

# Diode Characteristics

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## Introduction

This paper examines various electrical characteristics of a typical silicon junction diode. Useful mathematical relations are shown and illustrated with plots.

All of the plots are based on a typical sample of a very common small signal diode, the 1N4148 using a spreadsheet, diode\_plots.xls, written by the author and posted on his web site: <http://www.kennethkuhn.com> . Because parameters vary from diode to diode, these plots should be interpreted as representative rather than absolute. Variations from diode to diode would typically be in the plus or minus several percent. To illustrate temperature effects, several of the plots are created using three temperatures: the high temperature is 100 C, the medium temperature is 25 C, and the low temperature is 0 C.

## Forward current versus voltage

The standard equation for current through a diode is:

$$I = I_S * (\exp^{(V/(n*k*T/q))} - 1) \quad \text{Eq. 1}$$

Where:

I is the current through the diode

$I_S$  is the reverse saturation current

V is the voltage across the diode (can be positive or negative)

n is a junction constant (typically around 2 for diodes, 1 for transistors)

k is Boltzmann's constant, 1.38E-23 Joules/Kelvin

T is temperature in Kelvins

q is the magnitude of an electron charge, 1.609E-19 coulombs

Looking at Equation 1 it would appear that the current should decrease as the temperature increases. The exact opposite is what really occurs. The reverse saturation current,  $I_S$ , is a strong positive function of temperature as discussed below. The increase in  $I_S$  with temperature more than offsets the effect of T in the exponential above.

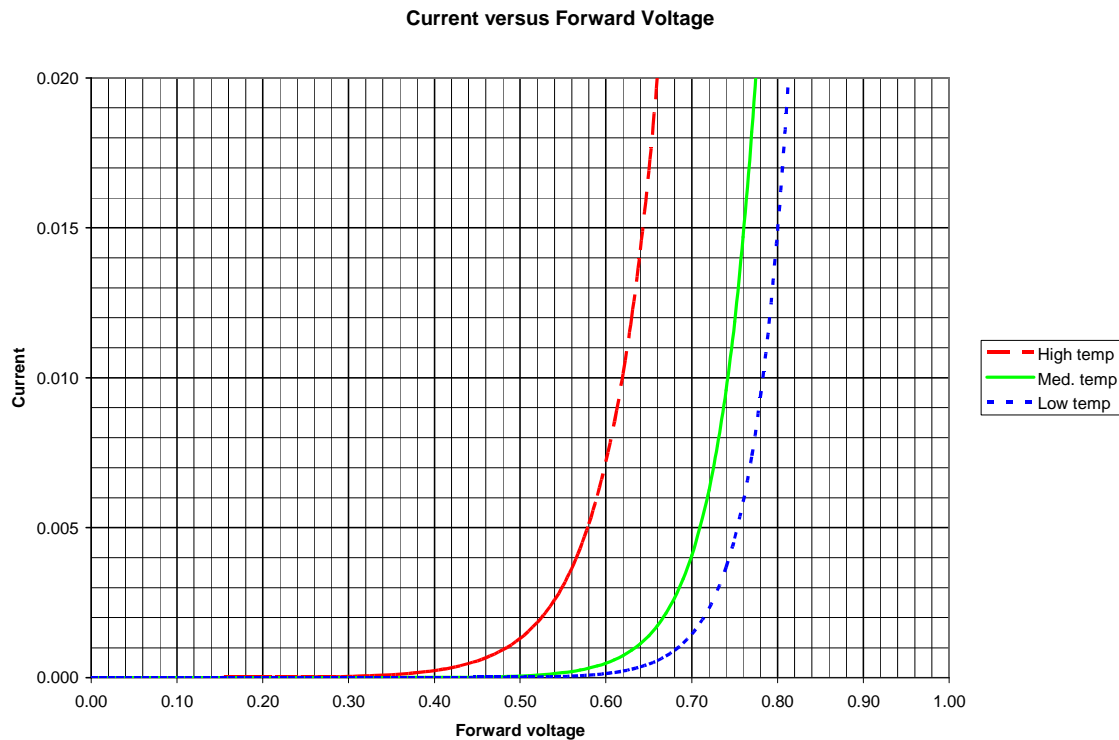
The junction constant, n, is typically a constant at low currents and varies as the current becomes significant and may also vary somewhat with temperature. For this discussion, n will be taken as constant.

The sub-expression,  $kT/q$ , has units of voltage and is referred to as the thermal voltage and is typically around 26 millivolts at room temperature.

$$V_T = k*T/q \quad \text{Eq. 2}$$

## Diode Characteristics

Figure 1 shows a plot of Equation 1 for three temperatures. The strong temperature dependence can be clearly seen. There is a very important thing to note about the plot in Figure 1 – it is not possible to directly obtain the plot by applying a voltage and measuring the resulting current. Doing that will quickly destroy the diode because of a condition known as thermal run-away. Any power applied will heat the diode which in turn will result in the current increasing thus further heating the diode because of the negative temperature coefficient. This can be easily seen in Figure 1. The only way to collect the data for the plot is to apply a current and measure the resulting voltage across the diode. Diodes are current operated devices and should never have a direct voltage applied from a low-impedance source.



