PIN Diode Switch Circuit for Short Time High Current Pulse Signal

by

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"If your problems have solution, no need to worry.
If your problems have no solution, why worry?"
- Anonymous

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ABSTRACT

The protection of devices from transients is an important general problem and is investigated here in regard to a circuit with a sensor and transient pulses. The specific problem uses a sensor connected in series with a fast pulse source, of about hundred nano seconds duration and five hundred volts size.

The method of protection employed is based on using both series isolation and a shunt parallel to the sensor. The goal was to keep the sensor isolated during the time of the fast power pulse and then to have the sensor active at all other times.

PIN diodes are semiconductor devices commonly used to control RF and microwave signals. Their remarkable and useful aspect arises from their ability to behave as variable resistors in the high frequencies domain and their high power handling capacity using relatively low levels of excitation. PIN diodes are used in this project as solid state switches in order to provide an alternate path for the current and isolate the sensitive sensor throughout the high voltage pulse.

A prototype of the protection circuit was built using PIN diodes in a modified series-shunt configuration in order to provide a high isolation during the pulse application while allowing the sensor to be active and perform its required measurements when the pulse is not present.

Thesis Supervisor: Dr. Chathan. M. Cooke

Title: Principal Research Engineer

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A mi familia, gracias por su confianza y apoyo infinitos.

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Chapter 1 Introduction

1.1 System Overview

An electrical measurement system with a series connected sensor is to be protected. Figure 1.1 shows a simplified diagram of the test system. The sensor is in series with a high-voltage pulser. The pulser produces a short duration (~100ns) high voltage (~-500V) pulse.

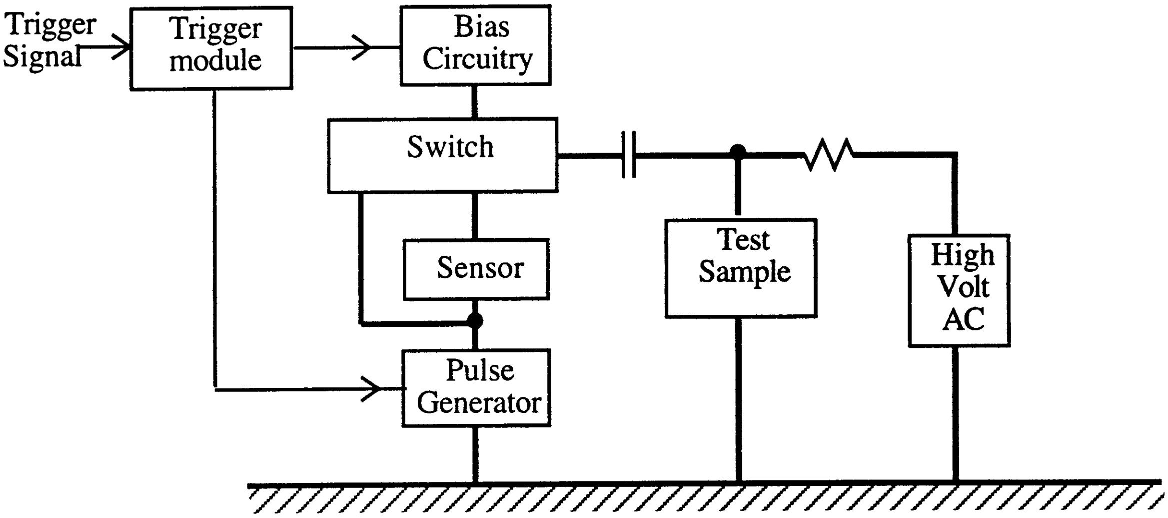


Figure 1.1 Complete System Block Diagram

A proposed PIN diode switch circuit is to be used to protect the sensor. The protection is achieved providing an alternate current path and isolating the sensor from the circuit during the pulse duration. PIN diodes are used as the solid state switches to provide the sensor isolation and the alternate path for the pulse generated current.

PIN diodes are widely used in the RF and microwave domain as signal controlling devices and were selected for this application due to their ability to behave as a bias current controlled resistor for high frequency signals. Due to the short duration of the applied pulse, it can be thought of as a short duration high frequency signal. PIN diodes are also capable of controlling high levels of signal using a relatively low level of bias current, a quality that also makes them suitable for the current application.

1.2 System Modules Description

This section presents a brief description of three of the modules depicted in figure 1.1 that were implemented in order to provide the desired protection to the sensor:

-*Trigger Module:* This module receives the trigger signal and generates the trigger signals for the pulse generator and the bias circuits. The trigger signal to the pulse generator is delayed to allow the bias circuit enough time to change the PIN diodes state in the ***Switch Module*** in order to isolate the sensor during the pulse application.

-*Bias Circuitry Module:* This module provides the bias currents and voltages necessary to operate the PIN diodes present in the *Switch Module.* It responds to the signal sent by the ***Trigger Module.***

- *PIN diode Switch Module:* This module provides the interface between the sensor and the system. It consists of two PIN diodes connected in a series-shunt configuration. Depending on the bias state, it will either connect the sensor to the system ***(Conduction State)***, or it will isolate it and provide an alternate path around the sensor for the pulse current ***(Isolation State)***. The necessary voltages and currents needed to bias the diodes in their different states are provided by the ***Bias Circuitry Module*** described previously.

1.3 Project Overview

In the following chapters, an introduction to the PIN diode theory is presented (Chapter 2) followed by the experimental characterization of some PIN diodes (Chapter 3). Included is a comparison between the experimental results and the manufacturer data.

Based on both the experimental and the data sheet information, a diode selection is made and a switch circuit is realized using two PIN diodes (Chapter 4). One of the diodes is connected in series with the sensor while the other is shunt across it and the series diode. A driver circuit was developed in order to provide the required currents and voltages to bias the two diode circuit.

The proposed two PIN diode switch circuit and driver is experimentally tested for compliance with the desired behavior. The goal is to maintain connection of the sensor into the series test circuit except for a short period when a trigger pulse is initiated. During this short period, the sensor is isolated from test circuit while simultaneously an alternate current path is provided around the sensor.

Chapter 2 PIN Diode Theory

2.1 General Description

PIN diodes are semiconductor devices composed of three layers (figure 2.1): a layer of highly positive doped material (P), an almost pure high resistivity intrinsic layer of finite area and thickness(I), and a final layer of highly negative doped material (N).

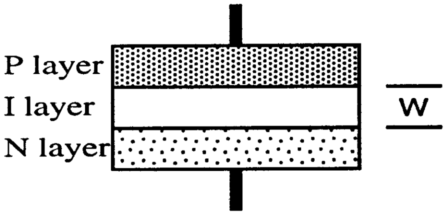


Figure 2.1 PIN Diode Structure

One of the most important features of PIN diodes is their ability to behave, under certain circumstances, as a current controlled resistor at RF and microwave frequencies. Although most PN junction diodes exhibit this characteristic to some extent, PIN diodes are optimized in design to achieve a relatively wide and linear resistance range [1,2].

The ability to control large RF signals while using much smaller levels of dc excitation makes the PIN diodes suitable for applications that include attenuating, modulating, limiting, phase shifting, and switching of RF and microwave frequencies signals.

The performance of a particular PIN diode in a given circuit or application is mainly determined by its design (geometry, semiconductor material used, packaging), bias condition (forward or reverse bias and level), and the frequency of the controlled signal.

2.2 Forward Bias Operation

During forward bias operation (current entering through the P layer), holes from the P region and electrons from the N region are injected into the I-layer affecting its conductance. The amount of charge stored in the intrinsic layer during forward bias condition is dependent on the diode current magnitude and the average carrier lifetime (τ) in the intrinsic region as related by the following equation [1],

$$I_f = \frac{Q_d}{\tau} + \frac{dQ_d}{dt} \tag{2.1a}$$

When the bias consists of only a constant current, then the stored charge is constant and is equal to:

$$Q_D = \tau I_F \tag{2.1b}$$

Carrier lifetime, also known as *recombination time*, is the average time it takes for the stored charge to decay to 1/e of its initial value after the source of carriers (forward bias) is removed [3].

2.2.1 Forward Bias Resistance with Sinusoidal Signals

The PIN diode effective resistance for an ac sinusoidal signal is dependent on the device and on the signal itself. The density of charge stored in the intrinsic region, the frequency or period and magnitude of the non-bias signal applied to the diode establish the resistive performance of the device. Depending on whether the non-bias signal frequency is smaller or larger than the *transit time frequency* (2.2) the PIN diode behaves either like a normal PN junction diode or as a current controlled linear resistor.

$$f_t = \frac{1}{2\pi\tau} \tag{2.2}$$

The transit time frequency can also be expressed as a function of the intrinsic region width instead of the carrier lifetime,

$$f_t = \frac{K_p}{W^2} \tag{2.3}$$

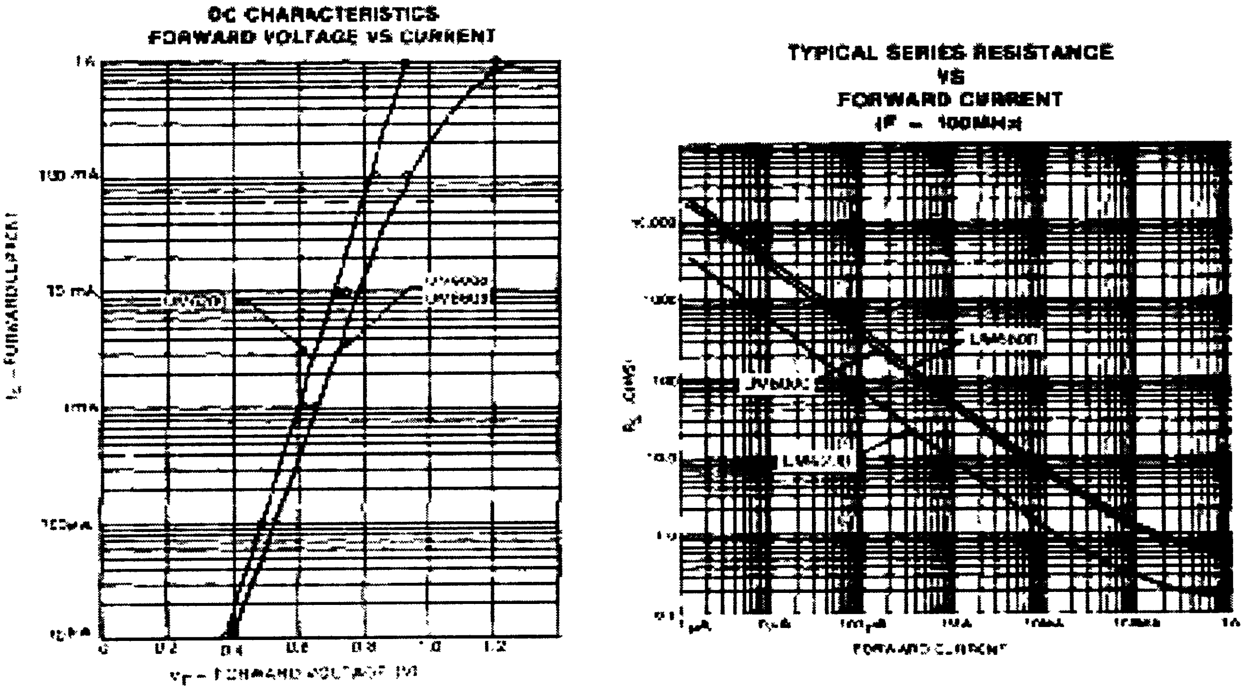
where K_p is a device dependent constant (for example, in some diodes $K_p \approx 1.3\text{x}10^{-3}$ Hz•m^2) and W is the I-region width, see figure 2.1.

