The exponential diode

A theoretical analysis of the *p-n* junction structure yields a single equation which describes the forward-bias and reverse-bias operation:

$$i_A = I_S\left(\exp\frac{v_A}{n\cdot V_T} - 1\right)$$

I_S is the reverse saturation current (in the range of μA for germanium and pA for silicon). A better name is the "scale current"; it arises from the fact that I_S is directly proportional to the cross-sectional area of the diode (e.g. – for a double area device we get a double value of diode current i_A for the same diode voltage v_A).

V_T is the thermal voltage; $V_T = \frac{k\cdot T}{q}$ with a typical value: V_T=26 mV for T=300K = 27dgr.C.

- k is the Boltzmann constant ($=1.38\cdot 10^{-23}$J/K),
- T is the absolute temperature (in Kelvin).
- q is the electronic charge ($=1.6\cdot 10^{-19}$ C).

$n=1\ldots 2$ is a coefficient; diodes made using the standard integrated circuits fabrication process exhibits $n=1$ (when operated in normal conditions) while diodes available as discrete two-terminal devices generally exhibits $n=2$.

Forward bias – voltage-current relationship

For $v_A >> V_T$, the exponential factor is much greater than unity, hence the "1" can be neglected in the diode equations and:

$$i_A = I_S\exp\frac{v_A}{n\cdot V_T}.$$

The exponential relationship between diode current and diode voltage means that:

- the forward current is much larger than the reverse current and
- the forward current increase very rapidly with small increases in v_A.

To derive a different relationship, sometimes more useful, one can consider two currents for two corresponding voltages: $i_1 = I_S\exp\frac{v_1}{n\cdot V_T}$, $i_2 = I_S\exp\frac{v_2}{n\cdot V_T}$. The current ratio is:

$\frac{i_1}{i_2} = I_S\exp\frac{v_1 - v_2}{n\cdot V_T}$, which can be rewritten as: $v_1 - v_2 = n\cdot V_T\ln\frac{i_1}{i_2} = 2.3\cdot n\cdot V_T\lg\frac{i_1}{i_2}$.

This equation simply states that for a decade (factor of 10) change in current, the diode voltage drop changes by "$2.3\cdot n\cdot V_T$", which is about 60 mV for $n=1$ and 115 mV for $n=2$.

A convenient approximate number of 0.1 V / decade for the slope of the diode logarithmic characteristic can be used (if the coefficient n is not known).

A small silicon rectifier diode can be considered to have a 0.6 V voltage drop at a current $i_A=1$ mA and a 0.1 V voltage drop change for a decade change in current.

Temperature dependence

At a given constant diode current, the voltage drop across the diode decreases by approximately 2 mV for every degree Celsius increase in temperature.

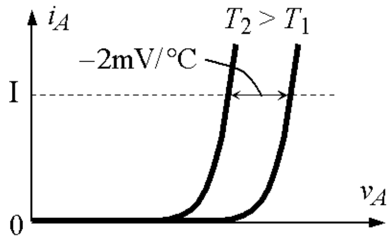


Figure The temperature influence over the forward characteristics of the diode;

At a constant current, the voltage drop decreases by about 2 mV for every degree Celsius increase in temperature.

The *pn* Junction in the Breakdown Regime

The two possible breakdown mechanisms are the Zener effect (with a breakdown voltage $V_Z < 5$ V) and the avalanche effect (that occurs when V_Z is greater than about 7 V).