*Figure 1: Forward Current versus Forward Voltage*

The -1 term in Equation 1 can be omitted when the forward voltage is greater than about 0.1 volts at room temperature. A chart of the approximation and the exact is shown below.

For  $n = 1$ ,  $V_T = 0.026$  volts

V	Approximation $\exp(V/(n*V_T))$	Exact $[\exp(V/(n*V_T)) - 1]$	error %
0.00	1.00	0.00	infinite
0.02	2.16	1.16	86
0.05	6.84	5.84	17
0.10	46.8	45.8	2.2
0.15	320	319	0.3
0.20	2191	2190	0.05

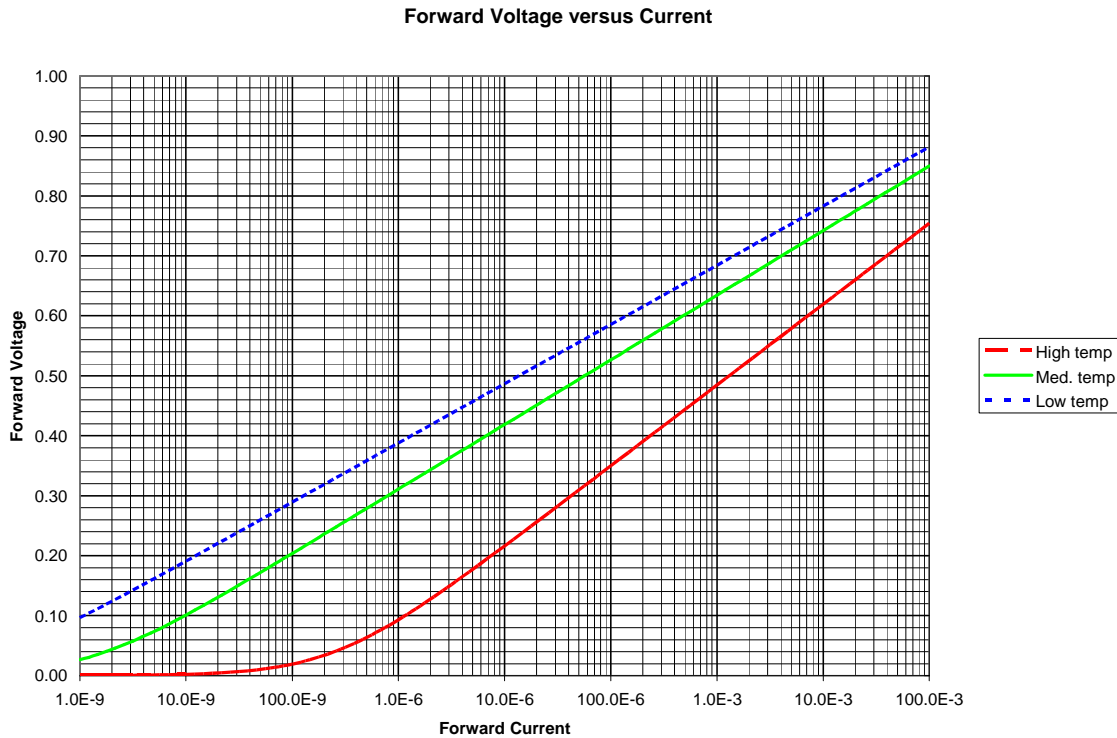
# Diode Characteristics

## Logarithmic forward voltage versus current

It is useful to plot the data in Figure 1 with the axis swapped as is done in Figure 2. An interesting observation in Figure 2 is that the forward voltage is a very linear function of the logarithm of the current through the diode. This characteristic is useful in building electronic logarithmic converters. It should also be observed that the slope is a function of temperature and that creates a complication as temperature compensation is required.