Low Frequency Case

When the period of the varying signal applied to the diode is longer than its intrinsic region carrier lifetime the diode behaves as a normal PN junction diode. Its incremental resistance is described by the dynamic resistance of its DC current vs. voltage characteristic curve (figure 2.2a) at any bias point. An approximation to the junction resistance at low frequencies is given by,

$$R_j = \frac{nKT}{qI_F} \tag{2.4}$$

where n is a device dependent constant (typically n≈1.8), K is Boltzman's constant, T is absolute temperature in Kelvin and q is the electron charge constant.



(a) (b)

Figure 2.2 PIN diode sample (a) I-V characteristic and (b) Forward Bias Series Resistance

High Frequency Case

For signal frequencies above the transit time frequency, the number free carrier charges stored in the intrinsic does not appreciably change within the short period of the signal, and they constitute a conductive gas or plasma (similar to the free electrons in a metal conductor) for the high frequency signal. The PIN diode behaves as a current controlled resistance (figure 2.2b) whose value can be expressed as,

$$R_f = \frac{W^2}{2\,\mu\,\tau\,I_F} \tag{2.5}$$

where μ is the mobility of carriers in the intrinsic region, W is the I-region width, τ is the carrier lifetime and I_F is the forward bias current. This resistance would be the effective resistance of a bulk crystal having a stored electric charge of free carriers [3].

The suitability of the PIN diodes for RF and microwave application arises from the fact that the high frequency resistance (2.5) is smaller than the corresponding low frequency resistance (2.4) at the same bias current.

2.2.2 Forward Bias Equivalent Circuit

Because of the frequency dependent behavior of the PIN diode, two equivalent circuits are commonly used [1]. The first one at low frequencies ($f<f_t$) is that of a normal PN diode while the other is for frequencies above ($f>f_t$). Figure 2.3 below shows these equivalent circuits, including the package parasitic.

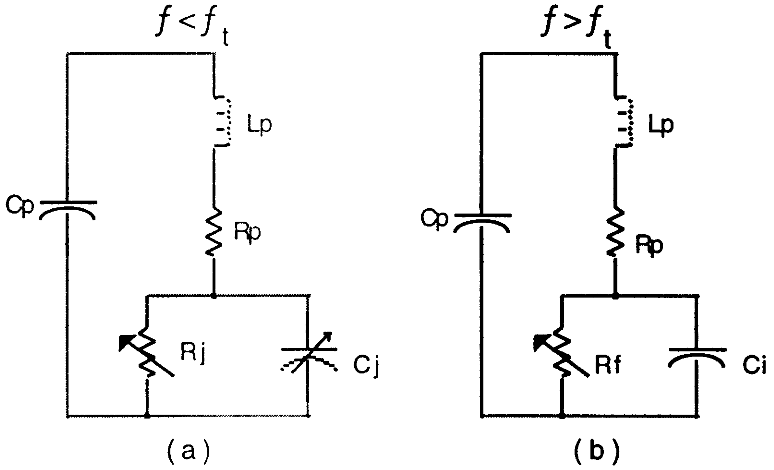


Figure 2.3 Forward Bias Equivalent Circuits (a) low frequency; (b) high frequency

In this figure, R_j is the junction resistance (2.4) and C_j the junction capacitance (a function of applied voltage); R_f is the I-region resistance (2.5) and C_i the I-region capacitance (a function of the I layer geometry); L_p, C_p and R_p are the diode's package parasitic.

2.3 PIN Diode in Reverse Bias

2.3.1 Operation Description

When a reverse bias is applied, a majority of the holes and electrons stored in the intrinsic region during forward bias return to the P and N layers. Almost no charge is stored in the depleted I-region, which can be thought of as a low loss dielectric. As the level of reverse bias is increased, the amount of stored charges decreases depleting the intrinsic layer.

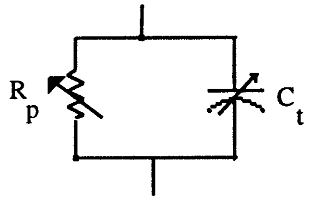
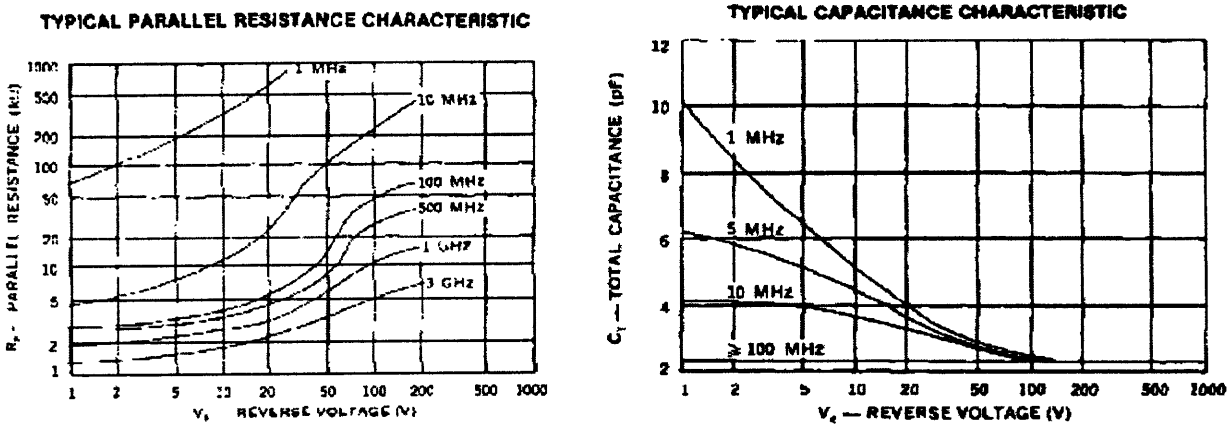


Figure 2.4 Reverse Bias PIN Diode Model

Under reverse bias, the PIN diode can be modeled as a parallel plate capacitor in parallel with a resistor (figure 2.4). The values of these reverse resistance and capacitance are dependent on the level of reverse bias applied and the frequency of the signals through the diode. (Figure 2.5)



(a) (b)

Figure 2.5 Pin Diode (a) Resistance and (b) Capacitance vs. Reverse Voltage Example

2.3.2 Reverse Bias Equivalent Circuits and Dielectric Relaxation Frequency

As discussed above, as reverse bias is applied the I region is depleted of mobile charges creating a parallel plate capacitance. However, some charges remain in a portion of the I-layer , the undepleted portion. The diode intrinsic region can be therefore divided into depleted and undepleted portions.

Due to the its stored charge, the undepleted portion can be represented as capacitor (C_{ur}) with a parallel connected resistor (R_{ur}). The value of R_{ur} and C_{ur} are dependent on the reverse voltage and signal frequency. The higher the reverse voltage, the smaller R_{ur} and C_{ur} (less charge stored)

The depleted region can be represented as a low-loss capacitor (C_{dr}).

Low Frequency

At low frequencies, the undepleted region reactance is greater than its resistance, effectively increasing the diode capacitance. The PIN diode can be modelled (neglecting parasitic) as the depleted region capacitance, in series with the undepleted region capacitor and parallel resistor (Figure 2.6a)

As frequency is increased the reactance of the undepleted region decreases, decreasing the total diode capacitance (figure 2.5). The frequency at which the undepleted region reactance and resistance are equal is called the *dielectric relaxation frequency*. This frequency is calculated as shown below,

$$f_R = \frac{1}{2\pi R_{ur} C_{ur}} \tag{2.6}$$

where R_{ur} and C_{ur} are the resistance and capacitance of the undepleted portion of the intrinsic-region at the given reverse bias voltage.

High Frequency

When the frequency increases beyond the dielectric relaxation frequency, the undepleted region resistance is shorted out by the undepleted region capacitance, and the PIN diode behaves as a linear capacitor (C_j), independent of reverse bias. A parallel resistance is present in the model to account for losses in the intrinsic region.

Figure 2.6b shows the reverse bias equivalent circuit frequency signals above the dielectric relaxation frequency.

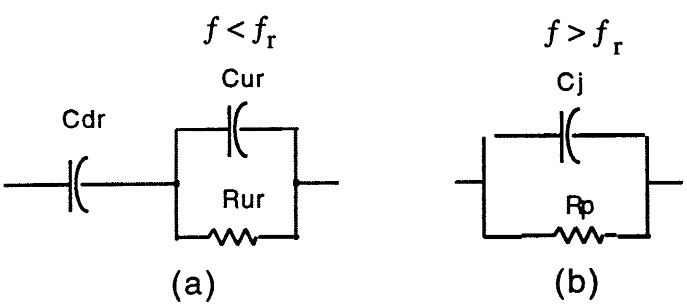


Figure 2.6 Reverse Bias Equivalent Circuits: (a) Low frequency; (b) High frequency

2.4 Switching Speed Characteristic

A commonly used definition for the switching speed of a PIN diode is the time required to change the level of stored charge in its intrinsic region. In most applications (switching, phase shifting, etc), the switching speed would be the time required to either store or deplete the charge in the diode's intrinsic region. This time depends on the diode physical parameters as well as the drive circuits used and bias points at which the diode is being operated.

2.4.1 turn-off time: Forward to Reverse Bias

Figure 2.7 shows a typical current curve through a PIN diode during turn-off. The forward bias current (I_f) is forcing an initial charge equilibrium according to equation (2.1b). In order to force the diode into reverse bias, it is necessary to apply a reverse current through the device such that the charge removed by it (the area between the zero current line and the reverse current curve) equals the forward bias charge stored in the intrinsic region (2.7).

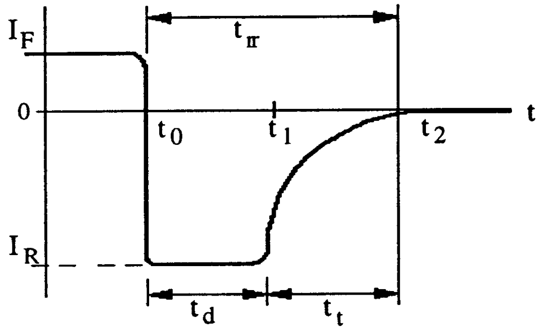


Figure 2.7 turn-off PIN diode current.

$$Q_D = I_F \tau = \int_{t_0}^{\infty} i_r \, dt \tag{2.7}$$

The elapsed time between the zero crossing of the reverse current (t_0) and the moment where the reverse current reaches ninety percent down from its maximum value (t_2) is called the *reverse recovery time* (t_{rr}) or *turn-off time* (T_{off}). This reverse recovery time is commonly used in industry as a figure of the switching capability of a PIN diode.

