

APPLICATION NOTE

PIN Diode Basics

Introduction

Basic Theory—Variable Resistance

A PIN diode is essentially a variable resistor. To determine the value of this resistance, consider a volume comparable to a typical PIN diode chip, say 20 mil diameter and 2 mils thick. This chip has a DC resistance of about 0.75 M Ω. Note: 1 mil = 0.001 inches.

In real diodes there are impurities, typically boron, which cannot be segregated out of the crystal. Such impurities contribute carriers, holes or electrons, which are not very tightly bound to the lattice and therefore lower the resistivity of the silicon.

The resistivity of the I region and thus the diode resistance is determined by the number of free carriers within the I region. The resistivity of any semiconductor material is inversely proportional to the conductivity of the material.

Expressed mathematically the resistivity of the I region is

$$1/P_I = q (\mu_N N + \mu_P P)$$

where q is the electronic charge ($q = 1.602 \times 10^{-19}$ coul.), μ_N and μ_P are the mobilities of electrons and holes respectively.

Consider electrons and holes travelling in opposite directions within the I region under the impetus of an applied, positive electric field. The I region will fill up and an equilibrium condition will be reached. In non-equilibrium conditions excess minority carriers exist, and recombination between holes and electrons proceed to restore equilibrium. Recombination often occurs because of interactions between mobile charge carriers and imperfections in the semiconductor crystalline structure, either structural defects or dopant atoms. The rate of recombination of holes and electrons is proportional to the carrier concentrations and inversely proportional to a property of the semiconductor called the LIFETIME, T_L , of the minority carriers. [2]

In the case of applied forward bias, the equation governing mobile charges in the I region is

$$\frac{dQ_S}{dt} = I_F - \frac{Q_S}{T_L}$$

where Q_S is the stored charge and $Q_S = q(N+P)$.

Under steady conditions the mobile charge density in the I region is constant, i. e.,

$$\frac{dQ_S}{dt} = 0, \text{ so that}$$

$$I_F = Idc = \frac{Q_S}{T_L}$$

We can next proceed to calculate the forward resistance of a PIN diode of cylindrical geometry with a thickness, W_I , and an area, A. We can ignore some details of analysis not critical to this note.

The forward current I_F was given before as

$$I_F = Q/T_L \text{ where } Q = \text{Charge per unit volume and}$$

$$Q = q (N+P) W_I A \text{ therefore}$$

$$I_F = \frac{q (N+P) W_I A}{T_L}$$

If there is not unneutralized charge in the I region, $P = N$ and then

$$I_F = \frac{2q N W_I A}{T_L}$$

and the resistivity of the I region, given previously, will now be

$$P_I (2q \bar{\mu} N)^{-1} \text{ where } \bar{\mu} = \frac{(\mu_N + \mu_P)}{2}$$

The resistance of the I region will then be:

$$R_F = \frac{P_I W_I}{A} = (2q \bar{\mu} N)^{-1} \frac{W_I}{A}$$

Combining equations yields:

$$R_F = \frac{W_I^2}{2I_F \bar{\mu} T_L}$$

The above relation is a fundamental equation of PIN diode theory and design. [3] Rigorous analysis such as reported by Chaffin [4] shows:

$$R_F = \frac{2kT}{qI_F} \sinh\left(\frac{W_I}{2\sqrt{DT_L}}\right) \tan^{-1}\left[\sinh\left(\frac{W_I}{2\sqrt{DT_L}}\right)\right]$$

Where k = Boltzmann’s constant, 1.38044 x 10⁻²³ joule/kelvin

T = Temperature in degrees kelvin

D = Diffusion constant

Typical data on R_S as a function of bias current are shown in Figure 1. A wide range of design choices is available, as the data indicate. Many combinations of W and T_L have been developed to satisfy the full range of applications.