Equation 1 can be solved for the forward voltage:

$$V = n \cdot V_T \cdot \ln[(I / I_S) + 1] \tag{Eq. 3}$$



*Figure 2: Forward Voltage versus Forward Current*

# Diode Characteristics

## Reverse saturation current

When negative voltages are applied to the diode the current becomes constant at  $-I_S$  as the exponential term in Equation 1 quickly approaches zero. That is why it is referred to as the reverse saturation current. The current is independent of applied voltage once a small voltage magnitude is exceeded. This current is very small and is typically in the low nanoampere region. The reverse saturation current is a strong function of temperature as illustrated in Figure 3. The following equation is a simplified model for the reverse saturation current and provides excellent results in normal operating regions.

$$I_S = I_K * \exp^{-E_g/nVT} \quad \text{Eq. 4}$$

Where:

$I_S$  is the reverse saturation current

$I_K$  is a constant derived from  $n$  and  $I_S$  at a known temperature

$E_g$  is the bandgap voltage for silicon (ranges from about 1.20 to 1.28 volts)

$n$  is the junction constant (typically around 2 for diodes, 1 for transistors)

$VT$  is the thermal voltage as previously discussed

The reverse saturation current should not be confused with an imperfection in diodes known as leakage current from a high value shunt resistance across the diode junction. Leakage current is often many times larger than  $I_S$ . Thus,  $I_S$  can not be directly measured and must be computed using data from the forward bias region (see the section on measuring diode characteristics).

