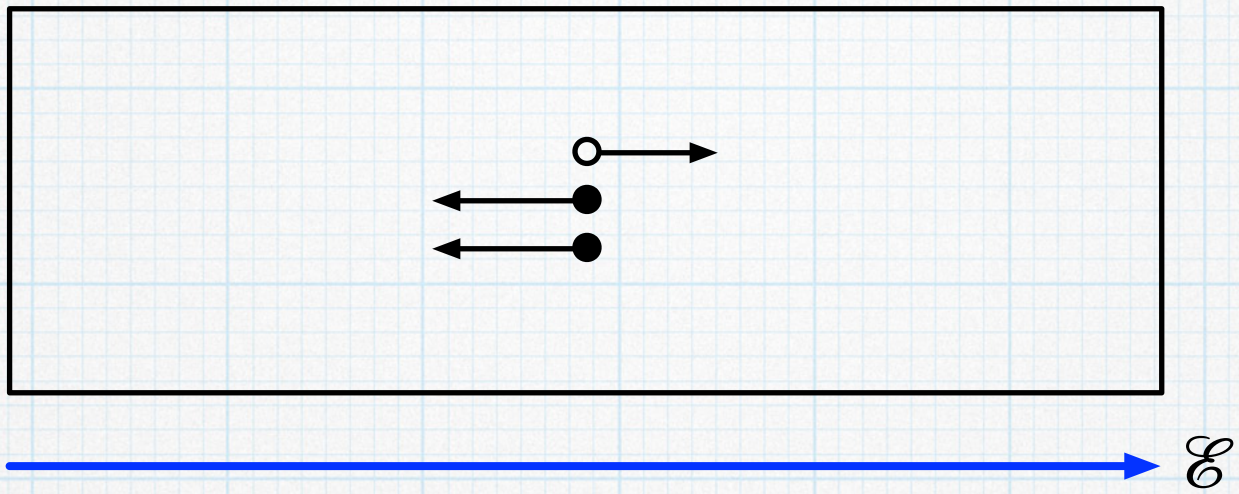
p-n junction under reverse-bias. The enhanced electric field is preventing the majority carriers (electrons on the left, holes on the right) from diffusing across depletion layer. Any minority carriers (holes on the left, electrons on the right) that come to the edge of the depletion layer will be swept across by the electric field. The trickle of minority carriers represents the reverse current of the diode.

Watch one electron that has entered the depletion layer from the right. It is being accelerated by the electric field, picking up speed and energy.

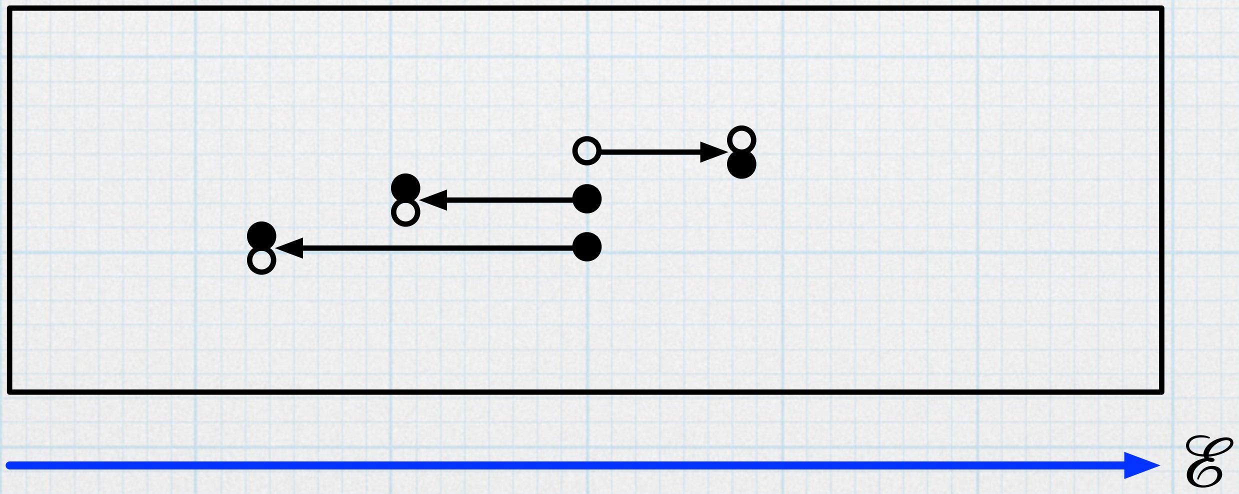
If it can accelerate enough, it might gain enough energy to collide with one of the *neutral* atoms in the base and knock loose an electron. Of course, in breaking loose an electron, there will be corresponding hole. One carrier becomes three.



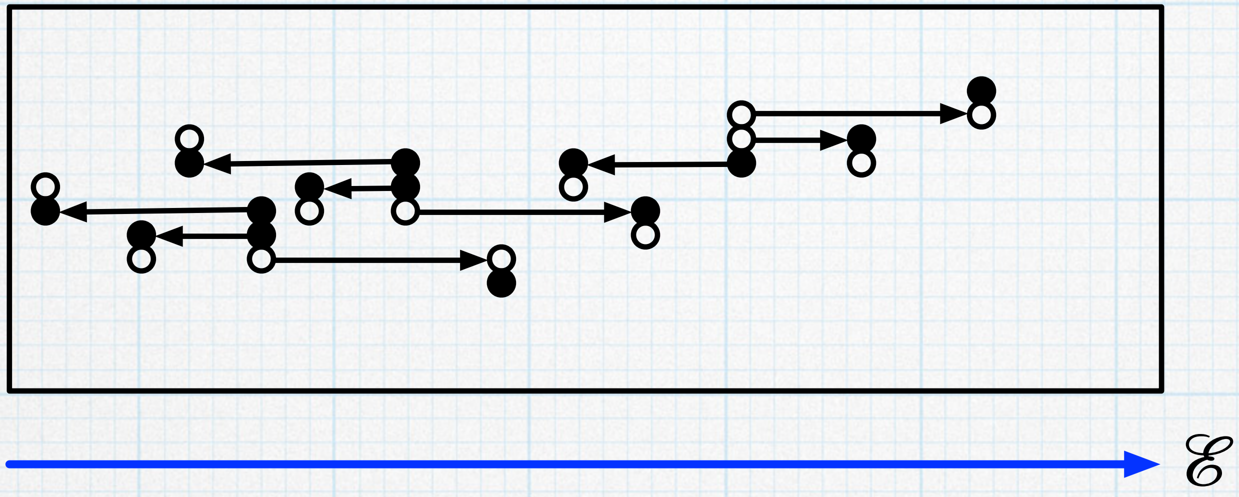
Now three carriers are being accelerated by the electric field.



