CHAPTER - 1

PIN DIODE GENERAL DESCRIPTION

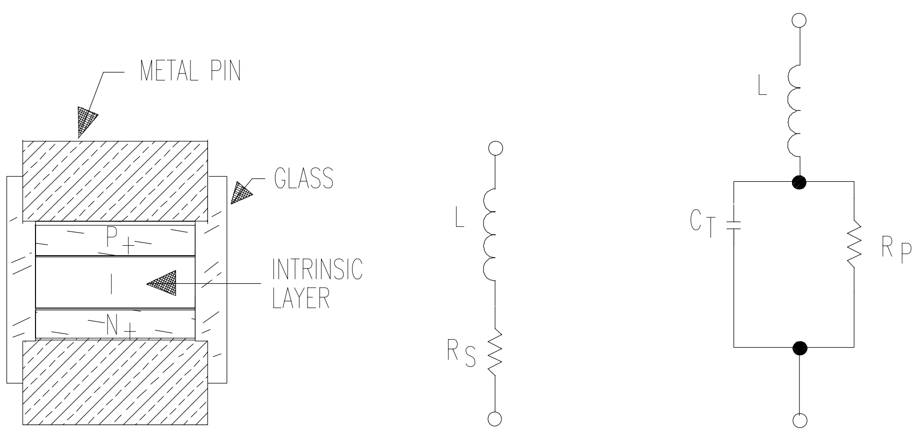
NOTES

PIN DIODE GENERAL DESCRIPTION

This chapter presents a general overview of PIN diode operating characteristics to form an adequate basis for the subsequent chapters on the various PIN diode functional circuits. Supplemental material on PIN Diode Physics is included in the Appendices section of the Handbook.

A microwave PIN diode is a semiconductor device that operates as a variable resistor at RF and Microwave frequencies. A PIN diode is a current controlled device in contrast to a varactor diode which is a voltage controlled device. Varactors diodes are design with thin epitaxial I-layers (for a high "Q" in the reverse bias) and little or no concern for carrier lifetime (Stored Charge).When the forward bias control current of the PIN diode is varied continuously, it can be used for attenuating, leveling, and amplitude modulating an RF signal. When the control current is switched on and off, or in discrete steps, the device can be used for switching, pulse modulating, and phase shifting an RF signal. The microwave PIN diode's small physical size compared to a wavelength, high switching speed, and low package parasitic reactances, make it an ideal component for use in miniature, broadband RF signal control circuits. In addition, the PIN diode has the ability to control large RF signal power while using much smaller levels of control power.

Microsemi PIN diodes offer a unique highly reliable package due to voidless construction, metallurically bonded pin structure, and an extremely rugged SOGO surface passivation. SOGO passivated devices may be driven into reverse voltage breakdown without the reverse voltage characteristic collapsing. Microsemi PIN diodes offer significant electrical and thermal advantages compared to PIN diodes manufactured by other suppliers. The Microsemi PIN diode is generally constructed using a PIN chip that has a thicker I-region, larger cross sectional area and longer carrier lifetime for the same basic electrical characteristics of series resistance (R_S), and capacitance (C_T). This results in PIN diodes that produce lower signal distortion at all frequencies and power levels as well as devices that are capable of handling greater average and peak power than those manufactured by conventional techniques. In addition, since there are no ribbons or wires within the Microsemi's package, large surge currents may be safely handled and the parasitic resistance and inductance are minimized.



(a) Cross Section of Basic PIN Diode

(b) Forward Bias Equivalent Circuit

(c) Reverse Bias Equivalent Circuit

Figure 1.1 PIN Diode and the Corresponding Equivalent Circuits

A drawing of a PIN diode chip is shown in Figure 1.1 (a). The performance characteristics of the PIN diode depend mainly on the chip geometry and the processed semiconductor material in the intrinsic or I - region, of the finished diode. When the diode is forward biased, holes and electrons are injected into the I-region. This charge does not recombine instantaneously, but has a finite lifetime (τ) in the I-region. If the PIN diode is reverse biased , there is no stored charge in the I-region and the device behaves like a Capacitance (C_T) shunted by a parallel resistance (R_P). These equivalent circuit parameters are defined in the section below. If the d-c voltage across the PIN diode is zero, there remains some finite charge stored in the I-region, but it is not mobile. If operated at zero volts d-c, any PIN diode behaves as a somewhat lossy Capacitor. Some small d-c Voltage (called the "punch-through" Voltage) must be applied to the I-region to sweep out this remaining fixed charge. These ideas are developed farther in Appendix A.