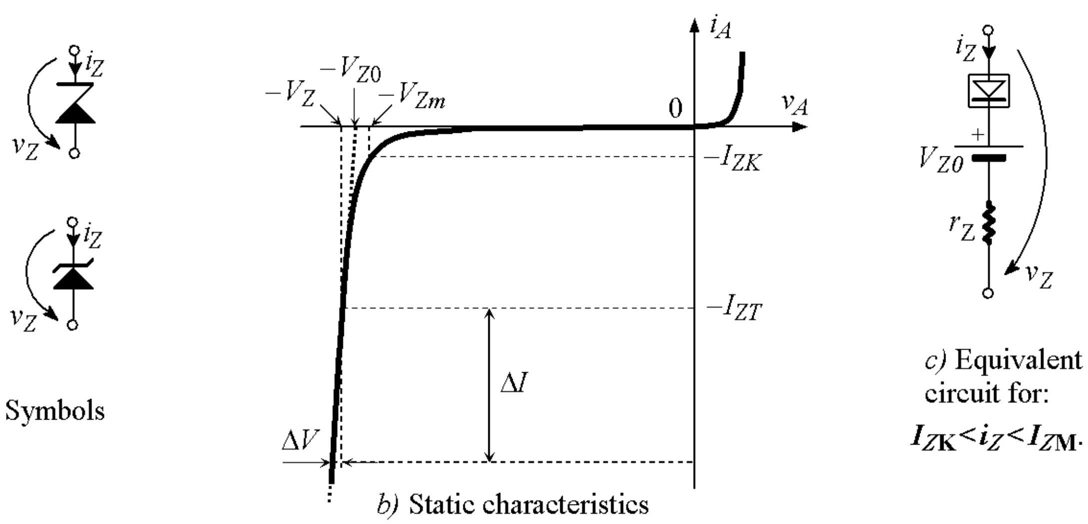
In heavily doped junctions, the depletion layer is very narrow and the electrical field becomes so strong that it can dislocate electrons directly from the covalent bonds and generate electron-hole pairs. These electrons and holes produce a rapid increase in reverse current (once the reverse blocking voltage is exceeded). This is the Zener breakdown process.

The avalanche breakdown occurs at a certain value of the electrical field, when the minority carriers gain sufficient kinetic energy to be able to break covalent bonds in atoms with which they collide. These new liberated carriers may themselves produce still more mobile electrons and holes through additional collisions; a rapid build-up of reverse current results (with a negligible change in the voltage drop across the junction).

The pn junction breakdown is not a destructive process, provided that the maximum specified power dissipation is not exceeded. Special diodes, called Zener diodes, have been manufactured to operate in the breakdown regime of the *pn* junction.

Zener Diodes

In normal applications of Zener diodes, current flows into the cathode and the cathode is positive with respect to the anode: $i_Z = -i_A > 0$, $v_Z = -v_A > 0$.



a) Symbols

b) Static characteristics

c) Equivalent circuit for: $I_{ZK} < i_Z < I_{ZM}$.

The Zener diode maintains an essentially constant voltage across its terminals over a specific range in reverse current values. A minimum value of reverse current I_{ZK} (knee current) must be maintained in order to keep diode in regulation. There is a maximum current I_{ZM}, above which the diode may be damaged (the maximum permitted power $P_{dZM}=V_Z I_{ZM}$, is exceeded).

Zener Equivalent Circuits

The ideal approximation: the voltage drop across the Zener diode is constant $v_Z=V_Z$ for a positive Zener current $i_Z>0$; the diode model is an ideal diode in series with a constant voltage source V_Z.

A more complex model indicated in the previous figure includes a series resistance; that is the incremental resistance of the Zener diode and it represents the ratio of voltage to current change: $r_Z = \frac{\Delta v_Z}{\Delta i_Z}$. The Zener data-sheet indicates the Zener voltage and r_Z at a particular value of current I_{ZT}, called the Zener test current.

Another parameter of the diode is the temperature coefficient that specifies the percent change in Zener voltage for each degree C change in temperature. A Zener diode with a nominal breakdown voltage of 5.1 V exhibits a point of zero temperature coefficient at modest current levels.

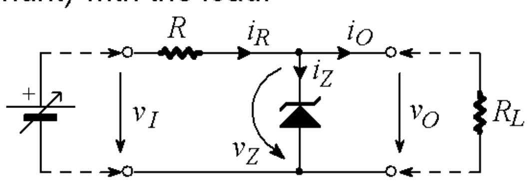
Forward biased, a Zener diode acts as a normal rectifier diode.

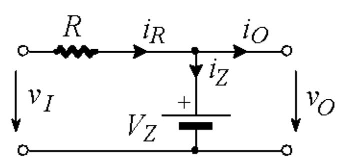
Zener Applications

The Voltage Regulator

A voltage regulator is a circuit whose purpose is to provide a constant dc voltage in spite of changes in the load current and possible changes in the dc power supply that feeds the regulator circuit.

The circuit of figure is known as a "shunt regulator" because the Zener diode is connected in parallel (shunt) with the load.