Each of them can collide with and ionize an atom, resulting in nine carriers in the depletion layer.

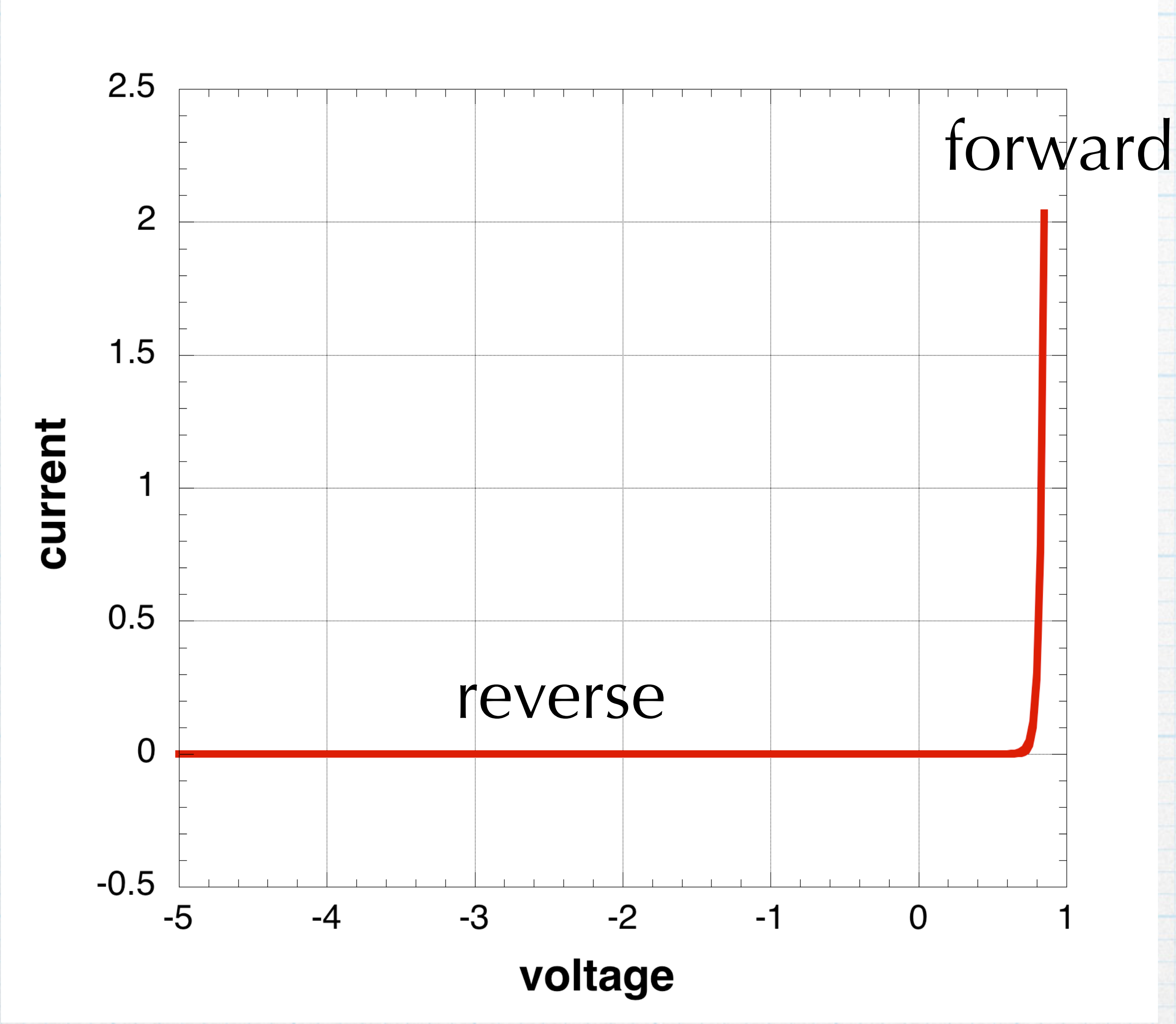


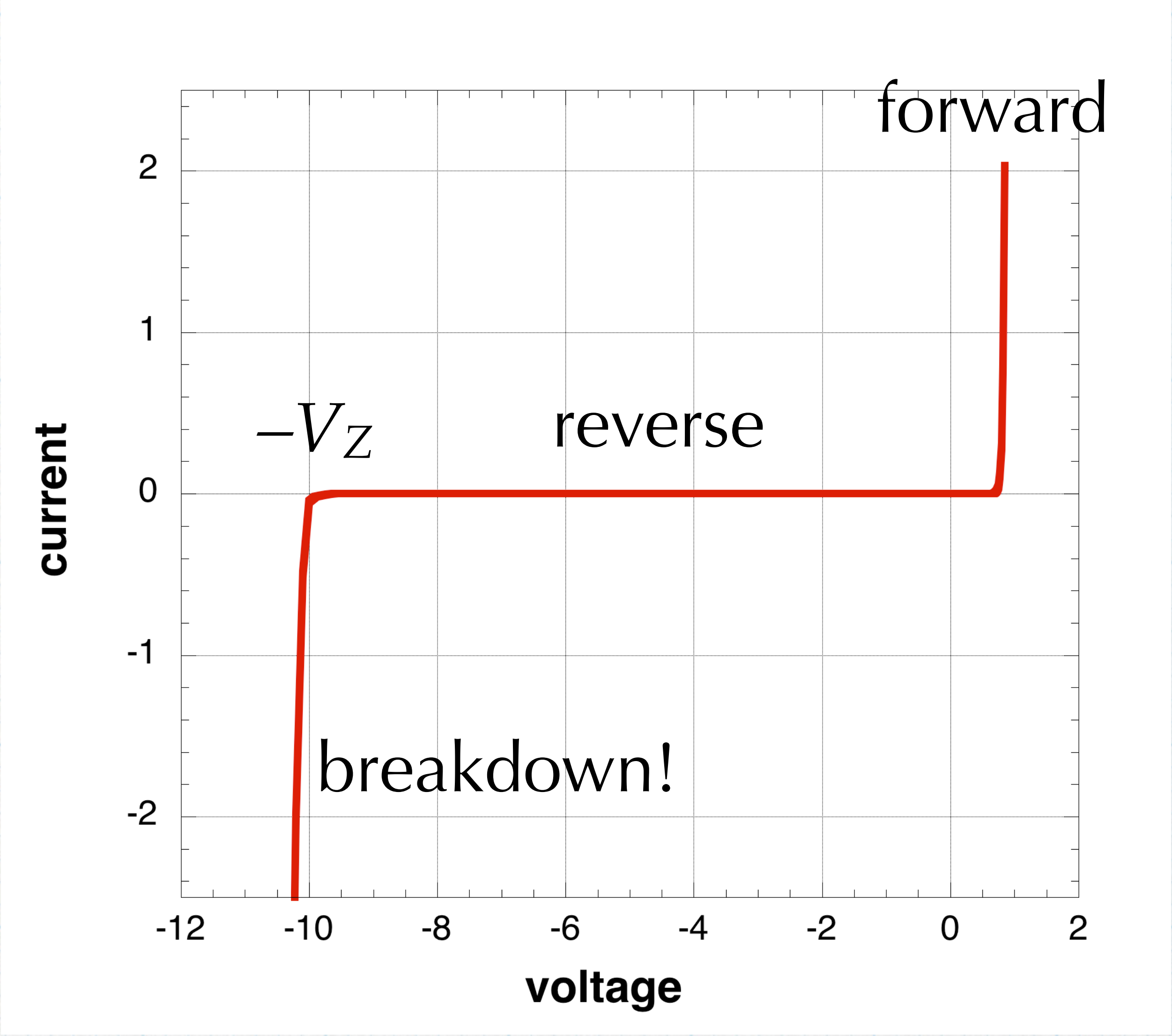
The multiplication process continues and the number of carriers increases rapidly.