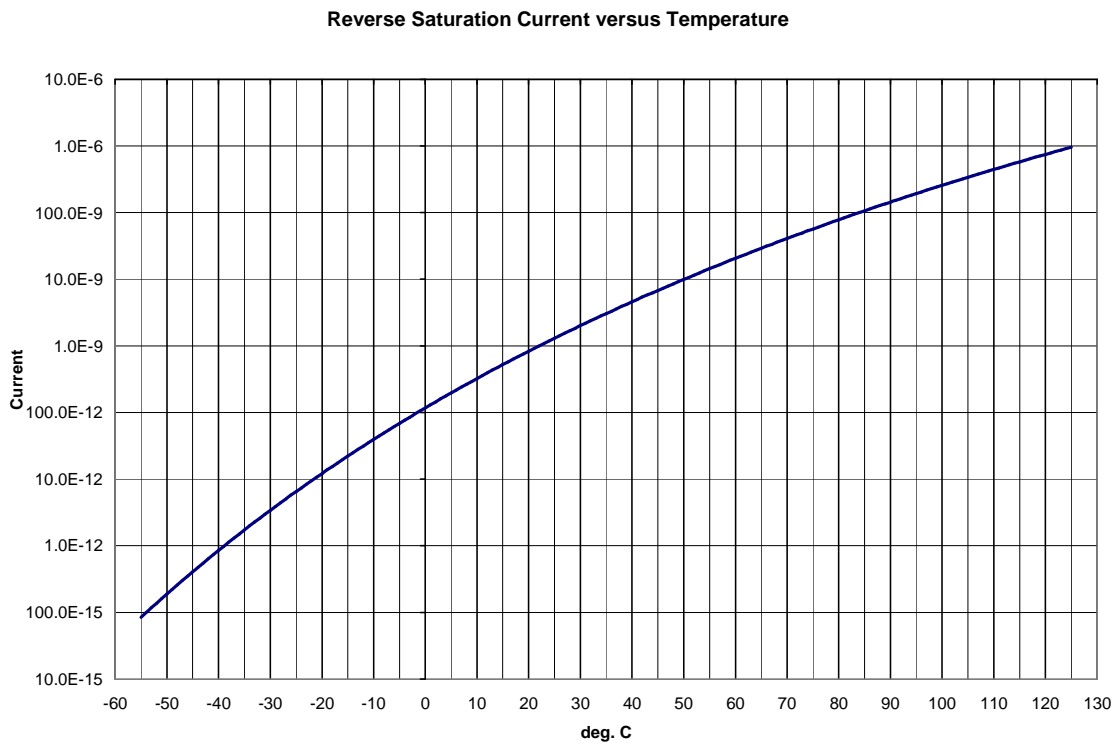


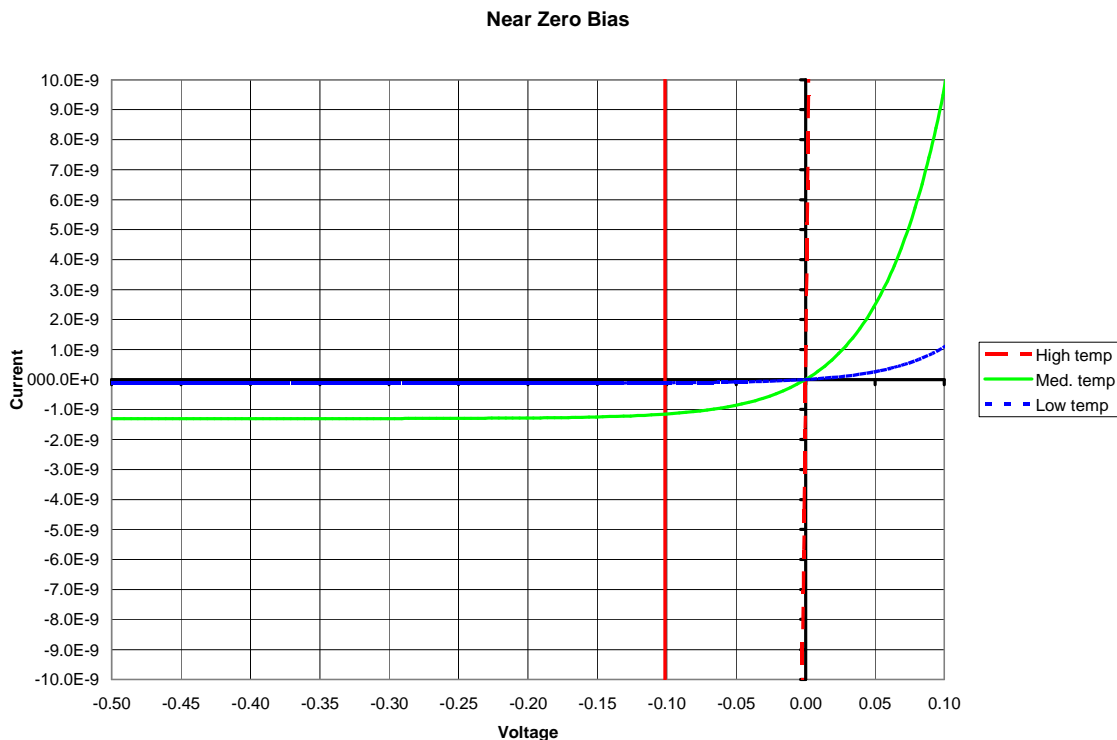
Figure 3: Reverse saturation current,  $I_S$ , versus Temperature

# Diode Characteristics

## Near Zero Bias

A theoretical plot of the diode current for the near zero bias condition is shown in Figure 4. Note that once the reverse voltage exceeds about -0.2 volts in magnitude that the reverse current is the value for  $I_S$  and is independent of reverse voltage – this is why it is referred to as the reverse saturation current. Only the plot for room temperature (25 C) is visible. The low temperature plot is too small to observe on this scale except for the small forward bias region. The high temperature plot is very steep passing through zero volts. This illustrates why it is important to keep diodes cool when reverse current is an issue.

The plot in Figure 4 does not include the effect of leakage shunt resistance across the junction resulting from imperfections in the manufacturing process. This resistance varies from hundreds of millions to tens of billions of ohms. This shunt resistance results in an increasing current with applied reverse voltage and the current can become many times  $I_S$ . The effect of this resistance is most important at low temperatures where  $I_S$  is very small. At high temperatures the effect of large  $I_S$  swamps the resistance.



*Figure 4: Near Zero Bias  
(the vertical red line at -0.1 volts is a Microsoft bug and not part of the actual plot)*

## Diode Characteristics

The plot in Figure 5 includes the effect of leakage shunt resistance. For this plot the resistance is 100 Mohms which was chosen for illustration and is very low compared to typical values of 1000 Mohms or more.

