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PIN Diode Fundamentals

A PIN diode is a semiconductor device that operates as a variable resistor at RF and microwave frequencies. The resistance value of the PIN diode is determined only by the forward biased dc current. In switch and attenuator applications, the PIN diode should ideally control the RF signal level without introducing distortion which might change the shape of the RF signal. An important additional feature of the PIN diode is its ability to control large RF signals while using much smaller levels of dc excitation.

A model of a Microsemi PIN diode chip is shown in Figure 1. The chip is prepared by starting with a wafer of almost intrinsically pure silicon, having high resistivity and long lifetime. A P-region is then diffused into one diode surface and an N-region is diffused into the other surface. The resulting intrinsic or I-region thickness (W) is a function of the thickness of the original silicon wafer, while the area of the chip (A) depends upon how many small sections are defined from the original wafer.

The performance of the PIN diode primarily depends on chip geometry and the nature of the semiconductor material in the finished diode, particularly in the I-region. Characteristics of Microsemi PIN diodes are controlled thickness I-regions having long carrier lifetimes and very high resistivity. These characteristics enhance the ability to control RF signals with a minimum of distortion while requiring low dc supply.

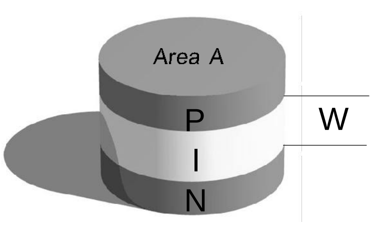


Figure 1 -PIN Diode Chip Outline

Forward Biased PIN Diodes

When a PIN diode is forward biased, holes and electrons are injected from the P and N regions into the I-region. These charges do not recombine immediately. Instead, a finite quantity of charge always remains stored and results in a lowering of the resistivity of the I-region. The quantity of stored charge, Q, depends on the recombination time, τ (the carrier lifetime), and the forward bias current, I_F, as follows (Equation 1):

$$Q = I_F \tau \qquad [Coulombs]$$

The resistance of the I-region under forward bias, R_S is inversely proportional to Q and may be expressed as (Equation 2):

$$R_S = \frac{W^2}{(\mu_N + \mu_p)\,Q} \qquad [Ohms]$$

where: W = I-region width
μ_N = electron mobility
μ_p = hole mobility

Combining equations 1 and 2, the expression for R_S as an inverse function of current is shown as (Equation 3):

$$R_S = \frac{W^2}{(\mu_N + \mu p)\,\tau\, I_F} \qquad [Ohms]$$

This equation is independent of area. In the real world the R_S is slightly dependent upon area because the effective lifetime varies with area and thickness due to edge recombination effects. Typically, PIN diodes display a resistance characteristic consistent with this model as shown in Figure 2. Resistance of the order of .01 Ω at 1 Amp forward bias increasing to about 10,000Ω at 1µA forward bias represents a realistic range for a Microsemi PIN diode.

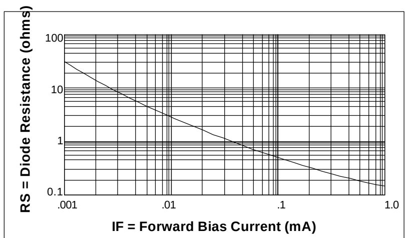


Figure 2

R_S vs Forward Current (UM4000 PIN Diode)

The maximum forward resistance, R_S(max), of a PIN diode is generally specified at 100 mA forward bias current. For some PIN diodes, Microsemi specifies not only the R_S(max) but also the R_S(min) at a lower forward bias current (10µA). These specifications ensure a wide range of diode resistance which is particularly important in attenuator applications. At the lower frequencies R_S is not constant but increases as the frequency is lowered. The normal PIN diodes which are designed to operate in RF and microwave frequencies exhibit this increase in R_S in the 1-10 MHz range. A properly designed PIN will maintain a constant R_S well into the 10 KHz region. Good examples for this frequency range are the UM2100 series devices.

The results obtained from Equation 3 are valid over an extremely broad frequency range when Microsemi PIN diodes are used in a circuit. The practical low resistance limitations result from package parasitic inductances and junction contact resistances, both of which are minimized in the construction of Microsemi diodes. The high resistance range of PIN diodes is usually limited by the effect of the diode capacitance, C_T. To realize the maximum dynamic range of the PIN diode at high frequencies, this diode reactance may have to be tuned out.

It should be noted that “skin effect” is much less pronounced in relatively poor conductors such as silicon, than with good metallic conductors. This is due to the fact that the “skin depth” is proportional to the square root of the resistivity of the conducting material. Thus, RF signals penetrate deeply into the semiconductor and “skin effect: is not a significant factor in PIN diodes below X-Band frequencies.