What started out as a single carrier crossing the depletion has exploded in a huge current. For obvious reasons, this is known as a carrier avalanche.

It occurs at a very specific threshold value for the electric field. Since the electric field depends on the applied reverse voltage, we see the current leap from essentially zero to a huge value with only a small change in the reverse voltage. The p-n junction can be designed to have the breakdown occur at a specific reverse bias.





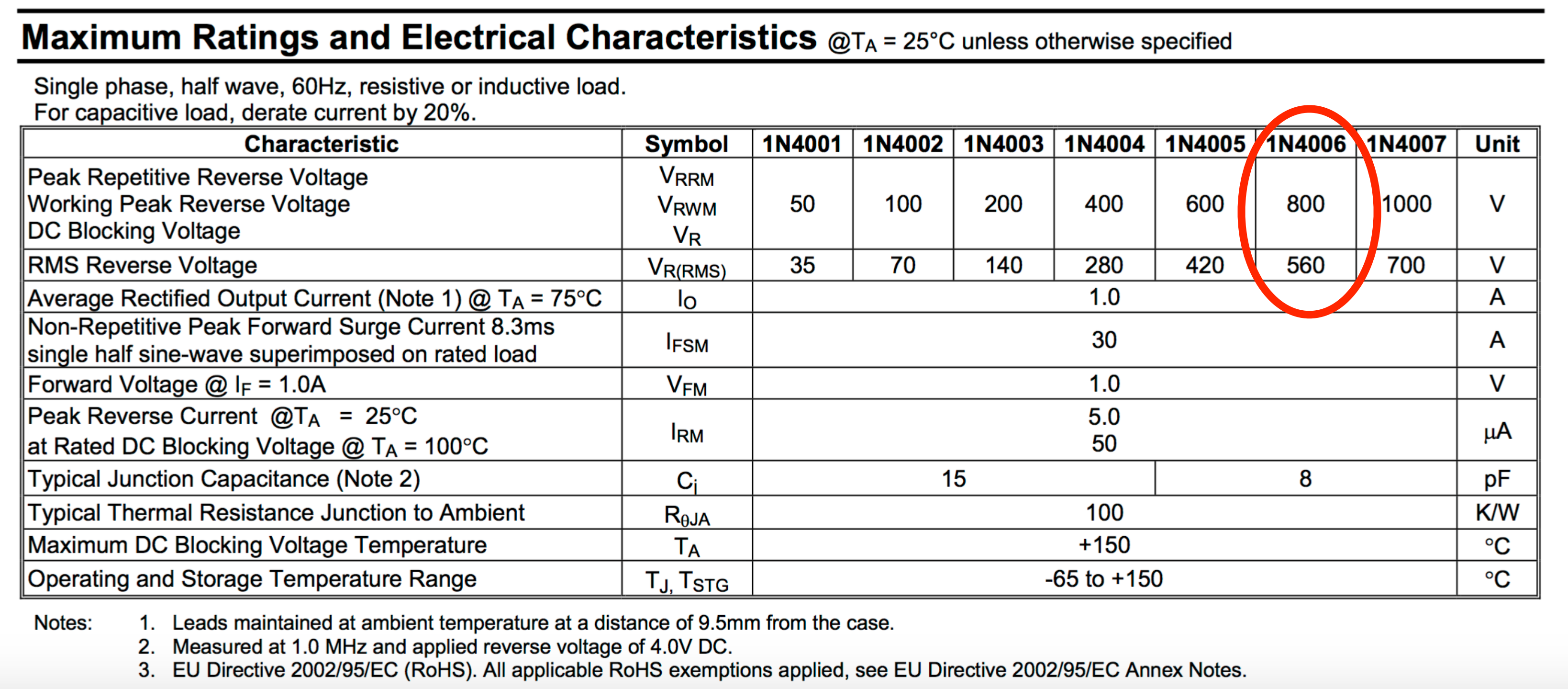
This huge reverse current is known as "breakdown", but the diode isn't broken. It is perfectly OK, as long as the current isn't allowed to become too big. (Big current = big power dissipation = burned diode.)

Breakdown voltage

Even though the avalanching effect is driven by the electric field, the external effect is to see a huge increase in current at a specific reverse *voltage*. This is known as the Zener voltage, V_Z, and the breakdown occurs at $-V_Z$.

Every diode will exhibit breakdown at some value of V_Z. Fortunately, a diode can be designed for a specific value of V_Z, ranging from about 2 V to over 1000 V.

For diodes meant to be used as rectifiers, having a breakdown current that flows when diode is supposed to be off would be bad – it defeats the purpose of the rectification. So rectifying diodes, like the 1N4006 (used in lab) are designed to have large V_Z.



Maximum Ratings and Electrical Characteristics @T_A = 25°C unless otherwise specified

Single phase, half wave, 60Hz, resistive or inductive load.
For capacitive load, derate current by 20%.