As can be seen from figure 2.7, the reverse recovery time may contain two prominent states. The first state (t_0 to t_1) is a plateau of constant reverse current and impedance and is called the *delay time*. This time is proportional to the ratio of forward current I_F and peak reverse current I_R, thus a reduction of the turn-off time can be achieved by decreasing this ratio and changing the delay time.

The second state (t_1 to t_2) is known as the *transition time*. During this period, the impedance of the diode increases rapidly while the magnitude of the reverse current decreases. This transition time depends primarily on diode design (geometry and materials), and only slightly on the forward bias current. The transition time determines the minimum realizable turn-off time for a given device [1].

Although the reverse recovery time is a good indicator of the switching speed of a PIN diode, other factors such as the driver characteristics, circuit topology and, as reported by Shammas et al. [10], the junction temperature and rate of fall of forward current, may significantly alter the resulting turn-off time of the device.

2.4.2 Turn-on time: Reverse to Forward Bias

The turn-on time can be defined as the time it takes to bring the PIN diode from reverse bias to a given level of forward bias. It can also be seen as the time it takes to bring the charge in the intrinsic layer to a given level in order to achieve a desired operation point (figure 2.8). It is normally measured as the time for the forward bias current to be within ten percent of its final value.

As mentioned previously, during reverse bias the intrinsic layer is depleted of charge and acts as a high impedance dielectric while during forward bias charge is stored in the I-region that provides a conduction mechanism. As in the forward to reverse transition, the turn-on process can be divided in two steps: the charge injection and charge storage phases.

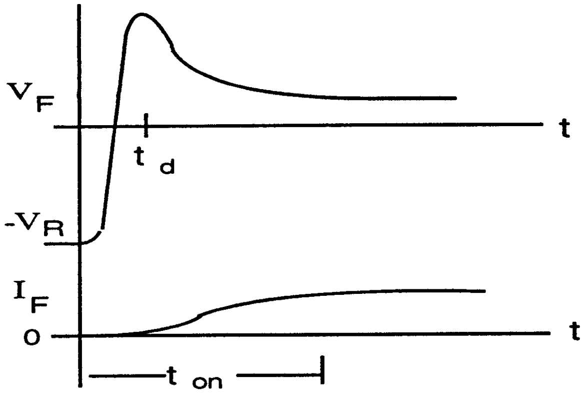


Figure 2.8 Typical PIN diode turn-on transient

When forward bias is first applied, holes and electrons are injected from the P and N layers into the intrinsic layer. During the first part of the transition the diode impedance remains high until holes and electrons meet at the middle of the intrinsic region. Once the carriers meet, the depletion region has been eliminated, charge starts to be stored in the intrinsic region decreasing the diode's impedance. The charge stored increases until it reaches its steady state value that is given by equation (2.1b).

The speed at which the charge is injected and stored, and thus the turn-on time of the diode, depends on the intrinsic region geometry, and composition, as well as the magnitude and rate of change of the forward current supplied to the device. The minimum achievable turn-on time for a given diode is therefore limited by the circuit topology, parasitic impedances (specially inductive elements) and driver characteristics.

For most PIN diodes, the turn-on time is usually shorter than the turn-off time and is not considered the important parameter in determining the switching speed of a PIN diode [1].

2.5 PIN Diode Limitations.

Device parameters, such as power dissipation limits and diode reverse breakdown voltage, and diode operation and signal parameters, such as diode bias, controlled signal frequency an duty cycle, limit the signal levels that can be safely controlled by a PIN diode without suffering device degradation or undesired signal behavior.

During forward bias operation, the duration and magnitude of the non-bias current is determined by the amount of stored charge relative to the charge variations due to the controlled signal. In order for the diode to remain in its forward bias condition, the amount of charge that might be removed by the non-bias signal has to be smaller than the bias induced charge. The following inequality (2.8) must hold,where T_r is the duration of the signal portion opposing the bias current thus removing charge from the diode's intrinsic region.

$$Q_D = I_F \tau > q_d = \int_{T_r} |i_d| dt \qquad (2.8)$$

As explained in previous sections, during forward bias operation, the frequency of the non-bias signal also needs to be greater than the transit time frequency (equation 2.2) in order for the diode to behave as a resistor whose value is smaller than the dynamic resistance value at the same bias point (small signal resistance from the I-V characteristic of the diode). During reverse bias, the threshold frequency for a linear capacitive behavior independent of reverse bias is given by the dielectric relaxation frequency (equation 2.6).

The maximum instantaneous reverse voltage applied to the diode at any time, must not exceed the diode breakdown voltage. Operation at reverse voltages above the breakdown voltage, causes the diode reverse current to increase rapidly and an avalanche or zener effect occurs which may result in degradation of the diode characteristics or permanent damage to the device.

The maximum power that a PIN diode can dissipate depends on the ambient temperature (T_{Amb}), its maximum operating junction temperature (T_{Jmax}), thermal resistance and circuit layout. The maximum power dissipation capability is given by

$$P_{max} = \frac{T_{Jmax} - T_{Amb}}{\theta_{jc} + \theta_{cA}} \qquad (2.9)$$

where θ_{jc} is the junction to case thermal resistance which is diode and package design dependent, and θ_{cA} is the case to ambient thermal resistance. The later is determined by the diode mounting and heat sinking. The sum of bias and non-bias signal average power dissipation through the PIN diode needs to remain below the maximum power dissipation limit set on equation (2.9). Operation above this limit decreases the useful life of the device and may cause irreversible damage to it.

Chapter 3 Diode Characterization

3.1 Basic Test Circuit

The characteristic of the PIN diodes were determined using the basic circuit depicted in figure 3.1.

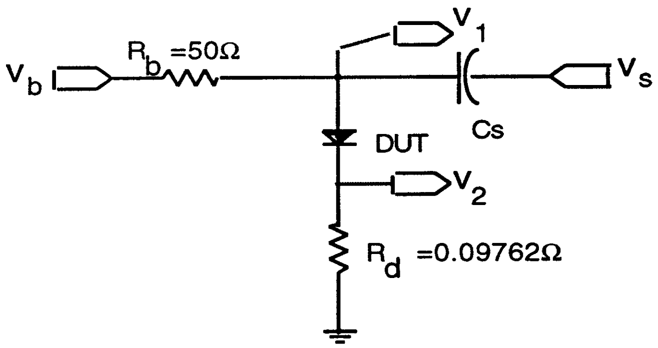


Figure 3.1 Basic Diode Circuit used for Characterization

On the circuit, the diode current is proportional (following Ohm's Law) to the voltage across R_d, which is measured at terminal V_2; the diode voltage is just the voltage difference between the terminals V_1 and V_2 (3.1)

$$v_D = v_1 - v_2$$
$$i_D = \frac{v_2}{R_d} \tag{3.1}$$

Depending on the parameter investigated, the different voltage sources are connected at terminals V_b and V_s, and the value of the coupling capacitor C_s is varied.

Three diodes from Microsemi's PIN diode families UM2100, UM4000, and UM6200 series were studied in order to determine their I-V curves, diode resistances and switching characteristics. The three diodes used had an axial package (type A) and were fabricated using similar processes, but differed in its size, thus presenting different characteristics due to their different carrier lifetimes. Table 3.1 presents the manufacturer published values for the electrical characteristics investigated.

	UM2104	UM4002	UM6204	Condition
Carrier Lifetime	25μs	5μs	0.6μs	I_F=10mA
Series Resistance	2.0Ω (2MHz)	0.5Ω	0.4Ω	100mA,100MHz
I region width	>200μm	150μm	40μm	

Table 3.1 PIN Diode's Manufacturer Electrical Characteristics

3.2 Forward Bias I-V Curves

The circuit in figure 3.1 was used to obtain the experimental PIN diode's characteristics. For the case of the forward bias I-V curve determination, terminal V_s remained open circuited and a DC voltage source was connected to terminal V_b. The diode voltage and current were then measured at different values of the voltage source V_b. Figure 3.2 below present the experimental forward bias I-V curves for the three diodes studied. Matlab was used to fit to the data points a semi-logarithmic first order equation of the form

$$\log_{10}(I_D) = K_1 V_D + K_2 \tag{3.2}$$

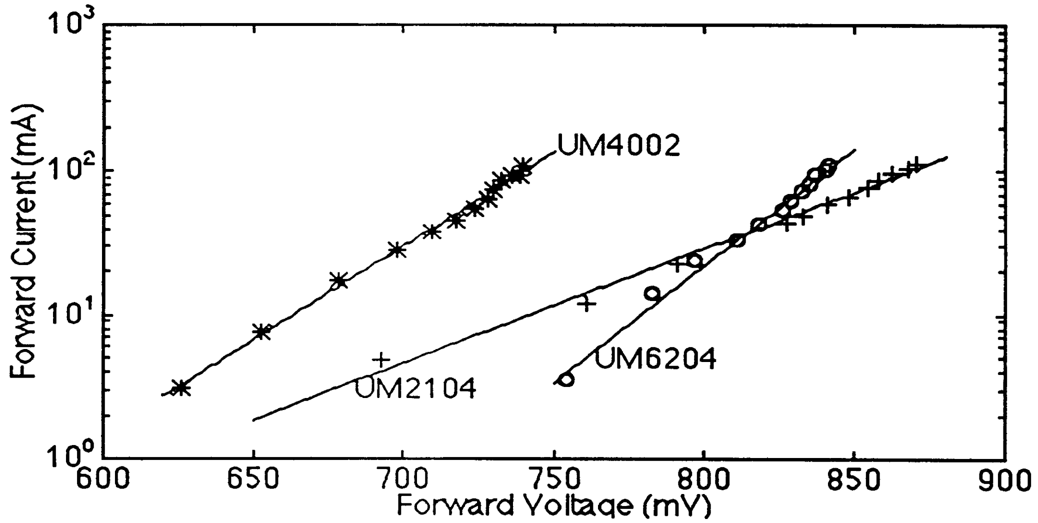


Figure 3.2 Experimental I-V Curves for PIN Diodes UM2104, UM4002 & UM6204

As seen from the previous figure, the I-V characteristic of a PIN diode resembles that of a common PN diode. Figure 3.3 in next page shows the I-V curves for the same three diodes together with their manufacturer reported mean I-V curves (Appendix B contains the diode's data sheets).