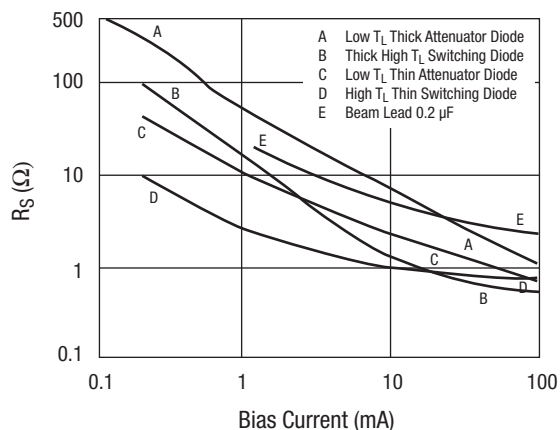


Figure 1. Typical Series Resistance as a Function of Bias (1 GHz)

Breakdown Voltage Capacitance, Q Factor

The previous section on R_S explained how a PIN can become a low resistance, or a “short.” This section will describe the other state—a high impedance, or an open.

Silicon has a dielectric strength of about 400 V per mil, and all PIN diodes have a parameter called V_B, breakdown voltage, which is a direct measure of the width of the I region. Voltage in excess of this parameter results in a rapid increase in current flow (called avalanche current). When the negative bias voltage is below the breakdown of the I region, a few nanoamps will be drawn. As V_B is approached, the leakage current increases. Typically leakage current occurs at the periphery of the I region. For this reason various passivation materials (silicon dioxide, silicon nitride, hard glass) are deposited to protect and stabilize this surface and minimize leakage. These techniques have been well advanced at Skyworks and provide a reliable PIN diode.

V_B is usually specified at a reverse current of 10 microamps.

In simplest form the capacitance of a PIN is determined by the area and width of the I region and the dielectric constant of silicon. This minimum capacitance is obtained by the application of a reverse bias in excess of V_{PT}, the voltage at which the depletion region occupies the entire I layer.

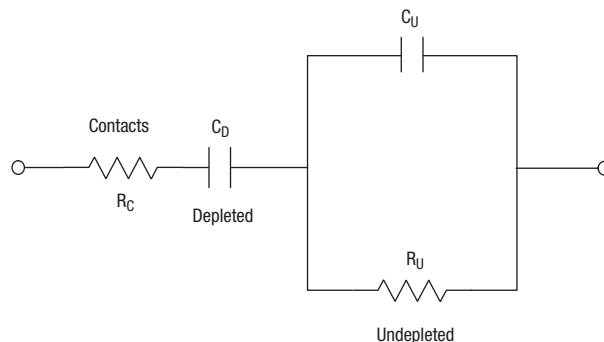


Figure 2. Equivalent Circuit of I Region Before Punch-Through

Consider the undepleted region: this is a lossy dielectric consisting of a volume (area A, length L) of silicon of permittivity 12 and resistivity ρ. The capacitance is

$$\frac{12E_0A}{L}, \text{ and the admittance is } \frac{24\pi 12E_0A}{L}$$

The resistance is proportional to L/A and the conductance to A/L. At voltages below V_{PT}, C_J will increase and approach ∞ capacitance at a forward bias of 0.7 V in silicon and 0.9 V in GaAs.

Skyworks measures junction capacitance at 1 MHz; this is a measure of the depletion zone capacitance.

For I region thickness of W and a depletion width X_d, the undepleted region is (W-X_d).

The capacitance of the depleted zone is, proportionally,

$$\frac{1}{X_d}, \text{ of the undepleted, } \frac{1}{W-X_d}$$

The 1 MHz capacitance decreases with bias until “punch-through” where X_d = W. At microwave frequencies well above the crossover, the junction looks like two capacitors in series.

$$C_T = \frac{C_d C_U}{C_d + C_U}, \text{ which is proportional to } 1/W$$

i. e., the microwave capacitance tends to be constant, independent of X_d and bias voltage.