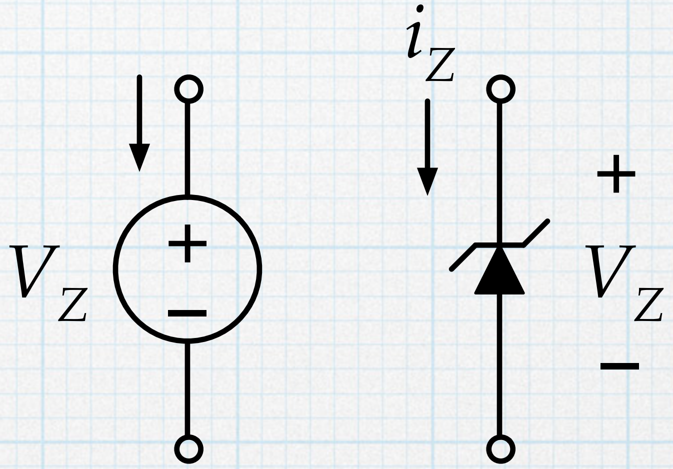
Characteristic	Symbol	1N4001	1N4002	1N4003	1N4004	1N4005	1N4006	1N4007	Unit
Peak Repetitive Reverse Voltage Working Peak Reverse Voltage DC Blocking Voltage	V_{RRM} V_{RWM} V_R	50	100	200	400	600	800	1000	V
RMS Reverse Voltage	$V_{R(RMS)}$	35	70	140	280	420	560	700	V
Average Rectified Output Current (Note 1) @ T_A = 75°C	I_O	1.0							A
Non-Repetitive Peak Forward Surge Current 8.3ms single half sine-wave superimposed on rated load	I_{FSM}	30							A
Forward Voltage @ I_F = 1.0A	V_{FM}	1.0							V
Peak Reverse Current @T_A = 25°C at Rated DC Blocking Voltage @ T_A = 100°C	I_{RM}	5.0 50							µA
Typical Junction Capacitance (Note 2)	C_j	15				8			pF
Typical Thermal Resistance Junction to Ambient	$R_{\theta JA}$	100							K/W
Maximum DC Blocking Voltage Temperature	T_A	+150							°C
Operating and Storage Temperature Range	T_J, T_{STG}	-65 to +150							°C

Notes:
1. Leads maintained at ambient temperature at a distance of 9.5mm from the case.
2. Measured at 1.0 MHz and applied reverse voltage of 4.0V DC.
3. EU Directive 2002/95/EC (RoHS). All applicable RoHS exemptions applied, see EU Directive 2002/95/EC Annex Notes.

From the data sheet for 1N400x family of rectifying diodes.

However, the breakdown can also be useful. The extreme steepness of the curve in the breakdown region can be used for *voltage regulation*.

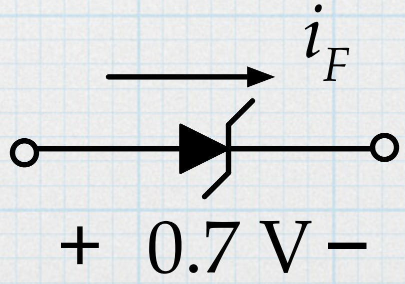
Some diodes are designed to have a smaller V_Z (a few volts to a few tens of volts) to serve as voltage references in a circuit. When a diode is designed with the intention of using its reverse breakdown, it is known as a *Zener diode*.



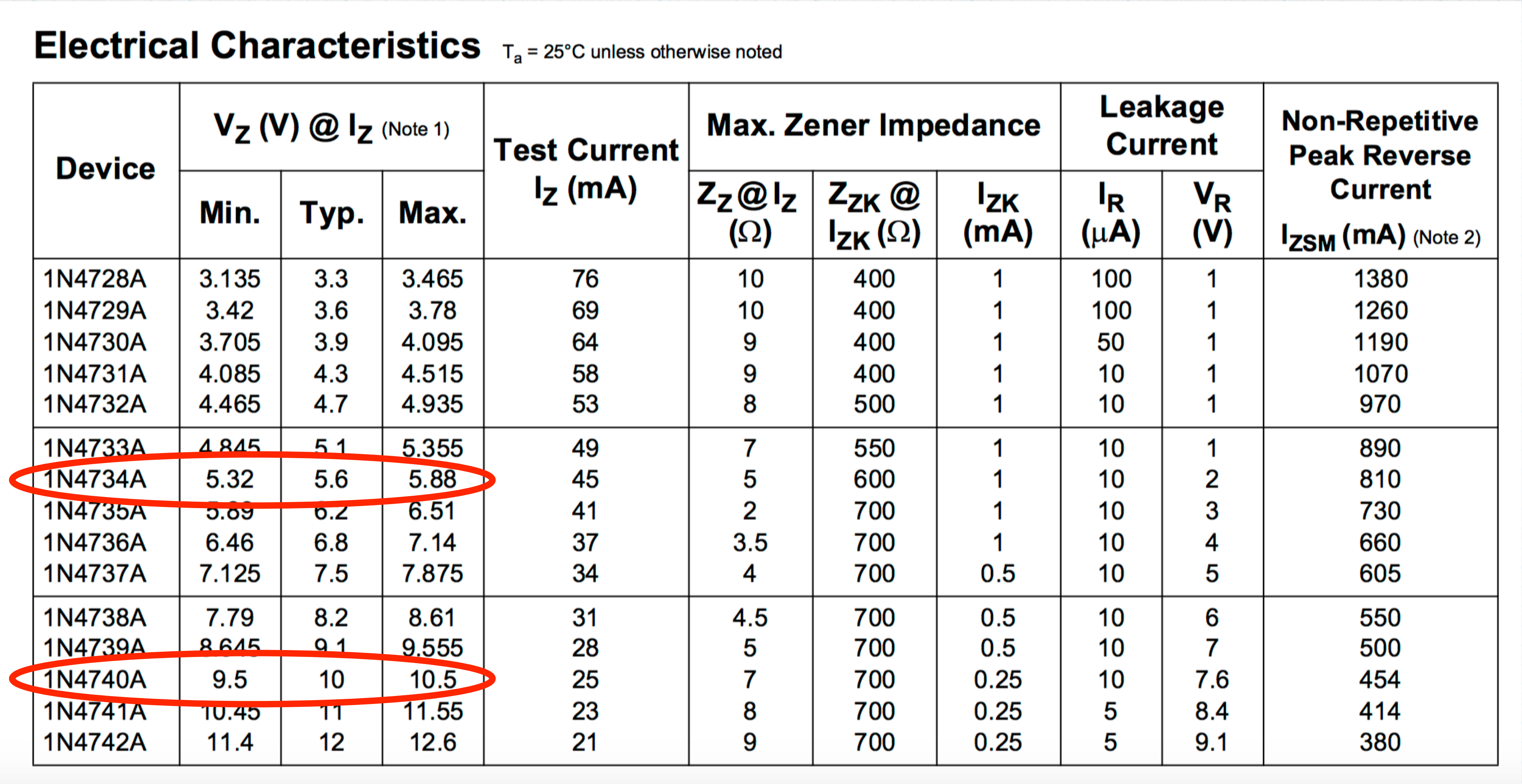
In the breakdown region, a Zener diode behaves very much like voltage source that is absorbing power.