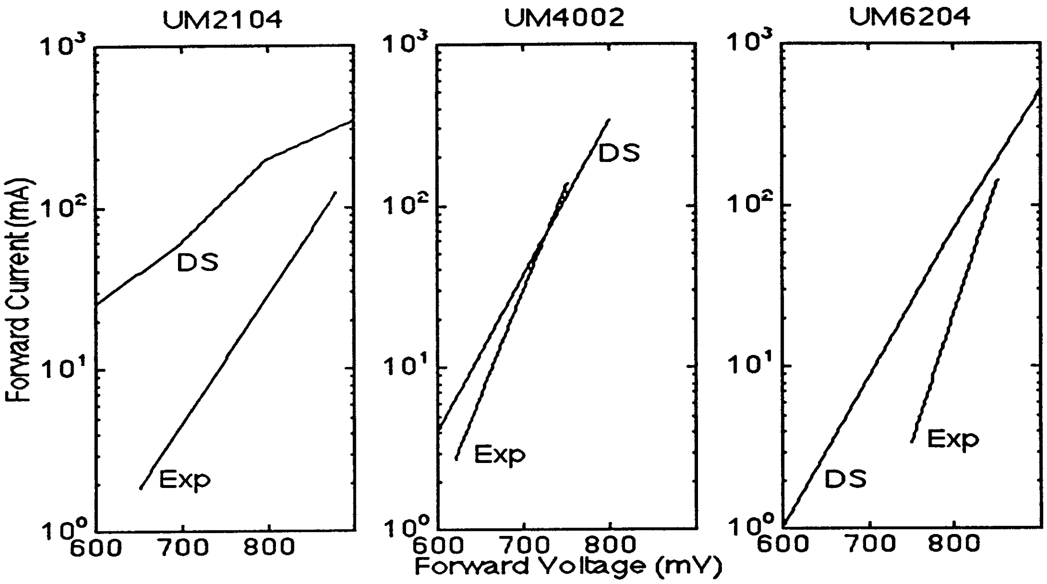


Figure 3.3 Data sheet vs. Experimental I-V Curves

3.3 Diode Resistance

As mentioned earlier, the series resistance presented by PIN diodes is dependent on the frequency of the non-bias signal applied to them. For low frequency signals, the series resistance presented is similar to that of a PN junction diode, that is the dynamic resistance from the I-V curve at a given bias point. The experimental low frequency resistance (R_{ac}) for the PIN diodes investigated was obtained from the experimental I-V curve. The resistance was computed using the parameters found for equation (3.2), and follows the relationship:

$$R_{ac}=\frac{dV_D}{dI_D}=\frac{1}{K_1 I_D} \tag{3.3}$$

The high frequency resistance (R_S) for the PIN diodes was obtained by connecting a 20MHz fixed amplitude sinusoidal voltage source to terminal V_S on the basic test circuit (figure 3.1) used on section 3.1. A 160pF capacitor was used for the coupling capacitor C_S. The diode resistance was computed at different values of bias current. The resistance is given by the ratio of the sinusoidal components of the diode voltage and current.

$$R_f=\frac{v_d}{i_d} \tag{3.4}$$

The resulting series resistances for the three diodes are plotted in the following figures. Figure 3.4 Shows the low frequency (R_{ac}) and high frequency (R_f) resistances for the three diodes studied.

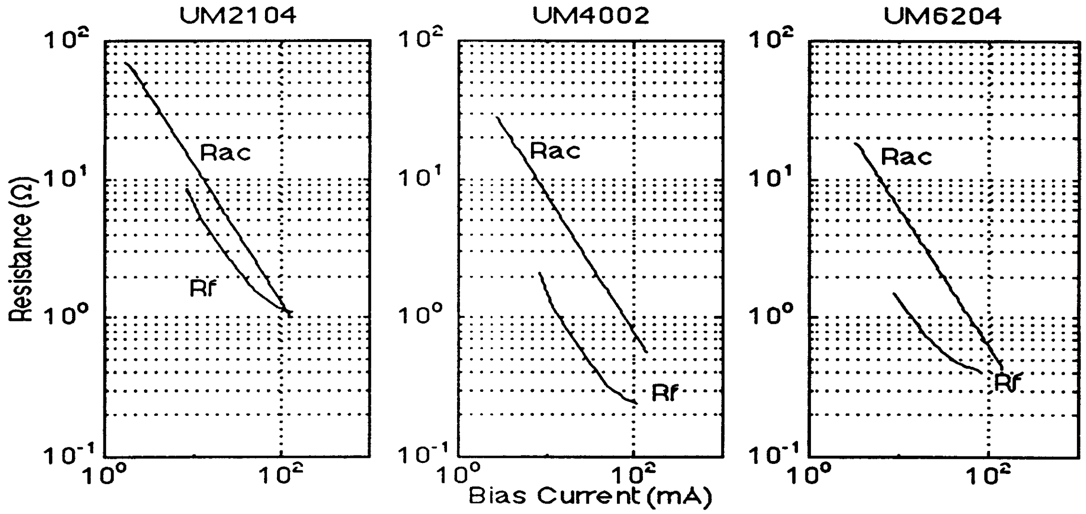


Figure 3.4 Low frequency and High frequency resistance vs. Bias current.

As expected from the theory, see section 2.2.1, the high frequency resistance was smaller than the low frequency resistance for the same bias current. Appendix A provides more details on PIN diode resistances. The next plot (figure 3.5) shows a comparison of the high frequency resistance for the three devices. As predicted from the theory (Equ. 2.5) the resistance is inversely proportional to the bias current. It should be also noted that the device with the widest I-region, diode UM2104 from table 3.1, presented the higher high frequency resistance.

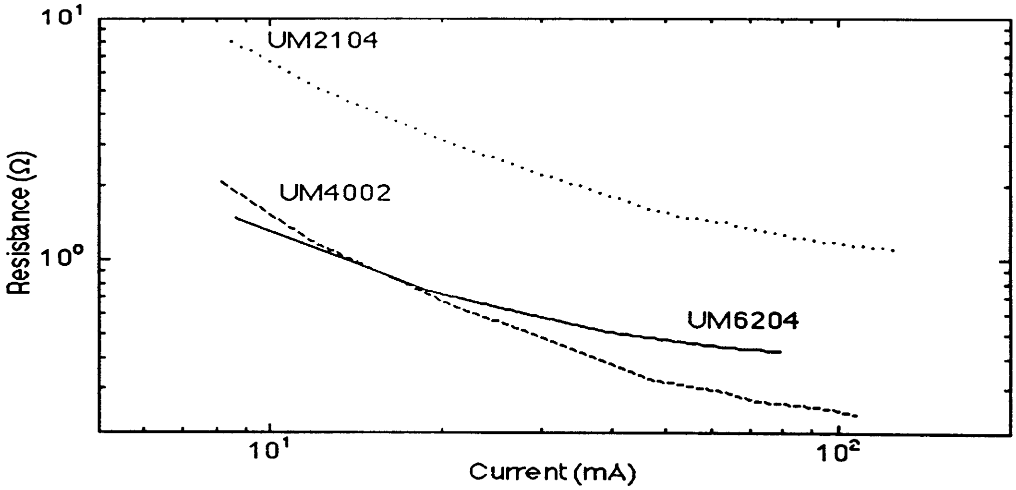


Figure 3.5 High Frequency Resistance Comparison

3.4 Switching Speed: On and Off.

The switching speed of the PIN diodes was investigated using the basic test circuit (figure 3.1) leaving terminal V_S open circuited and applying a bipolar 5Hz, 50% duty cycle square wave source to terminal V_b. The positive and negative voltage values of the square wave signal determined the forward and reverse bias conditions, respectively, of the diode under test.

Both the turn-on and turn-off times were measured for different conditions of forward and reverse bias. A summary the observations on the switching speed is presented using the following general equations,

$$T_{on}=\frac{f_1(V_R)\,g_1(\tau)}{h_1(I_F)} \tag{3.5a}$$

$$T_{off}=\frac{h_2(I_F)\,g_2(\tau)}{f_2(I_R)} \tag{3.5b}$$

where f, g and h are some unknown positive functions of the applied reverse voltage (V_R) [peak reverse current, I_R, for the turn-off time], the diode carrier lifetime (τ) and the applied forward current (I_F), respectively. This reflect that T_{on} increases with V_R and τ, while T_{off} increases with I_F and τ. Similarly, T_{on} decreases with I_F and T_{off} decreases with I_R. The following sections will present the qualitative effects of these parameters on the switching speed of the diodes. It should be noted that currents and voltages are set by the circuit design, while the carrier lifetime is given by the device.

3.4.1 Experimental Turn-off Time

Figure 3.6 in the next page show the turn-off current curves for the three different PIN diodes studied. It can be seen that the turn-off time is directly proportional to the transit time of a PIN diode. The PIN diode with the smallest transit time (UM6204) presents the shortest turn-off time, while the one with the largest transit time (UM2104) has the longest turn-off time.

Figures 3.7 and 3.8 present the effects of varying the peak reverse current and forward bias level, respectively, on the turn-off time of a PIN diode. The mentioned graphs show the diode current time response for the device UM4002. Similar graphs were obtained with the other two diodes,