The changes in the load current and the input voltage variations are transformed by the circuit in zener current variations. If we consider the ideal Zener model, for: $I_{ZK}<i_Z<I_{ZM}$, $v_Z=V_Z$ and $v_O=v_Z=V_Z=$ct.

The limits of v_I and i_O for the circuit to work correctly can be found with the ideal Zener model.

To analyze the influence of input voltage, the output current will be considered constant: $i_O=$ct $=I_O$, $i_Z = i_R - i_O = \frac{v_I - V_Z}{R} - i_O > I_{ZK}$ and $v_I > V_Z + R\cdot\left(I_{ZK} + I_O\right)$. In any case $v_I>V_Z$.

For $v_I=$ct $=V_I$, $i_O < \frac{v_I - V_Z}{R} - I_{ZK}$.

When the output terminals are open, the load current is zero, all the current is through the Zener and the current in the resistor is constant (for a given input voltage): $i_r = \frac{v_I - V_Z}{R}$.

When a load resistance is connected part of this current is through the Zener and part of it through the load: $i_R = i_Z + i_O$. As R_L decreases, i_O goes up and i_Z goes down. The circuit continues to regulate until i_Z reach its minimum value I_{ZK}. At this point the load current reaches its maximum value (with the regulator working properly).

Two parameters can be used to measure how will the regulator is performing its function:

- The Line Regulation: $LineRg = \left.\frac{\Delta v_O}{\Delta v_I}\right|_{I_O = ct}$ – it represents the change in v_O corresponding to a 1 V change in v_I.
- The Load Regulation: $LoadRg = \left.\frac{\Delta v_O}{\Delta i_O}\right|_{V_I = ct}$ – it represents the change in v_O corresponding to a 1 mA change in i_O.

The Maximum Limiting Resistance

The Zener current should be at least equal to the knee current in any conditions supported by the regulator; that means: $i_{Z\min} > I_{ZK}$. The worst case for $i_{Z\min}$

$i_{Z\min} = \frac{v_{I\_\min} - V_Z}{R} - i_{O\max} > I_{KZ}$ gives the limiting resistance: $R \le \frac{v_{I\_\min} - V_Z}{i_{O\max} + I_{ZK}}$.

Applications:

S4 – P1. Design a voltage regulator supplyied by $v_I = 9\ldots 12$ V for a maximum output current $i_{OM} = 100$ mA. Consider an ideal zener diode with $V_Z = 5.1$ V ($i_{ZK} = 0$ and $r_Z = 0$). Determine the series resistor value, maximum power disipated by the resistor and by the zener diode.

$$R \le \frac{v_{I\_\min} - V_Z}{i_{O\max} + I_{ZK}} = \frac{9 - 5.1}{100m} = 39\,\Omega,\ P_{dRM} = \frac{(v_{I\_\max} - V_Z)^2}{R} = \frac{(12 - 5.1)^2}{39} = \frac{47.6}{39} = 1.22\,\text{W},$$

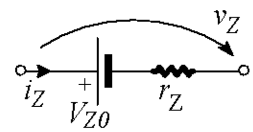
$$P_{dZM} = V_Z \cdot i_{Z\max} = V_Z \frac{v_{I\_\max} - V_Z}{R} = 5.1\frac{12 - 5.1}{39} = 5.1 \cdot 0.177 = 0.9\ \text{W}.$$

S4 – P2. It is required to design a zener shunt regulator to provide a regulated voltage of about 10 V. The available 10-V 1W zener of type 1N4740 is specified to have a 10 V drop at a test current of 25 mA. At this current its typical r_Z is 7Ω. The raw supply available has a nominal value of 20 V but can vary as much as $+/-25\%$. The regulator is required to supply a load current of 0 to 80 mA, Design for a minimum zener current of 5 mA.

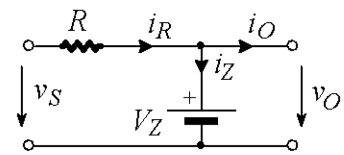
a) Find V_{Z0}.
b) Calculate the required value of R.
c) What is the change in V_O expressed as a percentage, corresponding to the $+/-25\%$ change in V_S?
d) By what percentage does V_O change from the no-load to the full-load condition?

e) What is the maximum current that the zener in your design should be able to conduct? What is the zener power disipation under these condition?

a) From the zener equivalent circuit: $v_Z = V_{Z0} + r_Z i_Z$;
At I_{ZT} we get $V_{ZT} = V_{Z0} + r_Z I_{ZT}$ and
$V_{Z0} = V_{ZT} - r_Z I_{ZT} = 10 - 7 \cdot 25m = 9.825\text{V}$.



b) The main condition for the circuit to work correctly is $i_Z > I_{ZK}$, for any i_Z that can appear in the circuit; $i_Z = i_R - i_O = \dfrac{v_S - V_Z}{R} - i_O$.