Note that even though we will treat a Zener as behaving like a power-absorbing voltage source, it is *not* a voltage source. It cannot be used to generate power that can be delivered to other parts of the circuit. When the diode is operating in the breakdown region, the current will always flow "backwards".

If a Zener is forward biased, it behaves like a conventional diode.



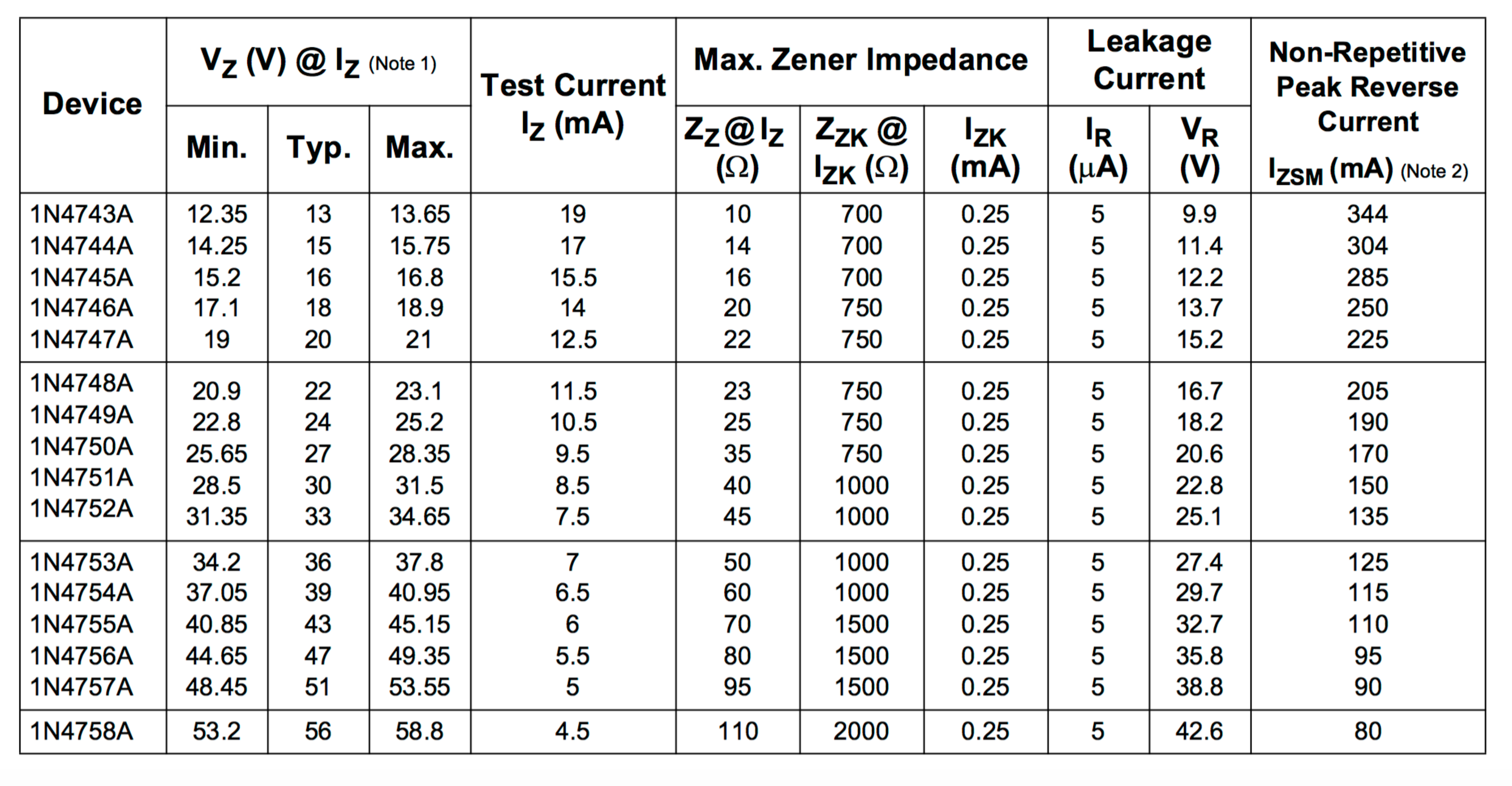
From the data sheet for 1N47xy family of Zener diodes.