However, since the undepleted zone is lossy, an increase in reverse bias to the punch-through voltage reduces the RF power loss.

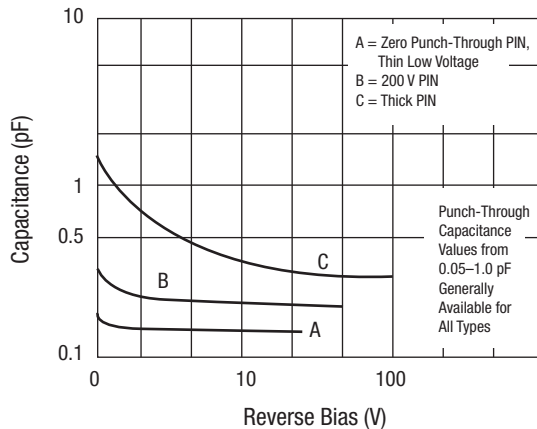


Figure 3. Typical Capacitance

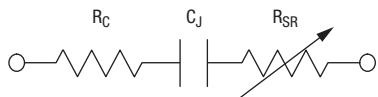


Figure 4. Simplified Equivalent Circuit, Series

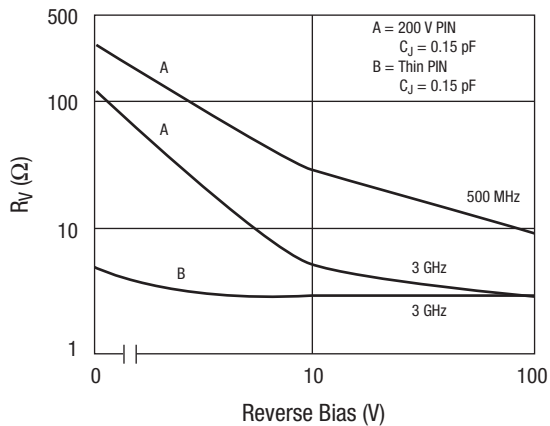


Figure 5. Reverse Series Resistance

A good way to understand the effects of series resistance is to observe the insertion loss of a PIN chip series mounted in a 50 Ω line.

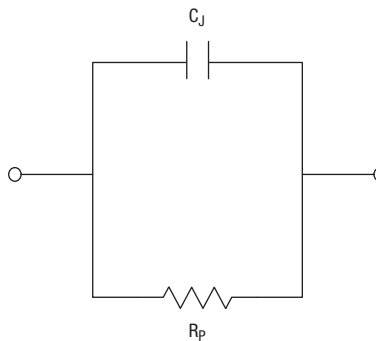


Figure 6. Simplified Equivalent Circuit, Shunt

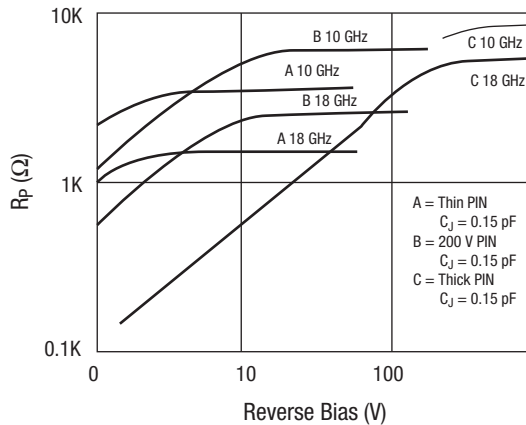


Figure 7. Reverse Shunt Resistance

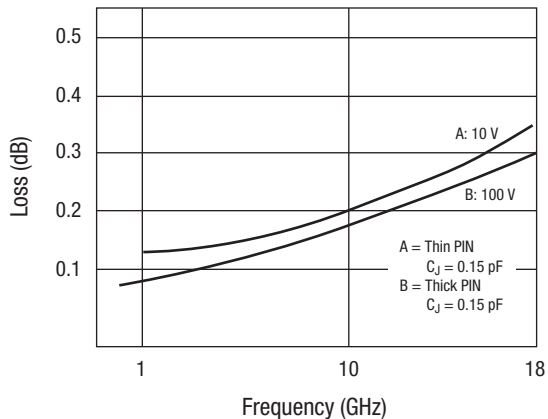


Figure 8. Insertion Loss vs. Frequency

An accepted way to include reverse loss in the figure of merit of a PIN is to write the switching cutoff frequency