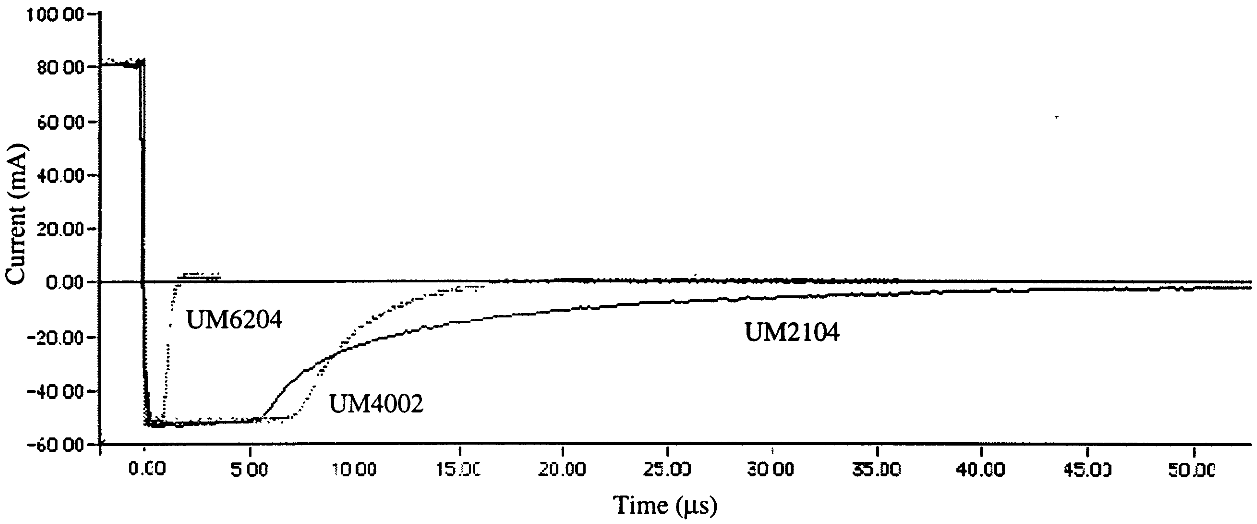


Figure 3.6 Recombination Time Effect on Turn-off Time

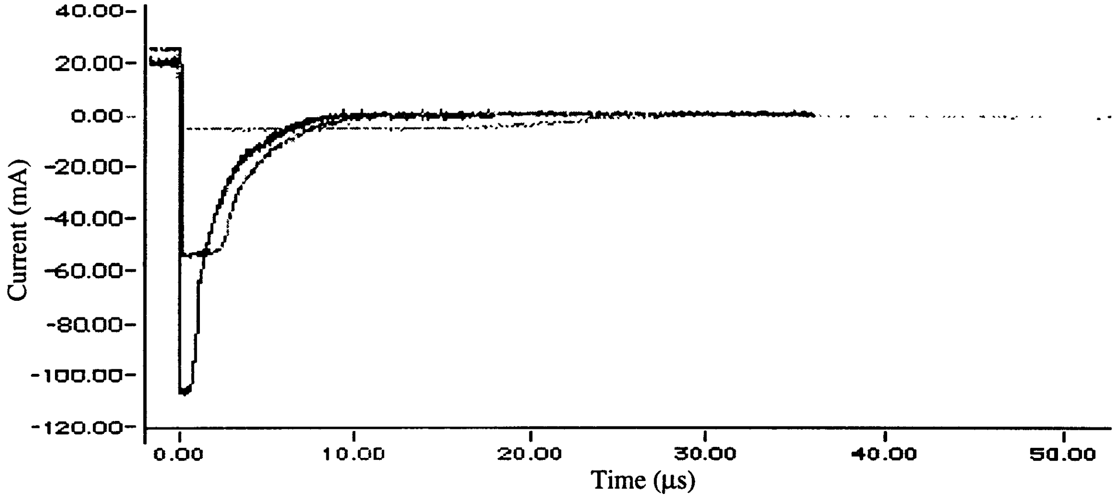


Figure 3.7 Effect of Peak Reverse Current on Turn-off Time for Diode UM4002

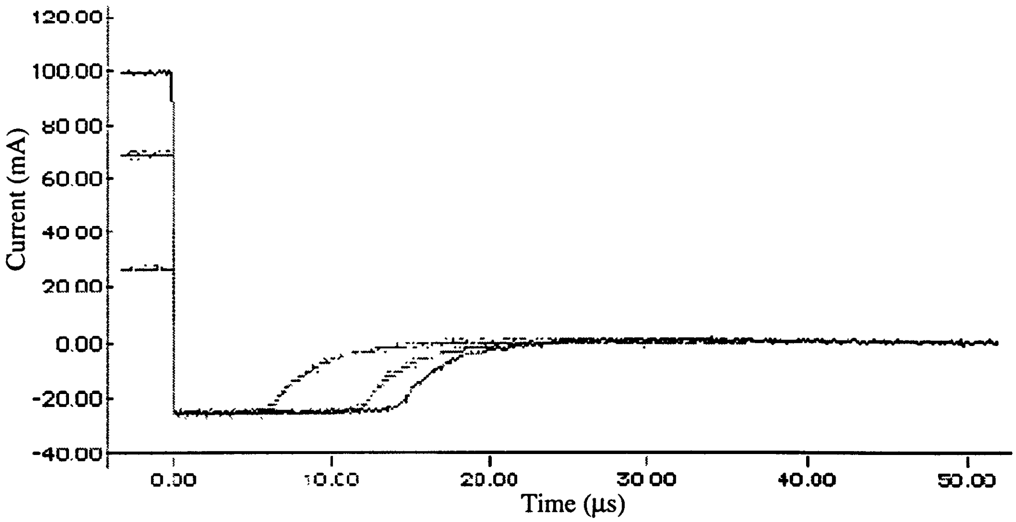


Figure 3.8 Effect of Forward Bias on Turn-off Time for Diode UM4002

although scaled in time due to their different transit times.

It should be noted that an experimental value for the diode's transit time value can be calculated using the current turn-off curves and the stored charge relationship presented in equation (2.7) which is repeated for convenience,

$$I_F \tau = \int_0^\infty i_r \, dt \tag{3.6}$$

The carrier lifetime would be approximated by performing a numerical integration of the diode reverse current over the turn-off time and dividing by the forward bias current,

$$\tau = \frac{\int_{t_0}^{t_2} i_r dt}{I_F} \tag{3.7}$$

See section 2.4.1 for the definition of times t_0 and t_2 on equation (3.7) The time period from t_0 to t_2 approximates the diode turn-off time. Table 3.2 shows some values computed using figure 3.6 graphs from the previous page together with the corresponding turn-off times.

Device	Experimental Value	Manufacturer Value	T_{off} (i_r is 10% peak value)
UM2104	9.9μs	25μs	~40μs
UM4002	6.1μs	5μs	~14μs
UM6204	0.7μs	0.6μs	~1.5μs

Table 3.2 PIN Diodes Experimental Carrier Lifetime (τ) Values and Turn-off Times

3.4.2 Experimental Turn-on Time

From the experimental results (figure 3.9 To figure 3.11) it can be seen that the turn-on time for the PIN diodes studied is much shorter than the turn-off time, thus making the turn-off time the important consideration in the diode speed characterization.

During the diode turn-on , the applied reverse voltage (figure 3.9) and forward bias (figure 3.10) are not determining factors in the turn-on speed of the device. Decreasing the reverse voltage or increasing the bias current are responsible for only a minor increase in the turn-on speed. The level of forward bias applied to a PIN diode in a given application is mainly decided by the desired diode forward bias impedance.

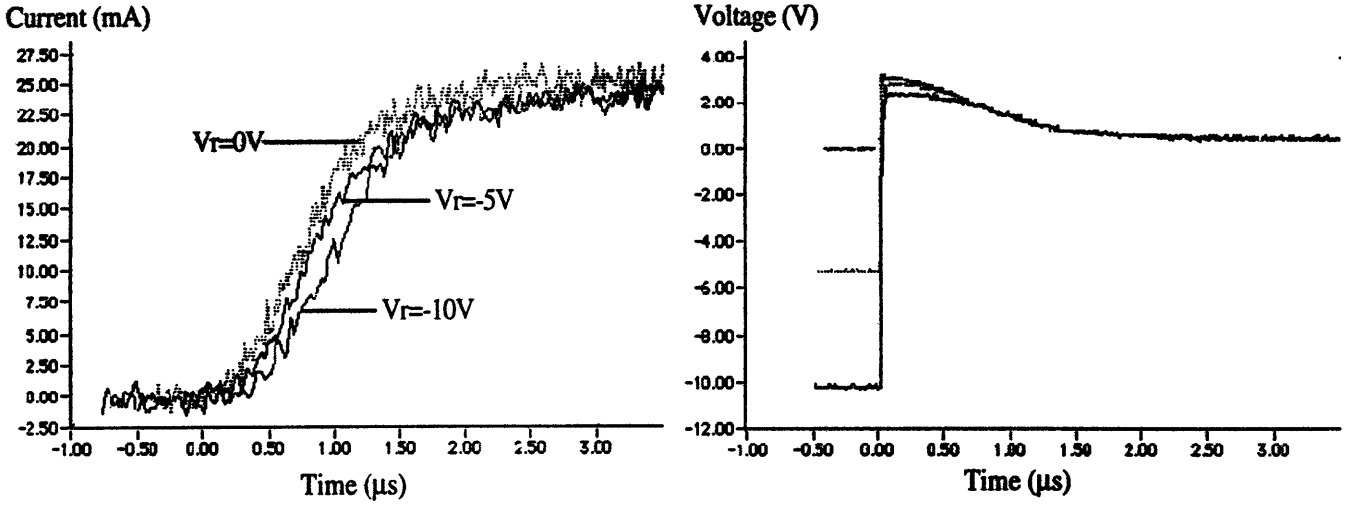


Figure 3.9 Reverse Voltage Effect on Turn-on Time for Diode UM4002

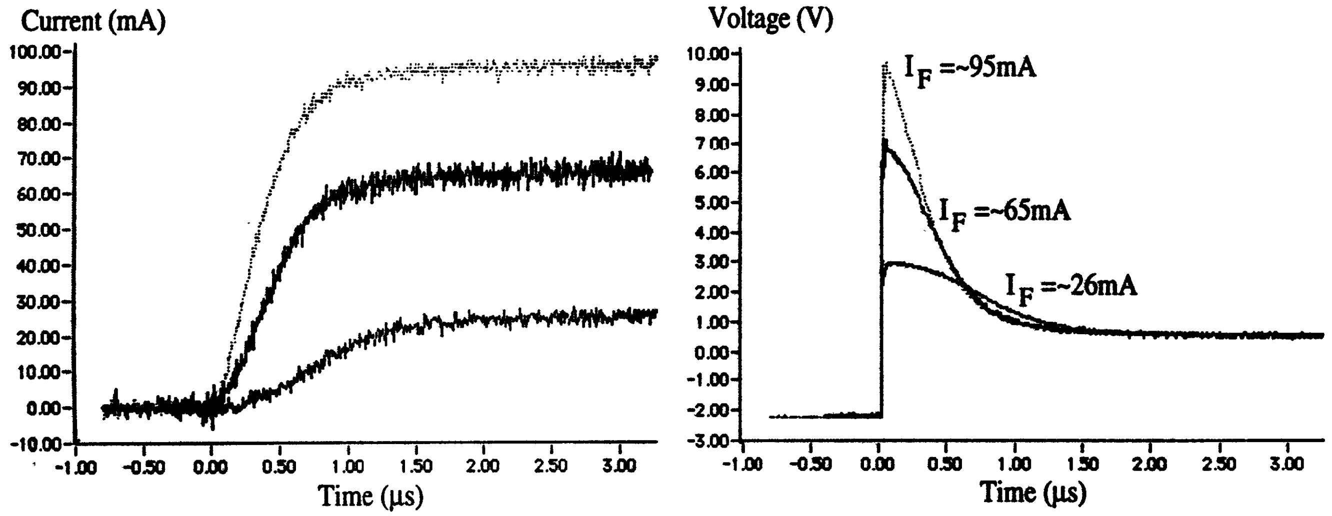
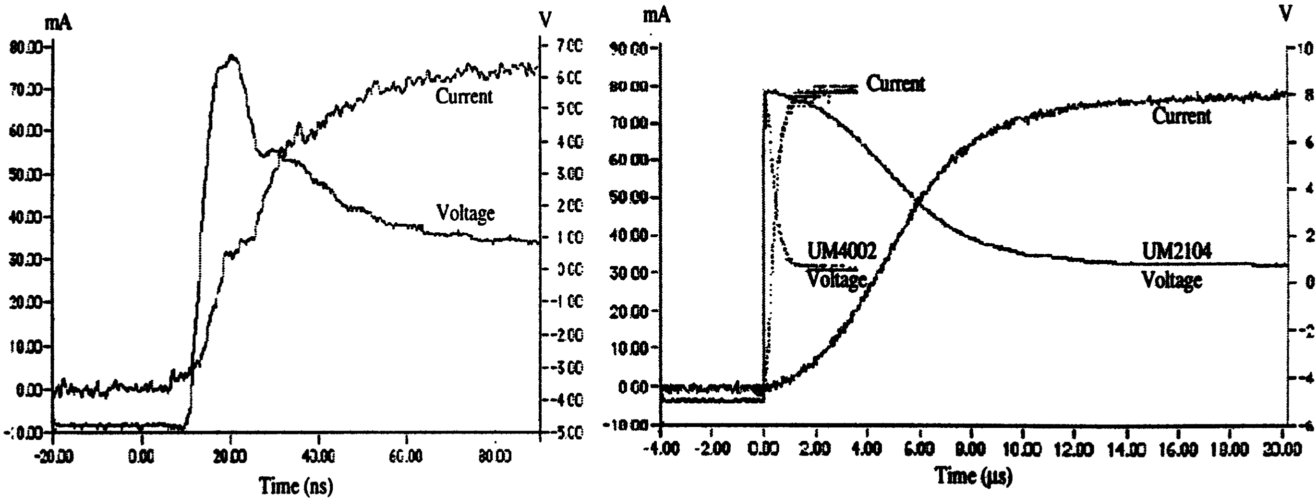