Electrical Characteristics

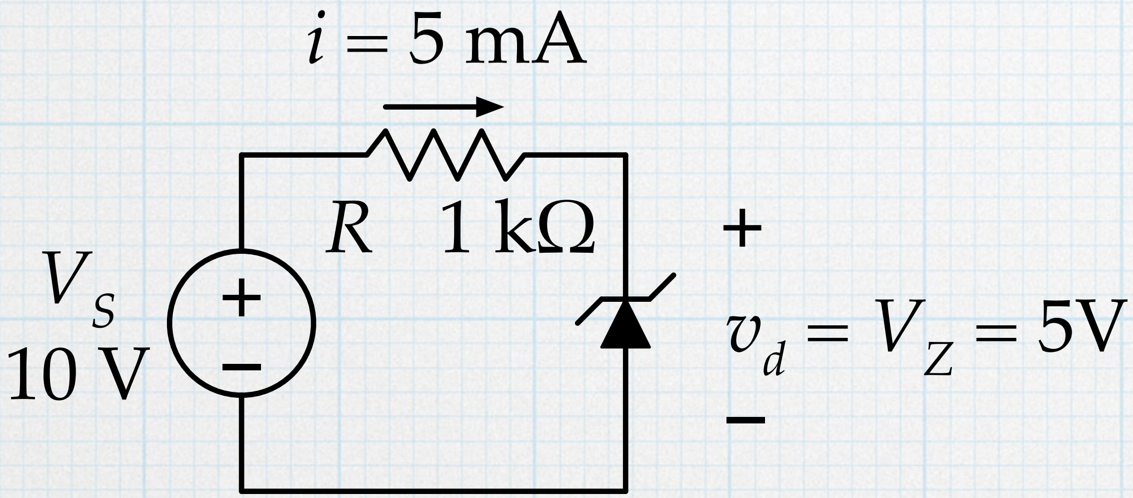
T_a = 25°C unless otherwise noted

Device	V_Z (V) @ I_Z (Note 1)			Test Current I_Z (mA)	Max. Zener Impedance			Leakage Current		Non-Repetitive Peak Reverse Current I_{ZSM} (mA) (Note 2)
	Min.	Typ.	Max.		Z_Z@I_Z (Ω)	Z_{ZK} @ I_{ZK} (Ω)	I_{ZK} (mA)	I_R (μA)	V_R (V)	
1N4728A	3.135	3.3	3.465	76	10	400	1	100	1	1380
1N4729A	3.42	3.6	3.78	69	10	400	1	100	1	1260
1N4730A	3.705	3.9	4.095	64	9	400	1	50	1	1190
1N4731A	4.085	4.3	4.515	58	9	400	1	10	1	1070
1N4732A	4.465	4.7	4.935	53	8	500	1	10	1	970
1N4733A	4.845	5.1	5.355	49	7	550	1	10	1	890
1N4734A	5.32	5.6	5.88	45	5	600	1	10	2	810
1N4735A	5.89	6.2	6.51	41	2	700	1	10	3	730
1N4736A	6.46	6.8	7.14	37	3.5	700	1	10	4	660
1N4737A	7.125	7.5	7.875	34	4	700	0.5	10	5	605
1N4738A	7.79	8.2	8.61	31	4.5	700	0.5	10	6	550
1N4739A	8.645	9.1	9.555	28	5	700	0.5	10	7	500
1N4740A	9.5	10	10.5	25	7	700	0.25	10	7.6	454
1N4741A	10.45	11	11.55	23	8	700	0.25	5	8.4	414
1N4742A	11.4	12	12.6	21	9	700	0.25	5	9.1	380

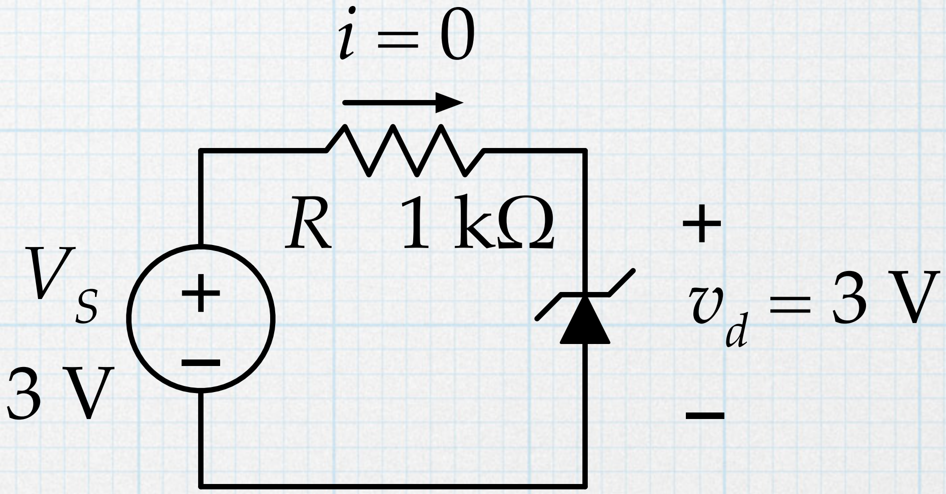


Device	V_Z (V) @ I_Z (Note 1)			Test Current I_Z (mA)	Max. Zener Impedance			Leakage Current		Non-Repetitive Peak Reverse Current I_{ZSM} (mA) (Note 2)
	Min.	Typ.	Max.		Z_Z@I_Z (Ω)	Z_{ZK} @ I_{ZK} (Ω)	I_{ZK} (mA)	I_R (μA)	V_R (V)	
1N4743A	12.35	13	13.65	19	10	700	0.25	5	9.9	344
1N4744A	14.25	15	15.75	17	14	700	0.25	5	11.4	304
1N4745A	15.2	16	16.8	15.5	16	700	0.25	5	12.2	285
1N4746A	17.1	18	18.9	14	20	750	0.25	5	13.7	250
1N4747A	19	20	21	12.5	22	750	0.25	5	15.2	225
1N4748A	20.9	22	23.1	11.5	23	750	0.25	5	16.7	205
1N4749A	22.8	24	25.2	10.5	25	750	0.25	5	18.2	190
1N4750A	25.65	27	28.35	9.5	35	750	0.25	5	20.6	170
1N4751A	28.5	30	31.5	8.5	40	1000	0.25	5	22.8	150
1N4752A	31.35	33	34.65	7.5	45	1000	0.25	5	25.1	135
1N4753A	34.2	36	37.8	7	50	1000	0.25	5	27.4	125
1N4754A	37.05	39	40.95	6.5	60	1000	0.25	5	29.7	115
1N4755A	40.85	43	45.15	6	70	1500	0.25	5	32.7	110
1N4756A	44.65	47	49.35	5.5	80	1500	0.25	5	35.8	95
1N4757A	48.45	51	53.55	5	95	1500	0.25	5	38.8	90
1N4758A	53.2	56	58.8	4.5	110	2000	0.25	5	42.6	80

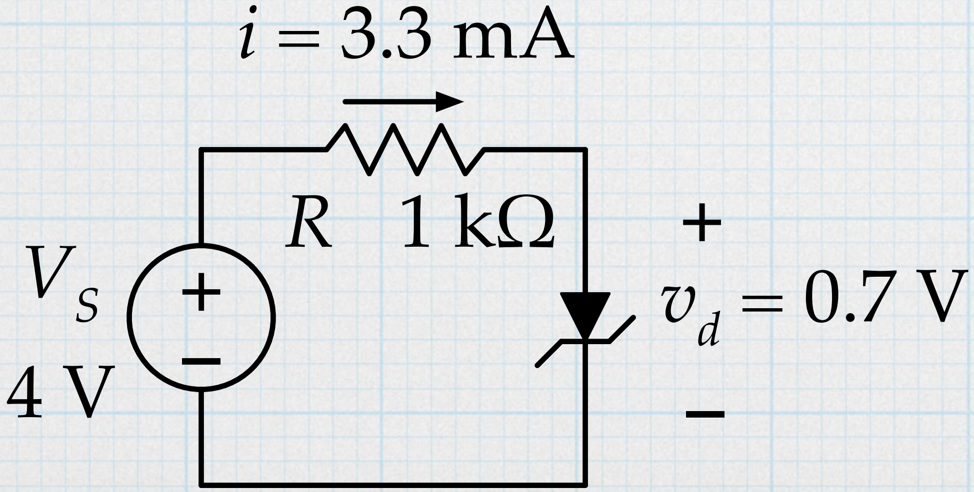
Like a regular diode in forward bias, the Zener operation in breakdown must have some means to prevent the current from becoming too big. Usually this is done using a protection resistor in series. If there is enough reverse voltage in a circuit, the Zener will go into breakdown. The voltage across the Zener (from cathode to anode) will be V_Z and the current will be determined by the limitations imposed by the attached circuitry. The Zener used in the simple examples breaks down at 5 V.