RF ELECTRICAL EQUIVALENT CIRCUITS PARAMETERS OF THE PIN DIODE

FORWARD BIAS EQUIVALENT CIRCUIT

The equivalent circuit for the forward biased PIN diode, Figure 1.1 (b), consists of a series combination of the series resistance (R_s) and a small Inductance (L_s). R_s is a function of the Forward Bias Current (I_f) and this function is shown in Figure 1.2 for the UM 9552 PIN Attenuator Diode. L_s depends on the geometrical properties of the package such as metal pin length and diameter. L_s is a small parasitic element that has little effect on Microsemi PIN diode performance below 1 GHz

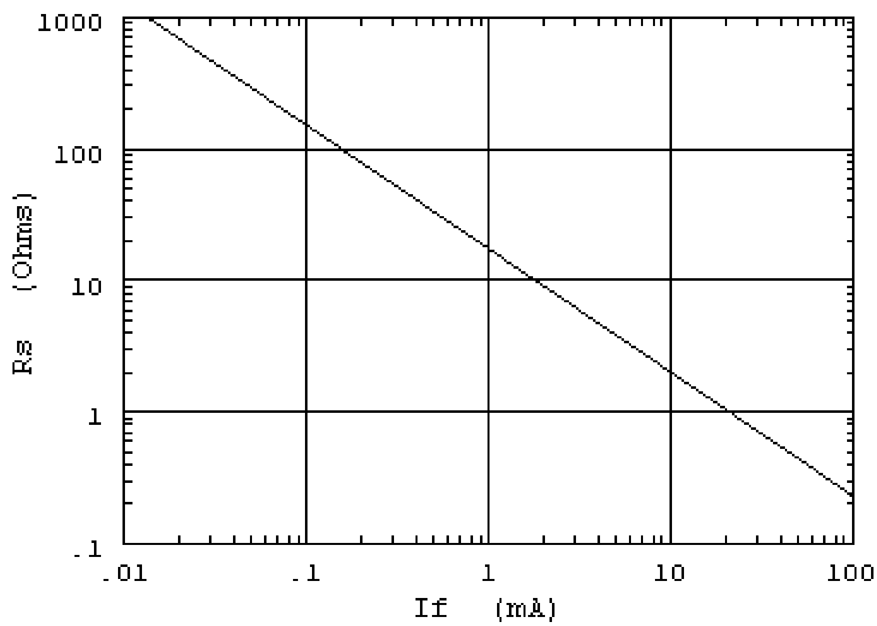


Figure 1.2. Typical Forward Biased Series Resistance vs Bias Current for the UM 9552 PIN Diode

The forward biased PIN diode is a Current Controlled Resistor, which is useful in low distortion Attenuator and Amplitude Modulator Applications. The R_s vs I_f relationship is described as:

$R_s = W^2 / (\mu_n + \mu_p)\, Q$ (Ohms) or $R_s = W^2 / (\mu_n + \mu_p)\, I_f \tau$ (Ohms)

where: $Q_s = I_f \tau$, W = I-region Width, I_f = Forward Bias Current, τ = Minority Carrier Lifetime

μ_n = Electron Mobility, μ_p = Hole Mobility

This equation is valid for frequencies higher than the transit time of the I-region: $f > 1300/ W^2$ (f in MHz and W in microns). It also assumes that the RF signal does not modulate the stored charge (Appendix A). At lower frequencies, the PIN diode rectifies the RF signal (just as any pn-junction diode would).

REVERSED BIAS EQUIVALENT CIRCUIT

The Reverse Bias Equivalent Circuit consists of the PIN diode Capacitance (C_T), a shunt loss element, (R_p), and the parasitic Inductance (L_s). The defining equation for C_T is:

$$C_t = \varepsilon A / W$$

which is valid for frequencies above the dielectric relaxation frequency of the I-region, ie:

$$f > 1 / 2 \pi\rho\varepsilon$$

where ε = dielectric constant of Silicon, A =Diode Junction Area, and ρ = Resistivity of Silicon.

Ct decreases somewhat from 0 Volts to the "Punch-Through" Voltage and remains constant for reverse bias Voltage (V_r) greater than the "Punch-Through" Voltage. The PIN diode's reverse bias Capacitance vs Voltage behavior is different than a pn-junction diode, which exhibits a continuously variable Capacitance vs Reverse Voltage out to the Breakdown Voltage (VBR). The reverse biased PIN diode is easier to Impedance match than the Varactor, because of its flat Ct vs Vr characteristic.