Figure 3.10 Forward Bias Effect on Turn-on Time for Diode UM4002



a) UM6204

b) UM4002 & UM2104

Figure 3.11 Effect of Transit Time on Turn-on Time

Diode	Carrier Lifetime (τ)	T_{on} (within 10% of final value)
UM2104	25μs	~16μs
UM4002	5μs	~1.5μs
UM6204	0.6μs	~75ns

Table 3.3 turn-on Times for Three Diodes with Different Carrier Lifetimes

The turn-on time of a PIN diode depends basically on the transit time of the device's intrinsic region. As can be seen in figure 3.11 and table 3.3, the device with the smallest transit time (UM6204) presented the shortest turn-on time, while the device with the longest transit time (UM2104) had the longest turn-on time, for the same driving conditions.

3.5 Switching Pulse Impedance

Given that the final application of this project is the switching of short timed pulses, an experiment was conducted in order to asses the ability of the PIN diodes to control the pulses, both in-phase and out of phase with the bias current. Once again the circuit in figure 3.1 was used with a coupling capacitor value of 0.56μF and bias and disturbance pulse generators connected to terminals V_b and V_S respectively.

The bias source was set to produce a 200Hz 50% duty cycle square wave providing a forward bias current of approximately ninety milliamperes and a reverse bias voltage around minus nine volts. The disturbance signal was produced by a 10 volts pulse (both positive and negative voltages were used) approximately ten microseconds long. The pulse was applied at different times in the square wave cycle in order to study the pulse diode impedance at four diode operation conditions: reverse to forward transition, forward bias, forward to reverse transition, and reverse bias.

Figures 3.12 And 3.13 show the observed current and voltage waveforms corresponding to both a positive and a negative pulse disturbances. Table 3.4 summarizes the pulse current and voltage observations in the four regions of operation when a 10V, 10μs pulse source was used .

Diode State	Diode Pulse Current	Diode Pulse Voltage	Diode Pulse Impedance
Rev. to Forw	~200mA	~7V	~35Ω
Forward Bias	~195mA	~90mV	~460μΩ
Forw. to Rev.	~200mA	~500mV	~2.5Ω
Reverse Bias	<0.5mA	~7V	>14KΩ

Table 3.4 UM4002 PIN Diode Pulse Impedances

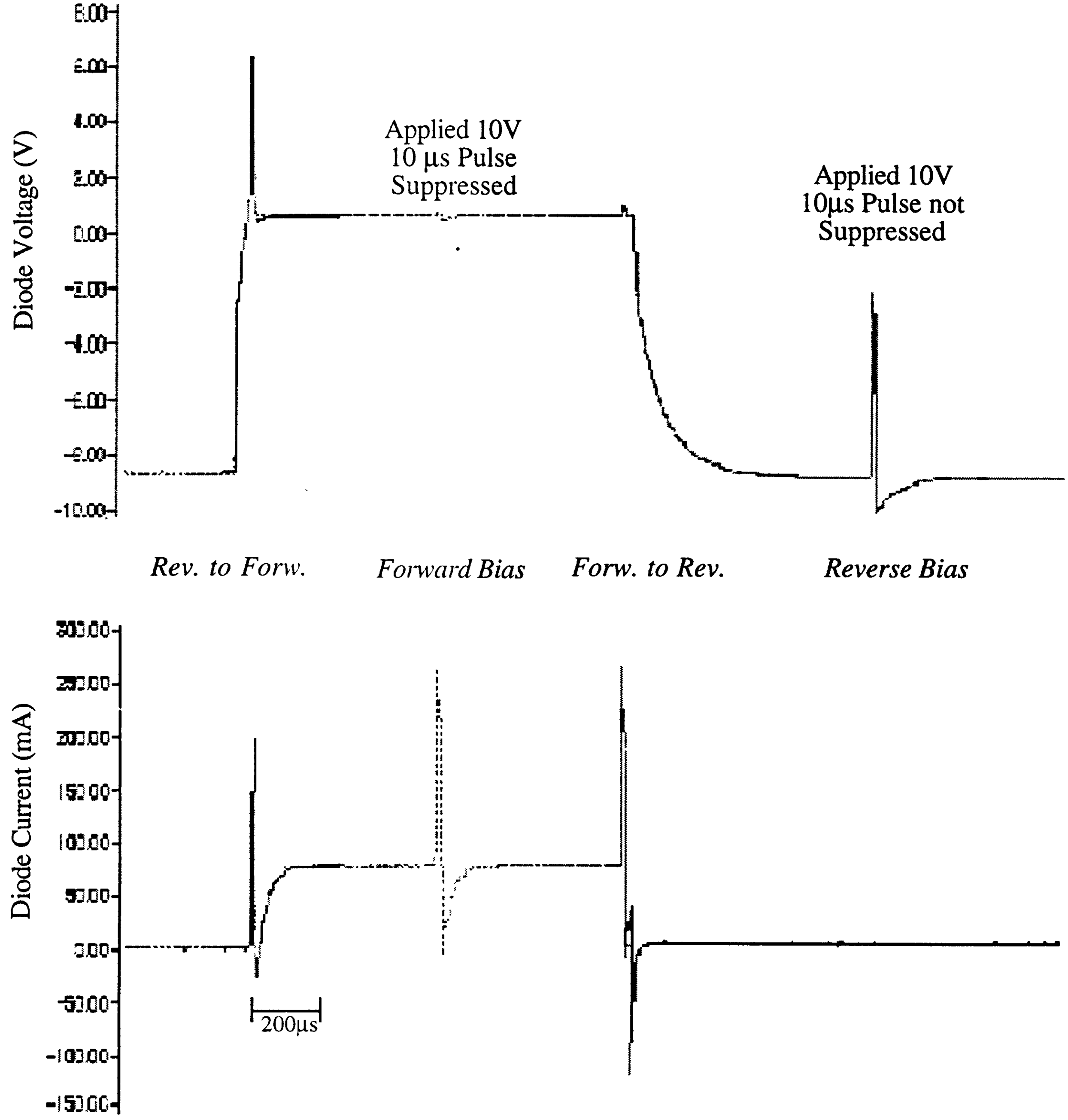


Figure 3.12 PIN Diode UM4002 Current and Voltage Waveforms for Positive Pulse

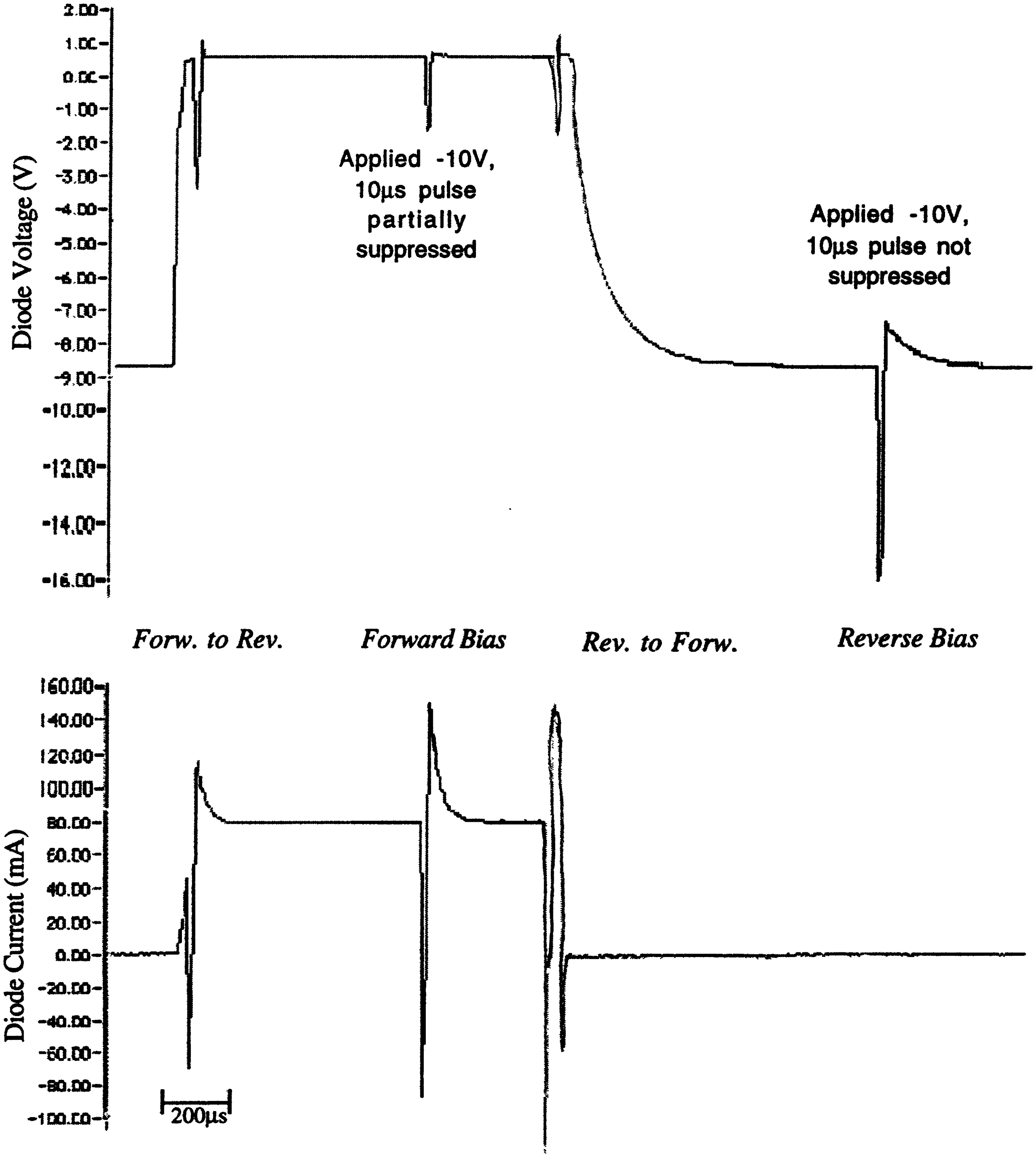


Figure 3.13 PIN Diode UM4002 Current and Voltage Waveforms for Negative Pulse

Chapter 4 The Two Diode Circuit

4.1 General Description

As mentioned previously, a circuit is needed to isolate and protect a delicate sensor from a high current short time pulse.and provide. In order to achieve the goal, the proposed circuit while isolating the sensor needs to: 1) provide an alternate path for the pulse induced current and; 2) disconnect the sensor from the current path.