Zener in breakdown.



Zener in reverse bias (not in breakdown).

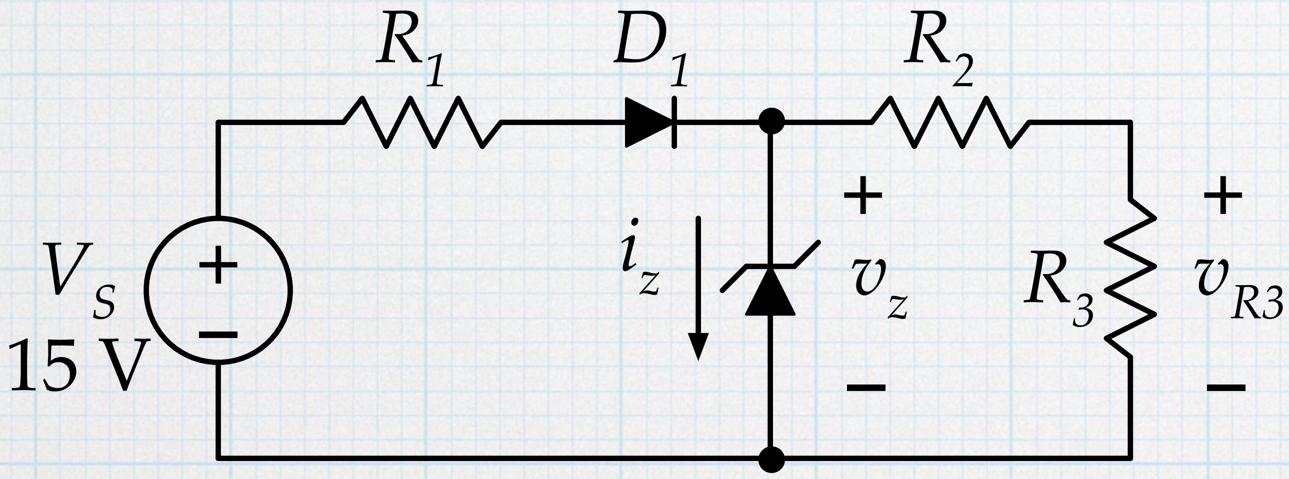


Zener forward biased.

Example 1

Analyzing circuits that have Zener diodes uses the same basic approach as regular diodes except that now there is a third option – breakdown. Generally, a circuit would not have a Zener that is intended to used in forward bias, so it is reasonable to limit the initial “guessing” to “off” or “breakdown”.

For the circuit below, find v_{R3} and i_z. The Zener diode has a breakdown at 6 V. The resistors are all 1 kΩ.



Since $V_S > V_Z$, the Zener is probably in breakdown, so $v_Z = 6$ V.

Then we can use a voltage divider to find v_{R3}.

$$i_z = i_{R1} - i_{R2}$$

$$v_{R3} = \frac{R_3}{R_3 + R_2} v_z = \frac{v_z}{2} = 3 \text{ V}$$

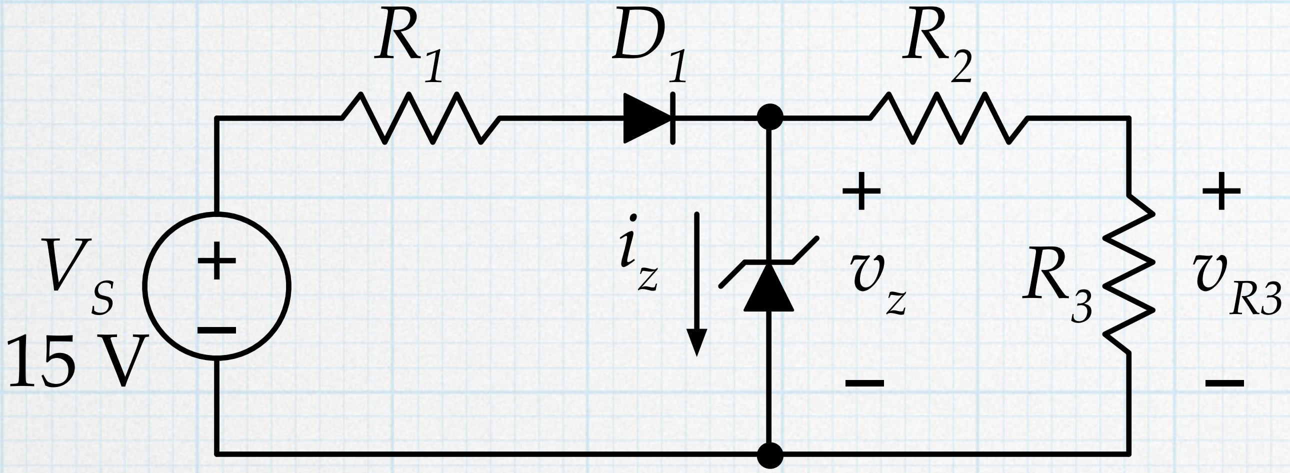
$$i_{R1} = \frac{V_S - 0.7V - V_Z}{R_1} = 8.3 \text{ mA}$$

$$i_{R2} = \frac{V_Z}{R_2 + R_3} = 3 \text{ mA}$$

So $i_z = 5.3$ mA.

Example 2

Repeat the previous example for V_S = 25 V and V_S = 5 V.

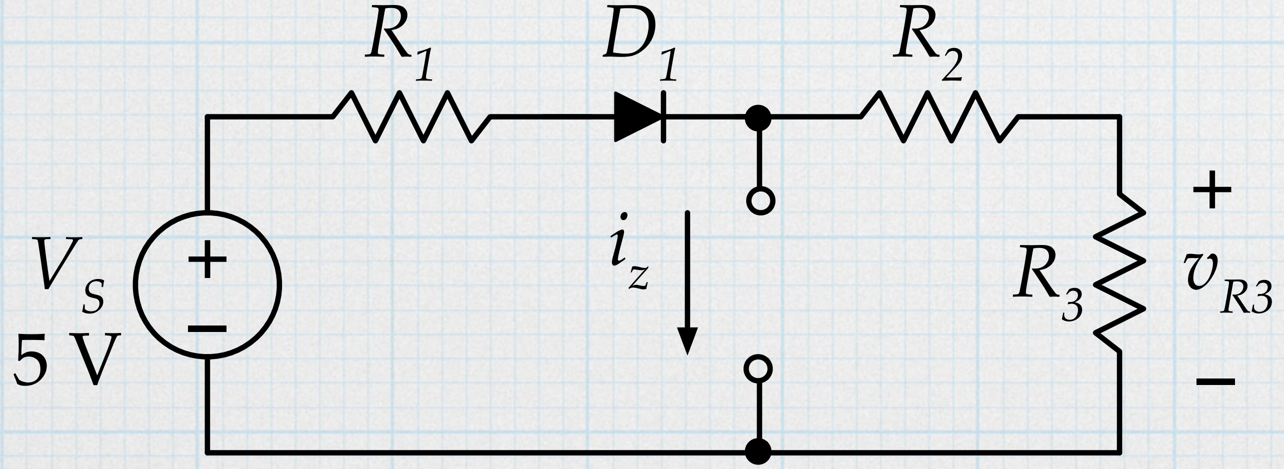


Since $V_S > V_Z$, the Zener is probably in breakdown, so v_Z = 6 V (still), v_{R3} = 3 V (still), and v_{R2} = 3 mA (still).