The shunt Loss (G_p) is maximum at 0 Volts and decreases to a fixed value as the reverse bias Voltage is increased. An upper cutoff frequency for the PIN diode could be defined as that frequency at which L_s resonates with the periodic average value of C_t.

LARGE SIGNAL MICROWAVE PIN DIODE OPERATION

Under large RF Power control conditions in the Microwave bands (1 GHz and above), the following bias considerations apply:

Forward Bias Condition:

The PIN diode must be forward biased (Low Loss or ON State) so that the stored charge, Qs, is much larger than the RF induced charge that is added or removed from the I-region cyclically by the RF current. This relationship is shown by the inequality: $Q_s >> I_{rf} / 2 \pi f$

Reverse Bias Condition:

High Frequency versus Low Frequency

A PIN diode, designed for high frequency operation is usually fabricated to have low capacitance because the reactance of the diode in the OFF condition must be large compared to the line impedance. The ratio of the PIN's area to thickness is adjusted to obtain the desired capacitance. The resistivity or doping level of the I-layer is not critical as long as it is greater than 20 to 50 Ohm-cm for operation at 1 GHz. The transit time and the relaxation frequency requirements are easily obtained.

In contrast operation at low frequencies places more constraints on the PIN designer (< 10 MHz or even more so, below 1 MHz). Low relaxation frequency requires very high resistivity levels for the I-layer. Microsemi uses 10,000 Ohm-cm Silicon to obtain the low relaxation frequency. Long transit time requires very thick I-layers. Microsemi manufactures PIN diodes with I-layer thickness of 500 µm. Large values of Q_S are required to control the RF signal at low frequencies and are very critical in attenuator applications where the dc bias current may not be increased without changing the resistance value of the PIN diode. Large values of Q_S (τ > 0.1millisec) are obtained by careful process control and the use of a good passivating surface for the I-layer.

Above 1 GHz, the period of the microwave signal is much smaller than the PIN diode's minority carrier lifetime(τ). In this case, the reverse bias condition (Isolation State) is such that the PIN diode is biased beyond punch through (Appendix A). If large values of RF current are being switched, the reverse bias voltage must be large enough that the RF voltage during its forward excursion does not induce the flow of RF current through the PIN diode. If the PIN diode becomes warm when operating as a high power switch, the reverse bias voltage should be increased to minimize this effect. The PIN diode's reverse breakdown voltage (VBR) must be large enough so that the reverse excursion of the RF voltage does not cause the flow of avalanche current under reverse bias conditions [1,2]. As shown inFigure 1.3.

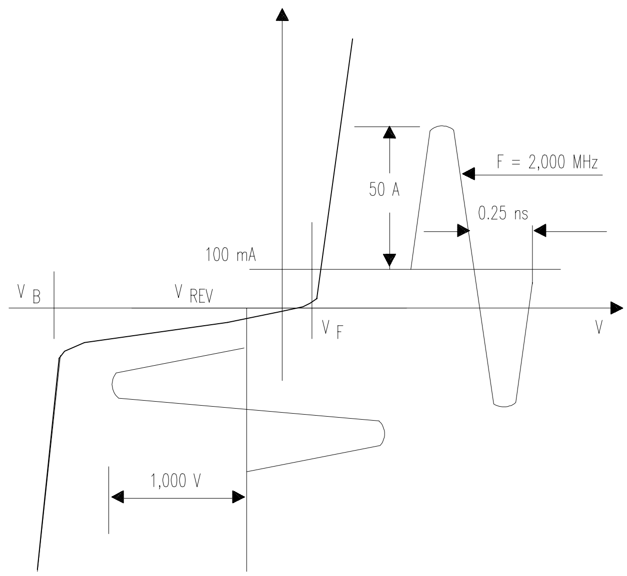


Figure 1.3 RF Voltage and Current Waveforms Superimposed on PIN Diode IV Characteristics

LOW FREQUENCY RF PIN DIODE OPERATION

Below the transit time frequency of the I-region, the PIN diode behaves as a PN junction diode, ie, it rectifies the RF voltage. For frequencies somewhat higher than the transit time frequency but below the Microwave Bands, sufficient reverse bias voltage should be applied to protect the PIN diode from burnout in a high power switch application(Figure 1.3). In this frequency range, lifetime may not be sufficiently large so that the d-c induced stored charge controls the RF power applied. To be completely safe, the reverse bias should be equal to greater than the peak value of the RF Voltage and the VBR should be equal to greater than the peak-to-peak value of the RF Voltage, so that no RF current flows during the positive half of the RF cycle [3,4].