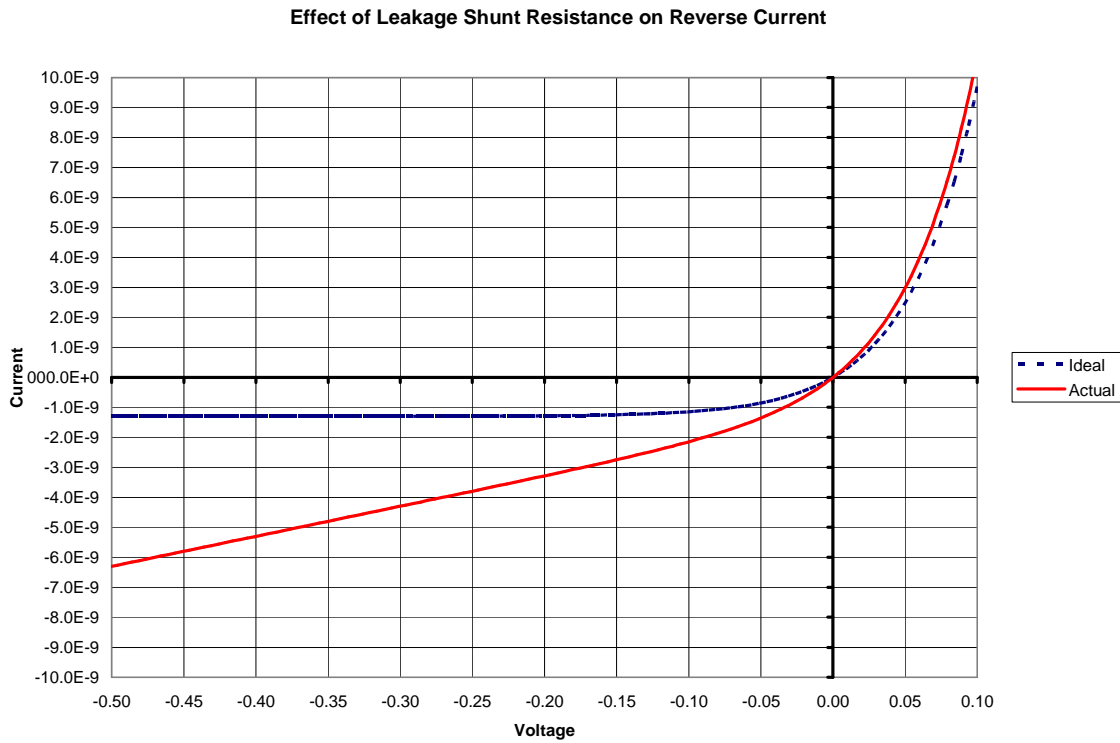


Figure 5: Effect of leakage shunt resistance

# Diode Characteristics

## Temperature effect on forward voltage

With a constant current, the forward voltage drop of a diode has a very linear negative slope with temperature. The slope is also a function of current which is why constant current must be used. This characteristic is useful for building electronic thermometers. This characteristic is shown in Figure 6. Note that the