$$i_{R1} = \frac{25\text{ V} - 0.7V - 6\text{ V}}{R_1} = 18.3\text{ mA}$$

So i_z = 15.3 mA.

If V_S = 5 V, there is not enough source voltage to turn on both D_1 and the Zener. Assume that the Zener is off, so i_z = 0.



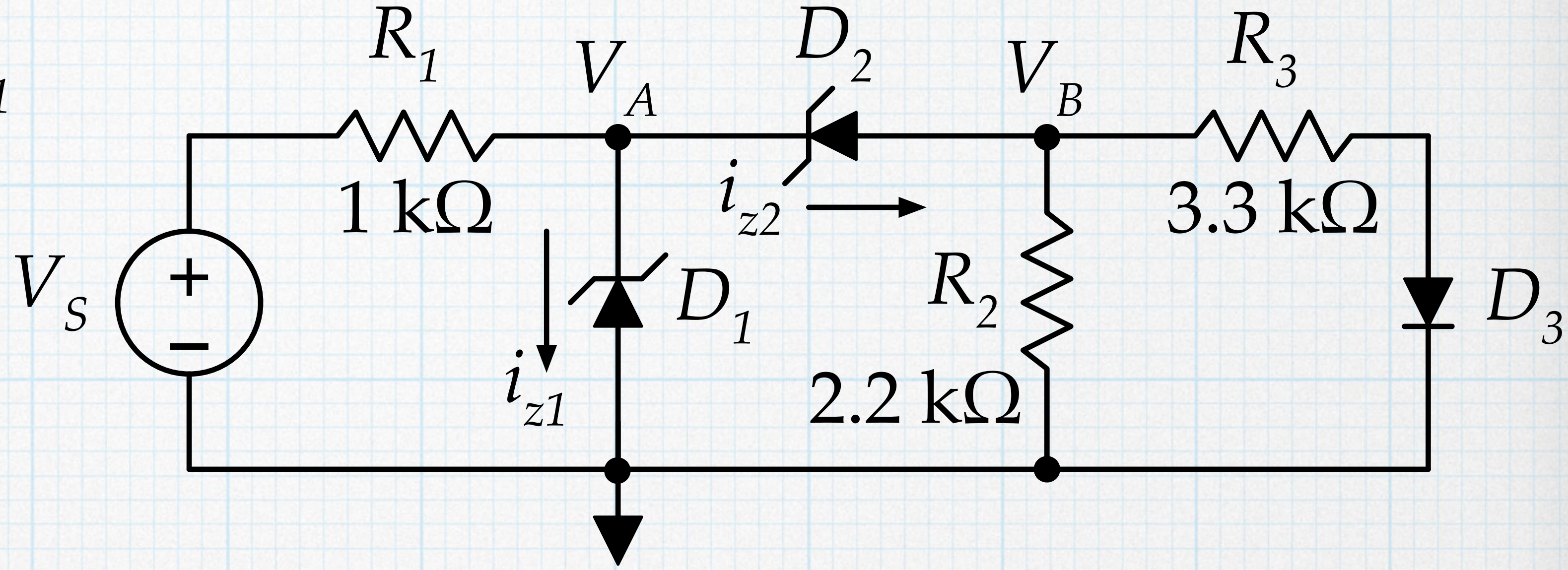
$$i_{R1} = i_{R2} = i_{R3}$$

$$i_{R1} = \frac{V_S - 0.7V}{R_1 + R_2 + R3} = 1.43\text{ mA}$$

$$v_{R3} = 1.43\text{ V}$$

Example 3

For the circuit at right, find i_{z1} and i_{z2} for the cases of V_S = 15 V, 8 V, and 4 V. Zener D_1 has a breakdown at 10 V and D_2 has a breakdown at 5 V.



V_S = 15 V.

There is enough source voltage so that D_1 should be operating in break down, so that V_A = 10 V. With V_A = 10 V, there is enough voltage so that D_2 should also be in break down, meaning that V_B = 10 V – 5 V = 5 V. Finally, with V_B = 5 V, D_3 should be in forward bias.

Then: $i_{R3} = (5\text{ V} - 0.7\text{ V})/(3.3\text{ k}\Omega) = 1.30\text{ mA}.$

$i_{R2} = (5\text{ V})/(2.2\text{ k}\Omega) = 2.27\text{ mA}.$

$i_{z2} = i_{R2} + i_{R3} = 3.57\text{ mA}$

$i_{R1} = (15\text{ V} - 10\text{ V})/(1\text{ k}\Omega) = 5\text{ mA}.$

$i_{z1} = i_{R1} - i_{z2} = 1.43\text{ mA}$

$V_S = 8$ V.

Now there is not enough source voltage to break down D_1 , so we don't yet know V_A. However, there should be sufficient voltage that D_2 is in break down, in which case $V_B = V_A - 5$ V. We can guess that D_3 will also be in forward bias, but we should check afterwards.

Note: with D_1 off, $i_{R1} = i_{z2} = i_{R2} + i_{R3}$.

$$\frac{V_S - V_A}{R_1} = \frac{V_S - (V_B + V_{Z2})}{R_1} = \frac{V_B}{R_2} + \frac{V_B - 0.7V}{R_3}$$

After a bit of algebraic grunt work, we find $V_B = 1.59$ V and so $V_A = 6.59$ V.

Then: $i_{R3} = (1.59\text{ V} - 0.7\text{ V})/(3.3\text{ k}\Omega) = 0.27$ mA → confirming D_3 is on.

$i_{R2} = (1.59\text{ V})/(2.2\text{ k}\Omega) = 0.72$ mA.

$i_{z2} = i_{R2} + i_{R3} = 0.99$ mA

$V_S = 4$ V.

There is not enough voltage to turn on either Zener, so there is no path for any current to flow. This is a dead circuit.