Since current flowing through a circuit follows the path of less resistance, introducing a "short circuit" across the desired element provides the alternate current path sought, while an "open circuit" in line with the device isolates it. The proposed circuit contains, therefore, a series connected switch and a shunt switch across the series switch and the protected sensor. Since the signal to be commuted is a short duration high voltage pulse, the two switches are implemented using PIN diodes. Figure 4.1 below shows a schematic diagram of the test system.

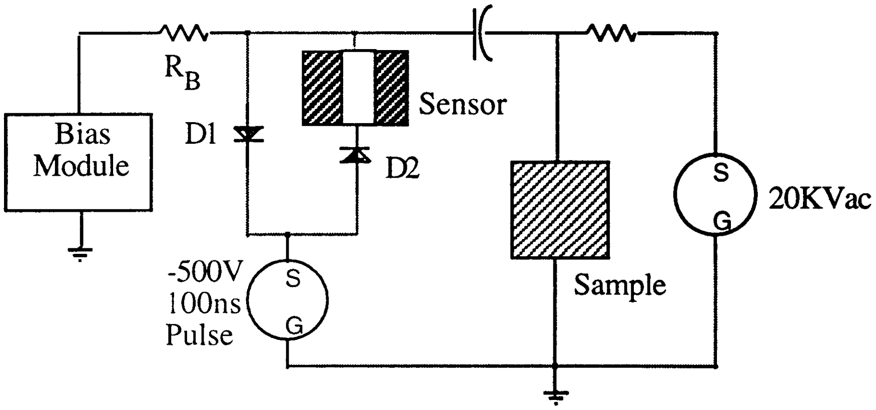


Figure 4.1 Complete Test System

Following the results presented in chapter 3, the PIN diodes used in the circuit are from the Microsemi's family UM4000. These diodes were selected because of their low impedance characteristic, high power rating and moderate carrier lifetime.

In order to analyze and test the designed circuit, a simplification of the system was made. The protected sensor was modeled by means of a 50Ω resistor, and the bias module was substituted by a bipolar square wave generator. To simplify the prototype of the circuit and the measurements, the disturbance pulse is applied through a coupling capacitor. Figure 4.2 shows the simplified model used to test the two diode circuit, being the voltage across the 50Ω load resistor the output of the system.

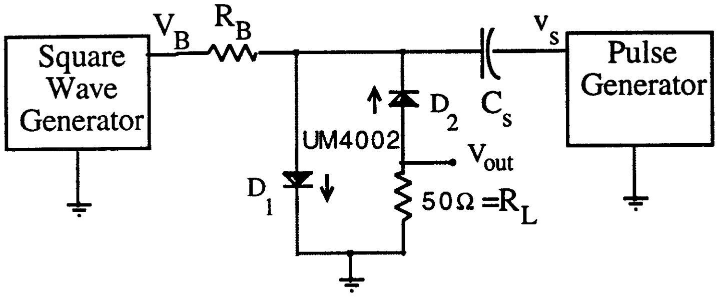


Figure 4.2 Two Diode Simplified System Circuit

4.2 Two Diode Circuit Operation

In the circuit configuration shown in figure 4.2, the two diodes are biased in complimentary modes: when diode D_1 is forward biased, diode D_2 is reverse biased and vice versa. One of the diodes is in a low impedance state while the other is in its high impedance state creating two operation states of the circuit which would be named the *conduction* and *isolation* states.

During the conduction state, diode D_2 would be forward biased (diode D_1 reverse biased) allowing current to flow through the sensor. Isolation mode would correspond to diode D_2 being reverse biased (diode D_1 forward bias), thus effectively isolating the load.

4.2.1 Steady State Analysis

To put the circuit into the conduction mode state, a negative voltage is needed at V_B (figure 4.2) to forward bias diode D_2 and reverse bias diode D_1. Under this conditions, the diode D_2 bias current is determined by the load line equation (4.1) and the diode I-V characteristic (3.2).

$$\begin{cases} |V_{B-}| = V_{D_2} + I_{D_2}(R_B + R_L) \\ \ln I_{D_2}) = K_1 V_{D_2} + K_2 \end{cases} \qquad (4.1)$$

The diode D_1 can be taken to be an open circuit, having almost zero current through it. The series diode bias current will generate a negative constant voltage present at the circuit output.

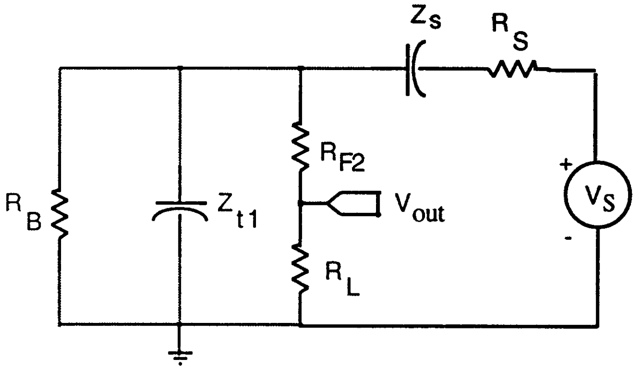


Figure 4.3 Small Signal Conduction State
Equivalent Circuit

Figure 4.3 shows the small signal equivalent circuit when in conduction mode. The series diode behaves as a linear resistor (R_{F2}) whose value depends on the bias current set by the equation system (4.1). The shunt diode can be represented by a capacitor (C_{t1}) dependent on the diode's reverse bias voltage.

The circuit transfer function during the conduction mode is given by the following relationship,

Conduction Mode

$$\begin{aligned}\frac{V_{out}}{V_s} &= \frac{R_L}{R_L+R_{F_2}} \frac{R_B \| Z_{T_1} \| (R_L+R_{F_2})}{R_B \| Z_{T_1} \| (R_L+R_{F_2})+Z_s+R_S} \\ &\approx \frac{R_L}{R_L+R_{F_2}+R_S(R_L+R_{F_2}+R_B)/R_B}\end{aligned} \tag{4.2}$$

The simplification realized in equation (4.2) is based on the assumptions that the coupling capacitor impedance is negligible for the signal V_S applied, and that the reverse bias diode capacitance is very small, thus making impedance Z_{T1} big compared to R_B and ($R_{F2}+R_L$). Since the forward biased diode resistance (R_{F2}) is usually small compared to the load (R_L), then (4.2) simplifies into,

$$\begin{aligned}\frac{V_{out}}{V_s} &= \frac{R_B}{R_B+R_S}, \quad R_L > R_B \\ \frac{V_{out}}{V_s} &= \frac{R_L}{R_L+R_S}, \quad R_L < R_B\end{aligned} \tag{4.3}$$

During isolation mode operation, a positive bias voltage is applied and the shunt diode (D_1) is now forward biased, while the series diode (D_2) is reverse biased. As in the conduction state, the forward biased diode operation point, in this case the shunt diode, is set by its I-V characteristic and the circuit load equation, with the assumption that the series diode can be replaced by an open circuit ignoring any diode reverse leakage current. No voltage appears across the load.

$$\begin{cases} V_{B+} = V_{D_1} + I_{D_1} R_B \\ \ln(I_{D_1}) = K_1 V_{D_1} + K_2 \end{cases} \tag{4.4}$$

The small signal equivalent circuit is now depicted in figure 4.4. Diode D_2 behaves as a small value capacitor and diode D_1 as a current controlled resistor.

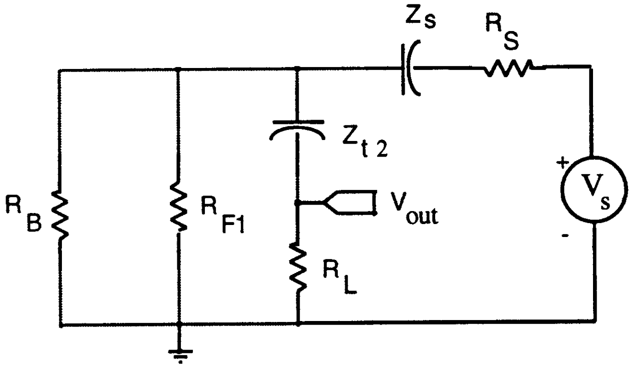


Figure 4.4 Isolation Mode Small Signal Equivalent Circuit

During the isolation mode, the circuit transfer function is given by equation (4.5) where the assumptions that 1) the diode series resistance (R_{F1}) is much smaller than any other impedance in the circuit, and 2) the reverse diode impedance (Z_{T2}) is much greater than the load resistance R_L were made to the simplification the equation.

<u>Isolation Mode</u>

$$\begin{aligned} \frac{V_{out}}{V_s} &= \frac{R_L}{R_L + Z_{T_2}} \, \frac{R_B \| R_{F_1} \| (R_L + Z_{T_2})}{R_B \| R_{F_1} \| (R_L + Z_{T_2}) + Z_s + R_s} \\ &\approx \frac{R_L R_{F_1}}{Z_{T_2} R_s}, \quad R_{F_1} << R_L < Z_{T_2}, R_{F_1} < R_B \end{aligned} \tag{4.5}$$

It can be seen that the output voltage is a function of both the series diode reverse bias and the shunt diode forward bias point. As the shunt diode bias current increases, its equivalent series resistance decreases causing a decrease on the output voltage. The reverse diode impedance (Z_{T2}) can also increase from lower reverse bias capacitance (C_{T2}) at higher reverse voltages.

Table 4.1 below presents the circuit transfer functions for both the conduction and isolation modes for the circuit model in figure 4.2. It also present the transfer function for the circuit that results directly from figure 4.1 ignoring the components to the right of the sensor loop. The bias resistor R_B in the test system will be in series with the pulse generator source resistance instead of being in parallel with the two diode and sensor loop.

Circuit State	Simplified Model	Test System
Conduction	$R_L/(R_L+R_S)$, $R_L<R_B$ $R_B/(R_B+R_S)$, $R_L>R_S$	$R_L/(R_L+R_{F2}+R'_S)$
Isolation	$(R_L R_{F1})/(Z_{T2} R_S)$	$(R_L R_{F1})/(Z_{T2} R'_S)$

Table 4.1 Two Diode Circuit Model Transfer Functions

4.2.2 Transient Analysis

Since the diodes in the circuit are complimentary biased, during the circuit state transitions, from conduction to isolation mode or vice versa, one of the diodes is turning off while the other is turning on. As presented in chapter 3, the switching speed of a PIN diode is dominated by its turn-off time, therefore in the proposed two diode circuit, the state transition time is dominated by the turn-off characteristic of the diode going into reverse bias. The circuit state transition time should be similar to the turn-off time of the diodes used under the operation conditions set by the circuit (Equations 4.1 and 4.4).