slope becomes steeper as the current through the diode is reduced. For practical temperature measurements it is important that the diode not heat with the applied current. The power dissipation should be less than 1 milliwatt. This means that the constant current should be no more than about 1 milliampere.

The plot in Figure 6 is based on Equation 3 but the x-axis is temperature instead.

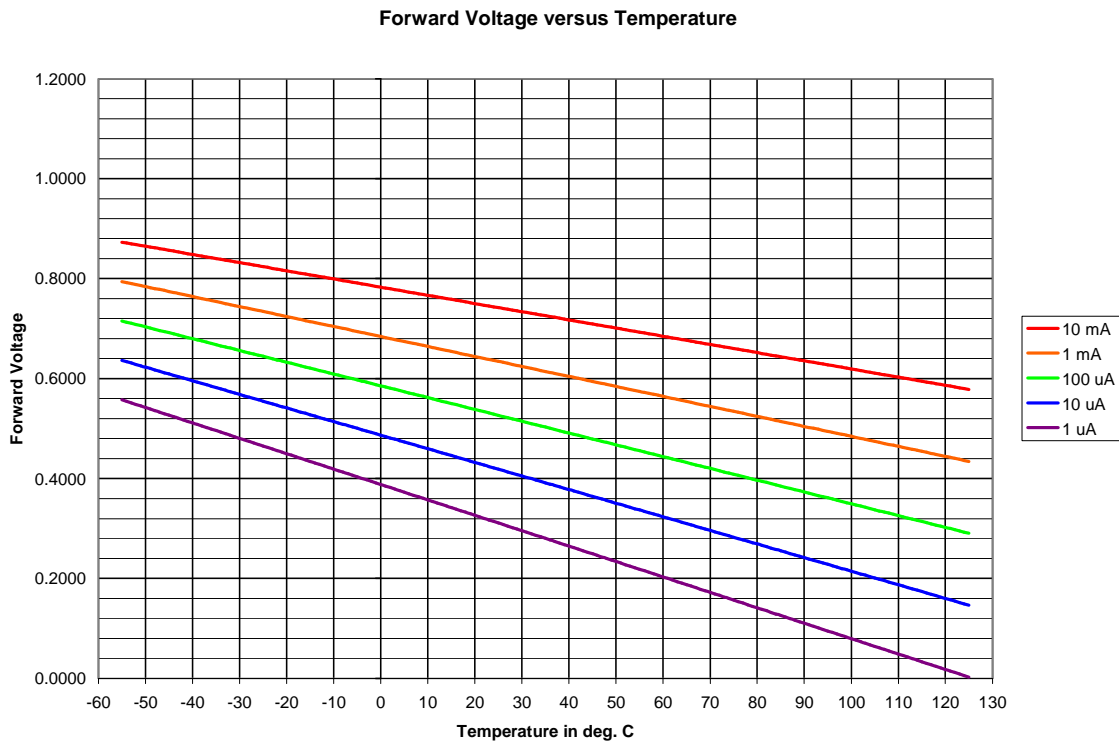
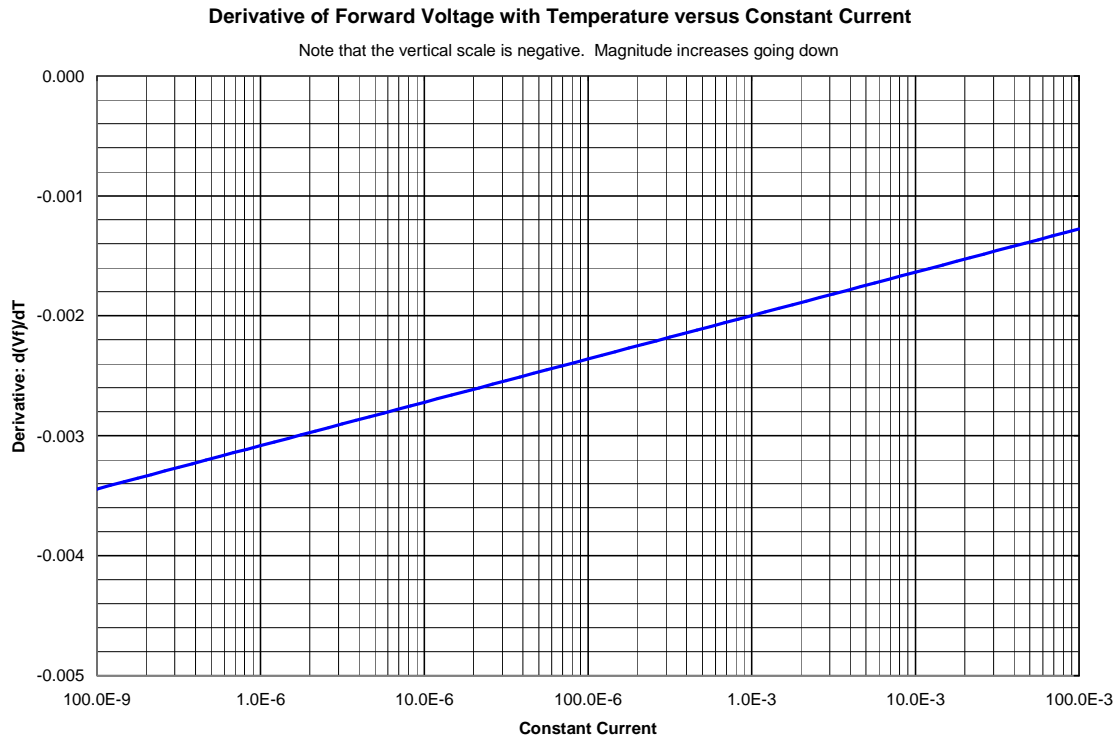