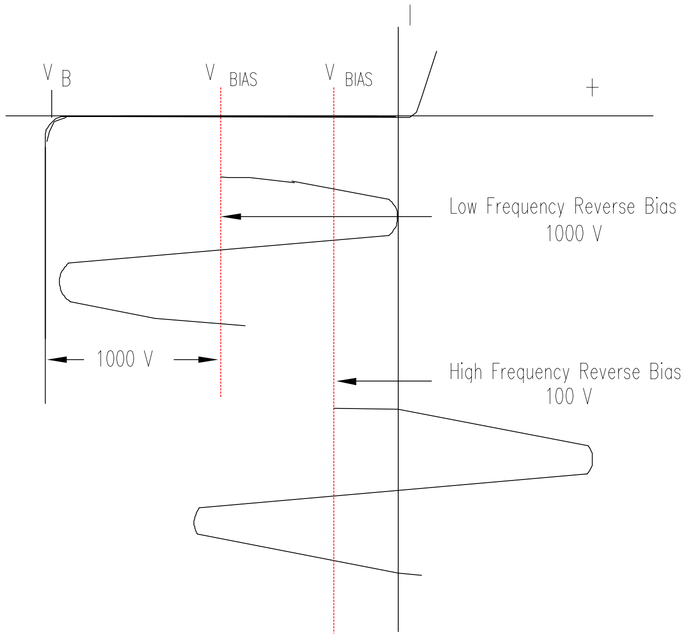


Figure 1.4 L F & H F Voltage Waveforms Superimposed on the I-V Characteristics of a PIN Diode

BIAS-CIRCUIT / RF CIRCUIT ISOLATION

In most applications, it is necessary to provide some degree of isolation between the low-frequency d-c bias circuit and the r-f circuit. Otherwise, RF current can flow into the power supply's output impedance, causing effects that are detrimental to the efficient operation of the power control circuit.

The d-c bias supply is isolated from the RF circuits by inserting a low-pass filter structure between the bias supply and the RF control circuit. For many switch application (Chapter 2), an RF inductor, in series with the bias line, and an RF by-pass capacitor, in shunt with the power supply output impedance, will provide 20 dB or more of d-c / r-f isolation. If higher values of isolation are needed, more complex low-pass filter structures are necessary.

Low-pass filters may significantly increase the switching time of the PIN diode. If a switching time of 100 ns is needed, the low-pass filter must show very little loss to frequencies up to 30 MHz (ie, the filter's cut-off frequency is at least 30 MHz). Shorter switching times require higher filter cut-off frequencies, which may lead to practical construction difficulties. Many commercially available bias tees are not adequate for biasing high power switch prototype circuits because the d-c current rating is too low.

PIN DIODE SWITCHING SPEED CHARACTERISTICS

Switching Speed (T_s) is discussed in detail for specific switch configurations and operating conditions in Chapter 2 and from a diode physics perspective in Appendix A. In switching applications, switching speed is the time required to either fill or remove charge from the I-region. Switching speed depends both on the driver circuit's operating conditions for specific switching states and on the diode's equivalent circuit parameters.

When a PIN diode is forward biased by current, I_F, the current flow results in charge, $Q = I_F\,\tau$, being stored in the I-region. This stored charge condition causes the PIN diode to be in the low resistance state. If the forward bias current is suddenly removed, the positive and negative charges in the PIN diode will recombine in a time period called τ, the minority carrier lifetime. If a large reverse voltage is applied to the forward conducting PIN diode, a reverse current, I_R, flows. T_{FR}, or the forward-to-reverse switching time, is expressed in terms of I_F, I_R, and lifetime τ, as

$$T_{FR} = \ln(1 + I_F / I_R)\,\tau \quad \text{(sec.)}$$

The shape of the typical I_F vs time curve, defining T_{FR}, is shown in Figure 1.5.