$$F_{CS} = \frac{1}{2\pi C_T \sqrt{R_S R_V}}$$

where R_S and R_V are measured under the expected forward and reverse bias conditions at the frequency of interest.

The punch-through voltage is a function of the resistivity and thickness of the I region. It is advisable to measure loss as a function of bias voltage and RF voltage to determine if the correct diode has been selected for your application.

Switching Considerations

Consider a PIN diode and a typical drive circuit. When the system calls for a change in state, the logic command is applied to the driver. There is delay time in the driver, in the passive components as well as in the transistors, before the voltage at Point A begins to change. There is a further delay before that voltage has stabilized. Most diode switching measurements are measured with the time reference being the 50% point of the (Point A) command waveform.

The diode begins to respond immediately, but there is a delay before the RF impedance begins to change. It is the change in impedance that causes the RF output to switch.

The driver waveforms shown are required for the fastest total switching times.

Reverse to Forward

In the high impedance state, the IV characteristics are inductive. This can be considered a function of the fact that the I region must become flooded with stored charge before the current (and RF impedance) stabilizes. Accordingly, the driver must deliver a current spike with substantial overvoltage. The capacitor paralleling the output dropping resistor is called a “speed-up” capacitor and provides the spike.

Typical total switching time can be on the order of 2% to 10% of the specified diode lifetime and in general is much faster than switching in the other direction, from forward to reverse.

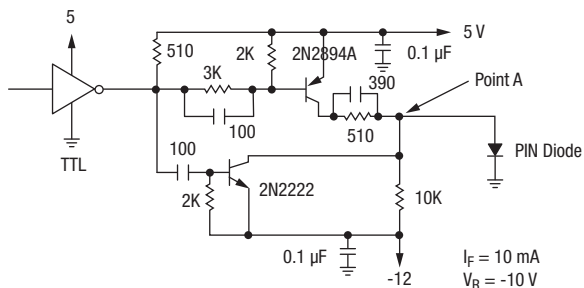


Figure 9. SPST Switch Driver for 10 ns

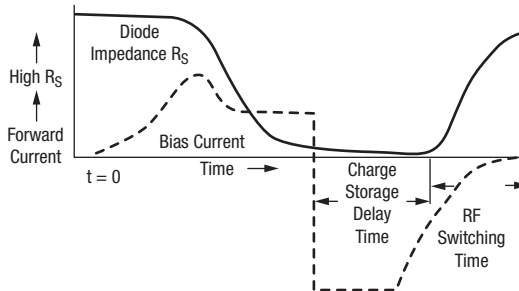


Figure 10. PIN Diode Switch Waveforms

Forward To Reverse

In this mode the problem is to extract the stored charge rapidly. Once again the solution is a reverse current spike coupled with a moderately high reverse bias voltage, with reverse current on the order of 10 to 20 times forward bias,

$$I/R = 0.10 \text{ to } 0.05 \text{ or less}$$

The charge storage delay will be 5% to 10% of the lifetime. Additionally the actual RF switching time will be minimized by a large negative bias and/or by a low forward bias.

Bias Circuitry

It is advisable to design the bias circuit to have the same characteristic impedance as the RF line to minimize reflections and ringing. Extraneous capacitance, in the form of blocking and bypass elements, must not be excessive. A typical 60+ pF bypass in a 50 Ω RF circuit produces a 3.0 nanosecond rise time. A few of these make it impossible to exploit the fastest PINs.