Figure 6: Forward Voltage versus Temperature

# Diode Characteristics

## Temperature slope of forward voltage

The slope of the forward voltage versus temperature curve varies with the magnitude of the constant current as shown in Figure 7. This plot is made by taking the derivative of Equation 3 with respect to current.



*Figure 7: Derivative of Forward Voltage with Temperature versus Constant Current*



# Diode Characteristics

## Forward dynamic resistance

The operating point on Figure 1 represents a conductance (or its reciprocal function, resistance) for small signals (less than about 20 mVpp). The resistance is the reciprocal of the slope of the line through the operating point. This makes it possible to have an electrically variable resistor – the resistance is inversely proportional to the current. Electronically variable resistors are useful for building multipliers and gain control circuits. By taking the reciprocal of the derivative of Equation 1 (leaving off the -1 term) we have the forward dynamic resistance.

$$r_d = n * V_T / I \tag{Eq. 5}$$

Observe that this resistance is a strong function of temperature. A plot of Equation 5 is shown in Figure 8.

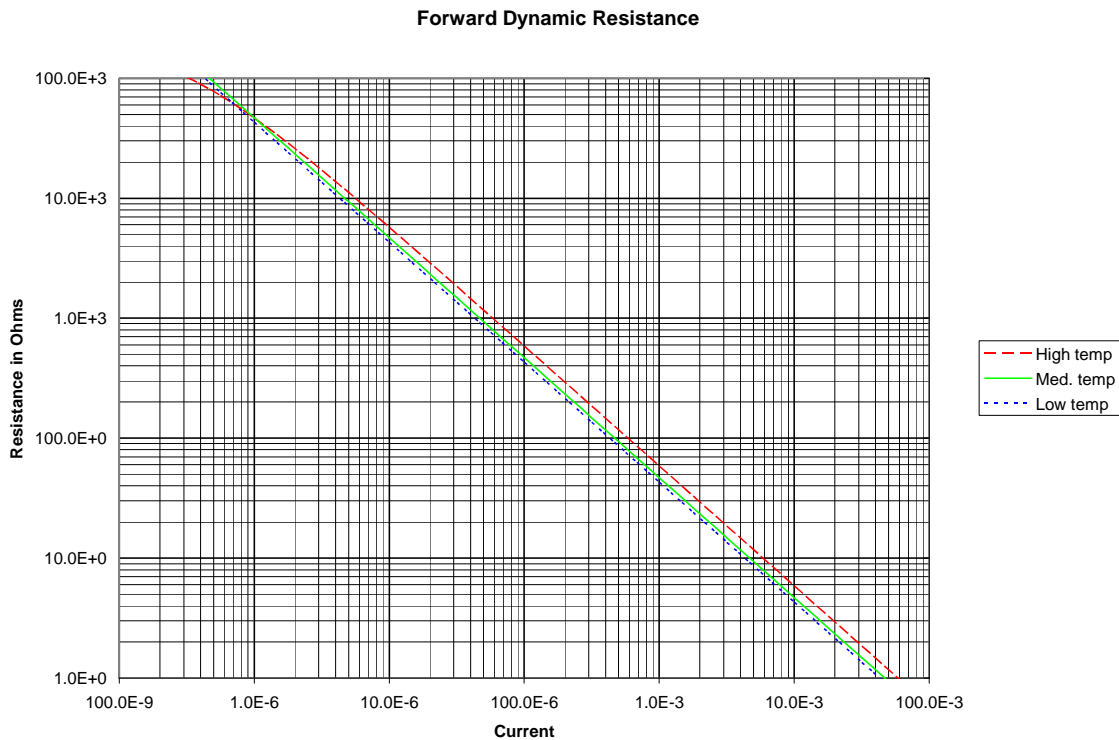


Figure 8: Forward Dynamic Resistance versus Current

# Diode Characteristics

## Bulk Resistance

All diodes have a bulk resistance,  $R_b$ , that is in series with the diode. This resistance is typically very small (typically around 1 ohm or less) and its effects are insignificant at lower currents. At higher currents the effect is to reduce the voltage across the junction by the current multiplied by the resistance. This results in the steep theoretical exponential current versus voltage curve transforming into a linear slope. Equation 6 is Equation 1 with the effect of  $R_b$  included. Equation 6 (which omits the  $-1$  term as that is not applicable for the higher diode currents) does not have a closed form solution as there is no known way to manipulate the equation such that either  $I$  or  $V$  is not involved with either a logarithmic or exponential term. Numerical solutions are the only way to solve Equation 6. Newton's method was used to generate Figure 9.

$$I = I_s * \exp^{((V-I*R_b)/(n*k*T/q))} \quad \text{Eq. 6}$$

Figure 9 is a plot of Equation 6 and shows the effect of a 1 ohm bulk resistance for the room temperature case of the diode. Notice how the current is significantly less than theoretical for higher diode voltages. Note that the slope is nearly linear.