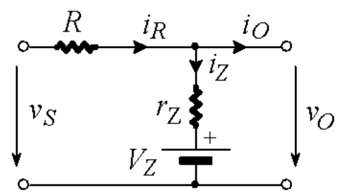
The previous inequality applied for minimum i_Z can be used to compute R, $i_{Z\min} = \dfrac{v_{S\min} - V_Z}{R} - i_{O\max} > I_{ZK}$ and

$$R \le \frac{v_{S\min} - V_Z}{i_{O\max} - I_{ZK}} = \frac{0.75 \cdot 20 - 10}{20m + 5m} = \frac{5}{25m} = 200\,\Omega.$$

c) Line regulation for $i_O = 0$ $(i_R = i_Z)$: $v_O = V_{Z0} + r_Z i_Z$,

$$v_O = V_{Z0} + r_Z \frac{v_S - V_{Z0}}{R + r_Z};\ \Delta v_O = r_Z \frac{\Delta v_S}{R + r_Z} = 7\frac{10}{207} = 0.338\text{V}.$$

$$LineRg = \frac{\Delta v_O}{\Delta v_I} \cdot 100 = \frac{0.338}{10} 100 = 3{,}38\,\%\ (34\,\text{mV/V}).$$



d) Assume the nominal value of raw supply: $V_S = 20\,\text{V}$.

For no-load condition we get: $v_{O\max} = V_{Z0} + r_Z \dfrac{V_S - V_{Z0}}{R + r_Z} = 9.825 + 7\dfrac{20 - 9.825}{207} = 10.169\text{V}$.

For full-load condition, the zener current is minimum and the output voltage is minimum:

$$i_z\left(1 + \frac{r_Z}{R}\right) = \frac{V_S - V_{Z0}}{R} - i_O,\ i_{z\min} = \frac{\dfrac{V_S - V_{Z0}}{R} - i_{O\max}}{1 + \dfrac{r_Z}{R}} = \frac{\dfrac{20 - 9.825}{200} - 20m}{1 + \dfrac{7}{200}} = \frac{30.875}{1.035} = 29.83\text{mA}.$$

$$v_{O\min} = V_{Z0} + r_Z i_{Z\min} = 9.825 + 7 \cdot 29.83m = 10.034\text{V};\ LoadRg = \frac{\Delta v_O}{\Delta i_O} = \frac{10.169 - 10.034}{20m} = 6.75\,\Omega.$$

That is also the Thevenin equiv.resistance seen at the output: $R_T = r_Z \parallel R = \dfrac{7 \cdot 200}{207} 6.76\,\Omega$.

e) The maximum zener current (and voltage) appears for the no-load condition:

$$i_{Z\max} = \frac{V_{S\max} - V_{Z0}}{R + r_Z} = \frac{25 - 9.825}{207} = 73.3\text{mA},\ v_{Z\max} = V_{Z0} + r_Z i_{Z\max} = 9.825 + 7 \cdot 73m = 10.34\,\text{V}.$$

The maximum power dissipated by zener is: $P_{dZ\max} = v_{Z\max} \cdot i_{Z\max} = 10.34 \cdot 73m \cong 0.76\,\text{W}$.

S4 – P3.

a) Determine the parameter of a zener diode (V_Z and r_Z) if one measured $v_{Z1} = 6.3$ V at $i_{Z1} = 50$ mA and $v_{Z1} = 6.3$ V at $i_{Z2} = 100$ mA.
b) Utilizing this dide, design a voltage regulator supplyied by $v_I = 12 \ldots 15$ V for an output current $i_O = 20 \ldots 80$ mA. Consider $i_{ZK} = 5$ mA. (Determine R and P_{dRM}.)
c) Determine the output voltage limits ($v_{O\min}$ and $v_{O\text{Max}}$).