Temperature Effects on Forward Resistance

Series Resistance

Two conflicting mechanisms influence temperature behavior. First, as temperature rises, lifetime increases, allowing a greater carrier concentration and lowering R_S . Secondly, however, at higher temperature change, mobility decreases, raising R_S . The net result of these competing phenomena is a function of diode design, bias current, RF power level, and frequency.

Figure 11 shows unlabeled curves of R_S vs. temperature with bias as a parameter. Most diodes show a monotonic increase of series resistance as temperature increases, while reverse losses tend to increase.

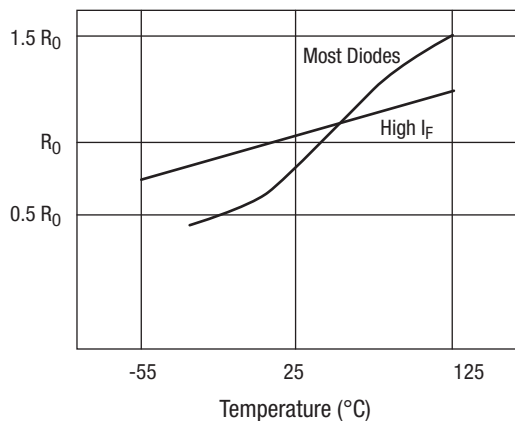


Figure 11. Series Resistance vs. Temperature

A typical fast switching diode will draw 10 mA at 850 mV at 25 °C. At -55 °C, the same V_F will draw about 500 microamps; at 100 °C, I_F will be 200 mA.