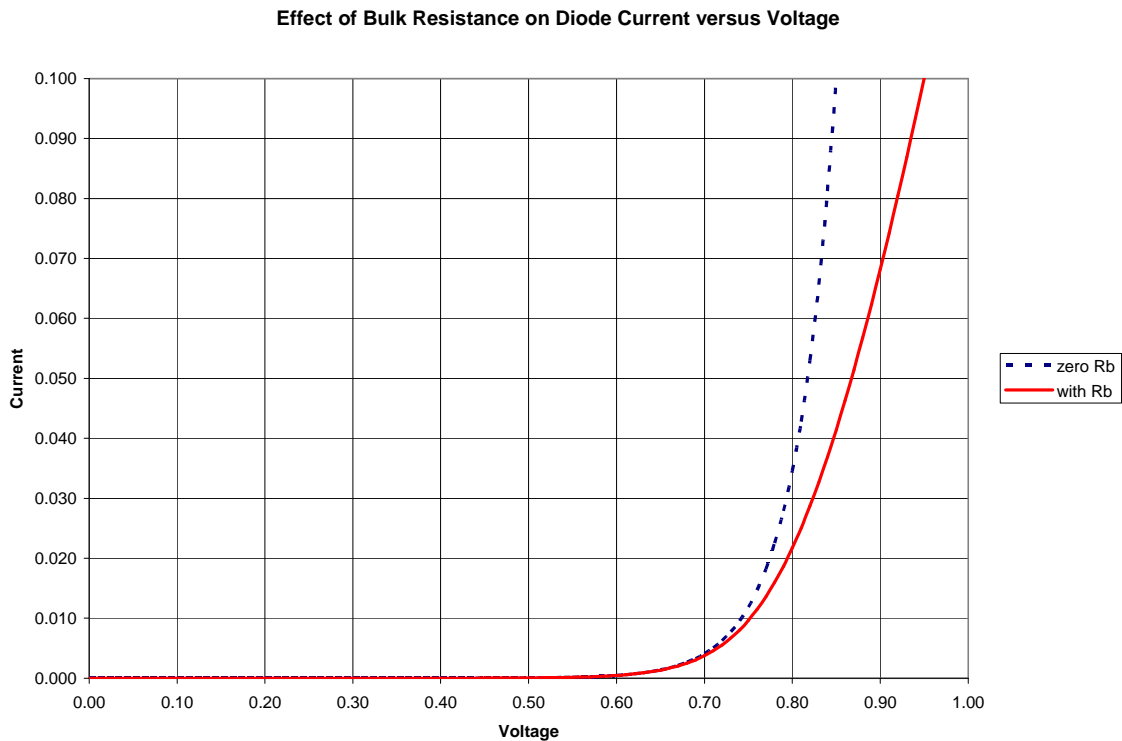


Figure 9: Effect of bulk series resistance

## Diode Characteristics

### Sensitivity to light

The PN junction will respond to light – particularly longer wavelengths such as red and infrared. This feature can be a problem for diodes in transparent cases such as the 1N4148. The effect of light is to significantly increase the reverse conduction. A voltage can appear across the diode in response to light in high impedance circuits. This can be observed by connecting a diode (in a transparent case such as a 1N4148) to a DVM on the 2 volt scale and varying the applied light. In situations where light sensitivity could be a problem it is common to enclose a transparent diode in an opaque sleeve.

There is a special type of diode known as a photodiode which is specifically made for sensing light. The case is transparent and often includes a lens to focus the light on the junction for increased sensitivity. Technically, it is usually infrared emission between around 800 to 1100 nanometers rather than visible light that these diodes are sensitive to. The sensitivity in the visible spectrum is usually poor except for what is known as blue-enhanced diodes. These diodes can be operated either in an unbiased voltage mode or a current mode using a fixed bias around 5 volts. The current mode is very linear over a wide range. The current is sensed by a virtual ground electrometer.

# Diode Characteristics

## Measuring Diode Characteristics

The mathematical model for diode operation can be completed by knowing  $I_S$  and  $n$ . Neither of these are directly measurable but both can be calculated from data obtained by measuring the diode current at two voltages with temperature constant.

We start with the following equation that omits the minus one term since our measurements will be at voltage levels high enough so that term is insignificant. Thus we have:

$$I = I_S * \exp^{V/(n*V_T)} \quad \text{Eq. 6}$$

Equation 6 can be solved for  $V$  by

$$V = n*V_T*\ln(I/I_S) \quad \text{Eq. 7}$$

$$V_H = n*V_T*[\ln(I_H) - \ln(I_S)] \quad \text{Eq. 8A}$$

$$V_L = n*V_T*[\ln(I_L) - \ln(I_S)] \quad \text{Eq. 8B}$$

Where H refers to the high voltage and high current measurement point and L refers to the low voltage and low current measurement point. These two points should be at currents less than 1 mA so that junction heating is insignificant. Good points to use are nominally 500  $\mu$ A for the high value and 5  $\mu$ A for the low value.

Subtracting Eq. 8B from Eq. 8A gives

$$(V_H - V_L) = n*V_T*[\ln(I_H) - \ln(I_L)] \quad \text{Eq. 9}$$

Eq. 9 can now be solved for  $n$

$$n = \frac{V_H - V_L}{V_T * [\ln(I_H) - \ln(I_L)]} \quad \text{Eq. 10}$$

As a reality check,  $n$  is typically between around 1.6 and 2.0 for diodes and should be very close to 1.0 for transistors. Suspect some error if  $n$  is less than 1.0 or greater than about 2.2. The most common type of errors are using an inaccurate temperature or that the high and low measurements were made at different temperatures.

We can now calculate  $I_S$  for the particular temperature the data was measured at. That temperature,  $T$ , must be known and the corresponding value of  $V_T$  used in the following equation.

$$I_S = I_L * \exp^{-V_L/(n*V_T)} \quad \text{Eq. 11}$$

## Diode Characteristics

As a reality check,  $I_S$  should be around 1 nanoampere give or take perhaps a factor of ten for diodes. For transistors,  $I_S$  will be extremely small – picoamperes or less.

The proof that these two values are correct is that they produce results that agree with measured data over a wide range when the model is plotted. The use of only two points for the calculations makes it extremely important to keep measurement errors small. Much better accuracy is obtained by using a spread of data over a wide operating range (say currents from 10 microamperes to 1 milliampere) and then using linear regression to identify  $n$  and  $I_S$ . That method is straightforward and is not shown here. For single situations one would enter data in a spreadsheet and then manually tweak  $n$  and  $I_S$  in the spreadsheet model to minimize the sum of error<sup>2</sup> between measured diode voltage and the voltage computed from the model.

The model for the complete diode characteristic including the effect of temperature on  $I_S$  can be determined by substituting the computed values for  $n$  and  $I_S$  from above and the thermal voltage based on the measured temperature into the following equation.

$$I_K = I_S * \exp^{(E_g/(n*VT))} \quad \text{Eq. 12}$$

As an example, at 25 C the calculated values for a sample diode was 1.83 for  $n$  and 1.3 nanoamperes for  $I_S$ .  $E_g$  was taken to be 1.23 – roughly a middle value.  $I_K$  was then computed to be 338 amperes. These are the values used to create all the plots in this paper.

More to come ...