At dc and very low frequencies, the PIN diode is similar to a PN diode; the diode resistance is described by the dynamic resistance of the I-V characteristics at any quiescent bias point. The dc dynamic resistance point is not, however, valid in PIN diodes at frequencies above which the period is shorter than the transit time of the I-region. The frequency at which this occurs, f_T, is called transit time frequency and may be considered the lower frequency limit for which Equation 3 applies. This lower frequency limit is primarily a function of W, the I-region thickness and can be expressed as (Equation 4):

$$f_\tau = \frac{1300}{W^2} \qquad [MHz]$$

where W is the I-region thickness in microns. For Microsemi PIN diodes, this low frequency limit ranges from approximately 5 KHz for the thickest diodes (UM2100 and UM2300 series) to approximately 1 MHz for the thinnest diodes (UM6200, UM7200).

Reverse Biased PIN Diodes

At high RF frequencies when a PIN diode is at zero or reverse bias, it appears as a parallel plate capacitor, essentially independent of reverse voltage, having a value of (Equation #5):

$$C = \frac{\varepsilon A}{W} \qquad [Farads]$$

where: ε = silicon dielectric constant
A = junction area
W = I-region thickness

The lowest frequencies at which this effect begins to predominate is related to the dielectric relaxation frequency of the I-region, f_τ, which may be computed as (Equation #6):

$$f_\tau = \frac{I}{2\pi\rho\varepsilon} \qquad [Hz]$$

where: ρ = I-region resistivity

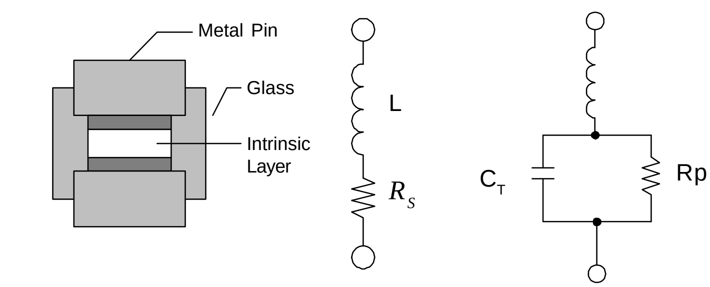
For Microsemi PIN diodes, this dielectric relaxation frequency occurs below 20 MHz and the total packaged capacitance, C_T, is specified for most Microsemi diodes when zero biased at 100 MHz. Additional data is supplied in the form of typical curves showing the capacitance variation as a function of reverse bias at lower frequencies.

At frequencies much lower than f_τ, the capacitance characteristic of the PIN diode resembles a varactor diode. Because of the frequency limitations of common test equipment, capacitance measurements are generally made at 1 MHz. At this frequency the total capacitance, C_T, is determined by applying a sufficiently large reverse voltage which fully depletes the I-region of carriers.

Associated with the diode capacitance is a parallel resistance, Rp, which represents the net dissipative resistance in the reverse biased diode. At low reverse voltages, the finite resistivity of the I-region results in a lossy I-region capacitance. As the reverse voltage is increased, carriers are depleted from the I-region resulting in an essentially lossless silicon capacitor. The reverse parallel resistance of the PIN diode, Rp, is also affected by any series resistance in the semiconductor or diode contacts.

Equivalent Circuits

Because of the unique construction of Microsemi diodes, the RF equivalent circuits are generally different and actually more simplified than those associated with PIN diodes constructed using conventional techniques. These equivalent circuits for Microsemi diodes are illustrated in Figure 3. Because of the absence of small wires or ribbons, the package capacitance is directly in parallel with the PIN chip, there is virtually no internal package inductance to consider as is the case with conventional PIN diodes. The full faced bond achieved between the silicon chip and the metallic pins, combined with the relatively large chip area, result in negligible contact resistance. Hence, the “residual series resistance” in conventional diodes, is for all practical purposes, nonexistent in Microsemi PIN diodes. Any self-inductance presented by the Microsemi diode is external to the diode’s capacitance and is similar to that of a conducting cylinder having the same mechanical outline as the diode chip and pins. Calculations using self-inductance equations show the Style A package inductance to be on the order of 0.10 nH for all Microsemi PIN diode types. Additional self-inductance is introduced by any lead attached to the Style A package. Thus at frequencies below 1 GHz, Microsemi package parasitic effects are usually negligible. At higher frequencies, the overall dimensions and materials of the diode package should be considered in both the diode selection and RF circuit design.



(a) Cross Section of Basic Diode (b) Forward Bias (c) Reverse Bias

Figure 3 - PIN Diode Equivalent Circuits