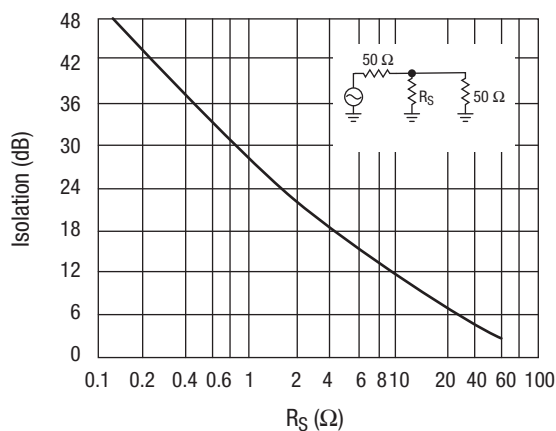


Figure 12. Shunt Diode Isolation vs. Forward Biased Resistance

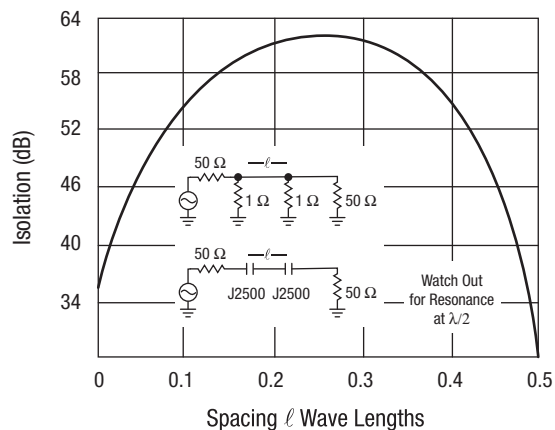


Figure 13. Isolation vs. Diode Spacing

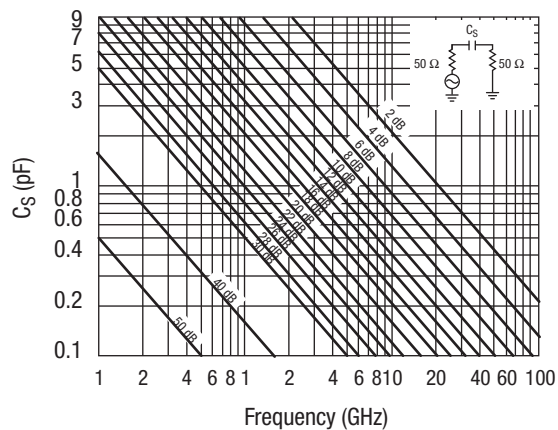


Figure 14. Isolation vs. Series Capacitance

Simple Circuit Performance Charts

Figures 12 and 13 refer to chips shunt mounted in 50 Ω microstrip. Figure 14 refers to series-mounted diodes. Figure 12 shows isolation as a function of diode series resistance R_S . Figure 13 shows isolation as a function of diode spacing for a shunt pair of 1.0 Ω diodes, and a series pair of diodes with $X_C = -j2500$.

How to Specify PIN Diodes

The uses for PIN diodes fall into three categories: series element, shunt element, and a limiter diode. The following guidelines should help in specifying a PIN diode for these applications.

For Series Diodes

R_S —The forward series resistance will determine the minimum loss in the insertion loss state. Normally the diode will have a resistance slightly higher than R_S due to the internal junction resistance because of limited forward current. The ideal PIN diode series resistance is low, however. Low series resistances are associated with high idle state capacitance and a trade-off must, therefore, be made between off-state capacitance (C_J) and series resistance (R_S). Skyworks does this by choosing the proper junction diameter for your application.

C_J —The capacitance (specified at 1 MHz at punch-through) is the off state capacitance, and for a series element determines the broadband isolation or, for narrow-band applications, the bandwidth of the switch.

Shunt Elements

R_S —The forward series resistance of the shunt element determines the maximum isolation that can be obtained from this element. The ideal diode has extremely low R_S ; however, diodes with low R_S have an associated capacitance (C_J) which may be high. The shunt element trade-off is to balance the required isolation with the effective insertion loss of a broadband switch at the band width of a narrow-band switch.

C_J —The capacitance (specified at 1 MHz at punch-through) needs to be a low value to maintain low loss, broadband switching. C_J will also determine the input VSWR of the switch for broadband applications.

V_B —The breakdown voltage of a PIN diode must be specified to assure the power handling of the switch component. In general the voltage must be high enough to prevent breakdown during the reverse bias condition, including the DC applied bias and the peak RF voltage. Failure to do so will cause a condition that can result in diode limiting and under severe circumstances can cause failure. For a simple shunt switch, a 100 V breakdown diode biased at 50 V can accommodate a peak voltage of ~50 V or power of 25 W average in a 50 Ω system. For maximum power handling, the reverse bias should be one-half of V_B .

Limiters

PIN diodes with low breakdown voltages can serve as power limiters. The onset of limiting is primarily determined by the V_B of the diode. The limiting function is also affected by the lifetime of the base region. For this reason the frequency range, peak power requirements and threshold need to be specified to choose a diode with minimum leakage. The power handling capability of limiter diodes is determined by V_B for short pulse applications and thermal heat sinking for long pulsed applications. The heat sinking is a composite of the thermal path in the diode and the mounting thermal resistance. Beam-lead diodes provide very low power handling capability due to the extremely high (1200 °C/W) thermal resistance—high powers can be achieved from shunt chips which can have thermal resistances below 5 °C/W. To determine the power handling capability of a limiter circuit one needs to determine the maximum power absorbed by the limiter diode. In hard limiting, the diode will reflect most of the power and only a small portion will be absorbed.

References

1. Watson, H.A. "Microwave Semiconductor Devices and their Circuit Applications," Chap. 2, McGraw-Hill, 1969.
2. op.cit. Watson, Chap. 9, "p-i-n Diodes" Olson, H.M.
3. ibid.
4. Chaffin, R.J. "Permanent Neutron Damage in PIN Microwave Diode Switches" Sandia Laboratories Report, SC-PR-70-853, Dec.1970.
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6. McDade, J.C. and Schiavone, F. "Switching Time Performance of Microwave PIN Diodes," *Microwave Journal*, Vol. 17 Dec. 1974.

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