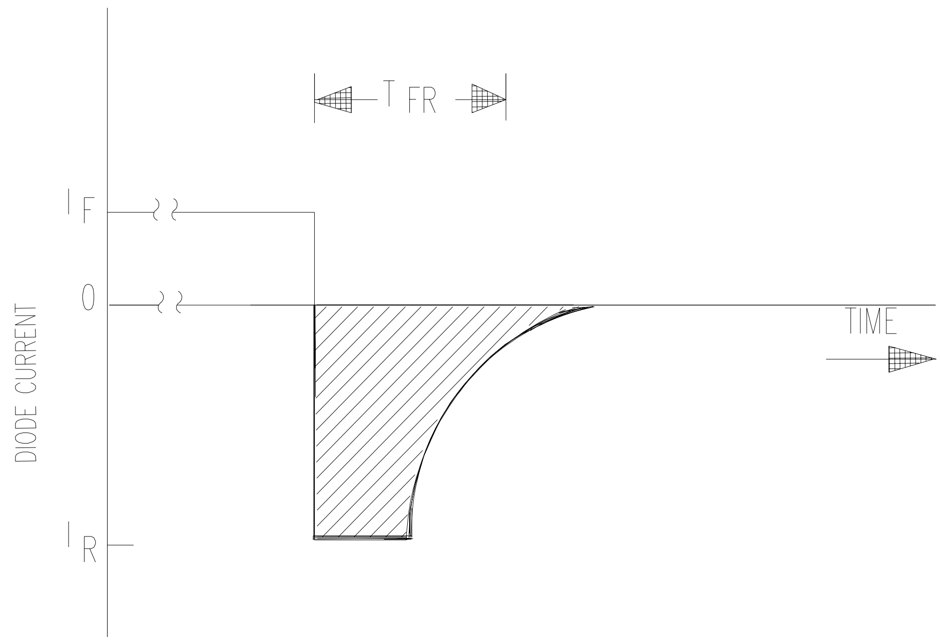


Figure 1.5. PIN Diode Reverse Bias Switching Speed

The speed with which charge is removed from the I-region during turn-off depends on the rise time and amplitude of the switching-voltage pulse applied to the PIN diode. By using spiked waveforms (referred to as overdrive) and by reducing the source impedance of the driver to allow high reverse current to flow, the TFR can reduced substantially.

The time required for the I-region to fill with charge primarily depends on the transit time of the I-region, (ie, the I-region width) and on the reverse voltage and forward bias current that the driver can supply. This reverse-to-forward switching time, T_{RF}, is usually faster than the turn-off time, T_{FR}.

PIN DIODE THERMAL IMPEDANCE

PIN diodes are used to control RF power in circuits such as switches, attenuators, modulators and phase shifters. These PIN diode applications are discussed in detail in the next four chapters. The process of controlling RF power naturally results in some of the RF power being dissipated in the controlling device. The amount of power dissipated is calculated for the various circuit PIN diode circuit configurations in the appropriate chapters.

As a PIN diode dissipates power, its junction temperature begins to rise. The diode's junction temperature depends on the amount of power dissipated, P_d, the ambient temperature T_{amb}, and the thermal impedance, (θ_J), between the diode junction and the diode's ambient temperature. The power rating of a PIN diode is the power dissipation that will raise the junction temperature from the ambient temperature (usually 25 ^oC) to its maximum allowable value, T_{Jmax} (150 ^oC).

The maximum power dissipation, Pd, is determined from the relationship:

$$P_d = (T_j - T_a) / \theta_J$$

where T_j is the maximum junction temperature for a Silicon PIN diode (175 ^oC) and T_a is the ambient temperature, usually that of the diode's heat sink. P_d is calculated as:

$$P_d = I_{RF}{}^2 R_s + I_{DC} V_{DC}$$

where I_{RF} is the RF current, I_{DC} is the dc current, and R_s is the value of the diode's series resistance at the value of forward bias (d-c) current chosen. Note, that P_d is the maximum power that the PIN diode can dissipate, **NOT** the maximum switched power! The maximum switched power, depends on the PIN diode's bias conditions related to the Characteristic Impedance of the Switch Circuit and the Voltage and Current from the RF Power Source.

WHY YOU SHOULD USE A PIN DIODE

1. Rugged, High Reliability
2. High Voltage Capability > 2000 Volts
3. High Current Capability > 25 Amperes continuous
4. High surge Current Capability > 500 Amperes (1 pulse 8.3 ms ,½ sine)
5. Low Distortion < -60dBc @ 455 KHz
6. High Power Gain > 10,000 : 1
7. Fast Switching speed < 100 ns
8. Small Physical Size
9. Various Thermal Packaging Available
10. RF Relay Replacement - mechanical, mercury, etc.