It is seen that for the circuit transitions, it is the diode turning off that controls the circuit state transition behavior. The circuit conduction to isolation state transition time is controlled by diode D_2 (series diode) turn-off time. In contrast, the circuit isolation to conduction state transition is governed by diode D_1 (shunt diode) turn-off time.

Given that the turn-off time of a PIN diode (see section 2.4) depends on its carrier lifetime, applied forward bias current and on the peak reverse current applied to switch it off, the two diode circuit state transition time will depend heavily on the chosen PIN diodes and their operation points.

4.3 Circuit Experimental Behavior

The two diode circuit in figure 4.2 was implemented using two Microsemi's PIN diodes model UM4002, a bipolar 200Hz square wave generator for the bias source, and a 5V 1μs long pulse as the disturbance source. All resistor were chosen to be 50Ω and the coupling capacitor 0.56μF.

4.3.1 Circuit Response in Fixed State

Table 4.2 below shows the measured operation point for the diodes in the isolation circuit (figure 4.2) , together with the theoretical operation points for both the conduction and isolation states. This values were measured using the circuit described in the previous paragraph and computed using the equations from the previous section.

The computed and measured values correspond to a bias voltage source of ±3V. For the constant state transfer functions magnitude computations the following approximations were made: a reverse diode capacitance of 10pF was used for both diodes; a forward resistance R_{F1}=0.5Ω for diode D_1 and R_{F2}=1.0Ω for diode D_2 were used; and an operating frequency of 2MHz was assumed for the circuit.

	Parameter	Shunt Diode		Series Diode		V_{out}/V_s
		V_{D1}	I_{D1}	V_{D2}	I_{D2}	
Conduction	Measured	-1.25 V	~0 mA	0.66 V	12 mA	0.57
	Computed	-1.84 V	<10μA	0.68 V	23 mA	0.33
Isolation	Measured	0.7 V	46 mA	-.7 V	~0 mA	1.52×10^{-4}
	Computed	0.71 V	46 mA	-0.71V	<10μA	62.5×10^{-6}

Table 4.2 Two Diode Circuit Steady State Results

4.3.2 Circuit Response vs Bias Point I_F

Given that the amount of isolation provided by the circuit is dependent on the bias applied to it, a test to investigate this variation was performed. The circuit in figure 4.2 was used with the same components values as before and a constant positive voltage source for bias.

A 5V 1μs pulse was applied for different values of diode D_1 bias current, and the output voltage measured. The ratio of the output voltage pulse to input pulse (circuit gain) is plotted versus diode

D_1 bias current in figure 4.5. A computed circuit gain versus D_1 bias current using data sheet values for the UM4002 (Appendix B) at a small signal frequency of 2MHz is also plotted on the figure.

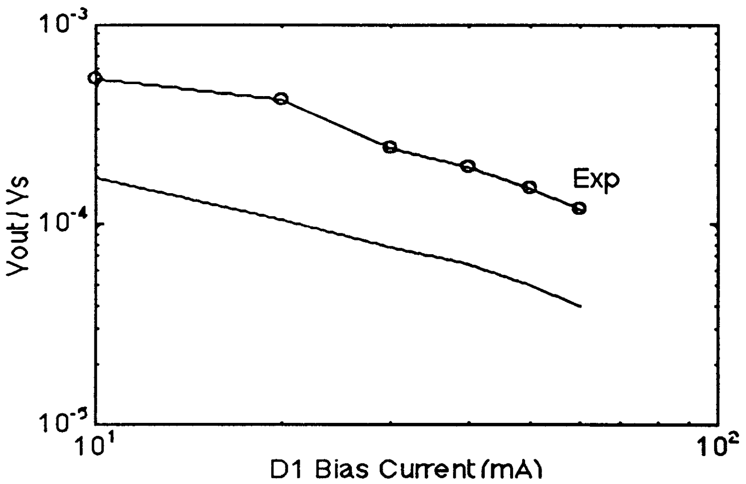


Figure 4.5 Circuit Gain vs. Bias Current

4.3.3 Circuit State Transition Response

Figure 4.6 below shows the conduction to isolation and isolation to conduction state transitions observed for the two diode proposed circuit. Different amplitude symmetric square waves were used to see the effect of bias voltage variation in the circuit transition times. The figure below shows the transition for two different bias voltage conditions.

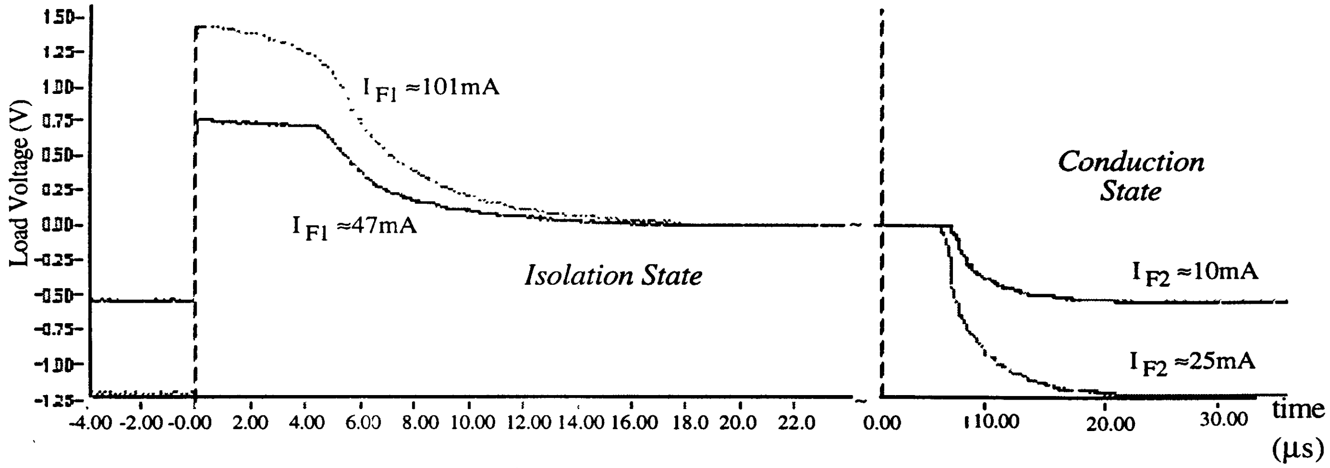


Figure 4.6 Circuit Switching Time Response (D_1 & D_2 are UM4002)

The steady state output voltage present in the isolation mode approximates zero volts. During the conduction state, a negative constant voltage is seen at the load due to the series diode bias current.

Both observed state transitions for the circuit are similar to the turn-off time observed for the PIN diodes used on it (figure 3.7 and figure 3.8). However, it can be seen in figure 4.6 that the isolation to conduction transition is slightly longer than the conduction to isolation transition. As explained previously, even though the two diodes are "identical", the bias current in the shunt diode during isolation is greater than the bias current during conduction in the series diode, causing a longer turn-off time for the shunt diode.

The link between the circuit transition times and the diode device turn-off time is emphasized in table 4.3 below

Diode UM4002		2 Diode Circuit	
turn-on	turn-off	Cond. To Isol	Isol. to Cond.
1.5~3.0μs	10~30μs	15~20μs	20~30μs

Table 4.3 Single Diode and 2 Diode Circuit State Transition Times

As seen in the previous figure, higher bias voltages (bias currents) applied to the circuit cause slower state transition. This transition time variation is, however, not big enough as to put an important constraint on the bias currents used on the circuit.

The desired isolation level and the magnitude of the signal controlled by the circuit are more important factors while choosing the bias currents to be used on the circuit in a given application. If significantly lower transition times are required, these might be achieved by using PIN diodes with smaller recombination times.

4.4 Pulse Impedance during Circuit State Transition

During circuit state transitions, a period exists during which charge is removed from and stored to the diodes. Since the impedance of a PIN diode depends on the amount of charge stored in its intrinsic region, the circuit isolation level is expected to vary during state transitions. To estimate this isolation level variation, a one microsecond disturbance pulse was applied at different instants during the state transition and the circuit output voltage measured at those instants. Figure 4.7 shows the observed circuit response when the pulse was applied during the conduction to isolation state transition.

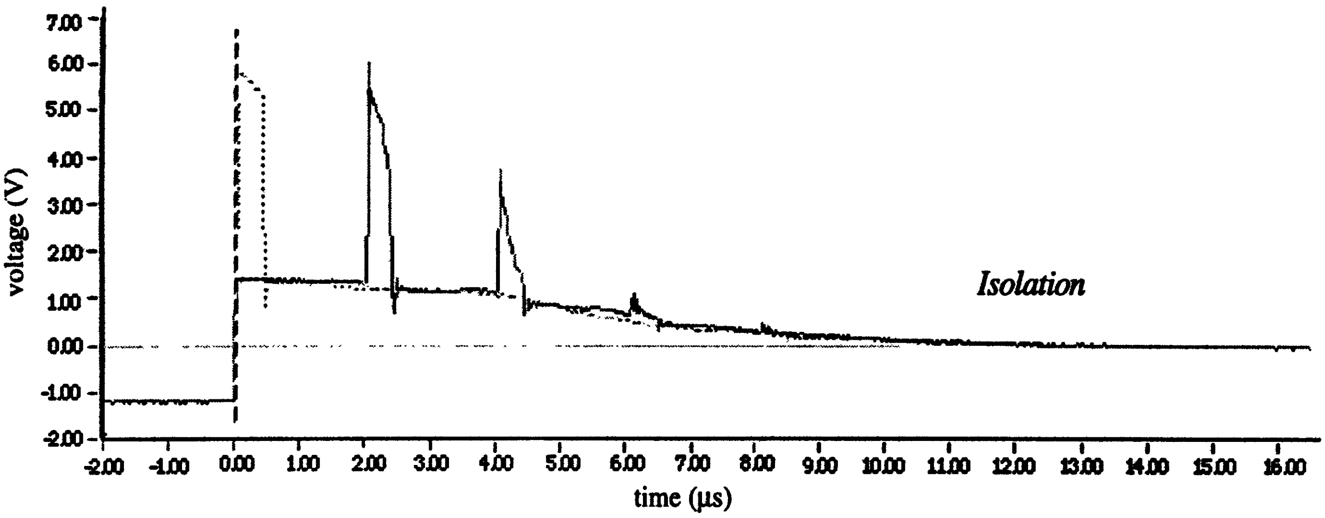


Figure 4.7 Circuit Conduction to Isolation State Pulse Transmission with UM4002 diodes

The output pulse magnitude decreases as the circuit enters the isolation state. When the series diode is totally in reverse bias (current approx. zero), and the shunt diode forward biased, then the pulse transmitted to the load resistance becomes minimal, and maximum isolation is achieved.

Figure 4.8 shows the output voltage pulse signal during the isolation to conduction state transition. It can be seen that once currents starts flowing through the series diode (output voltage non-zero) the magnitude at the output of the disturbance pulses increases considerably until the diode current reaches its steady state value.

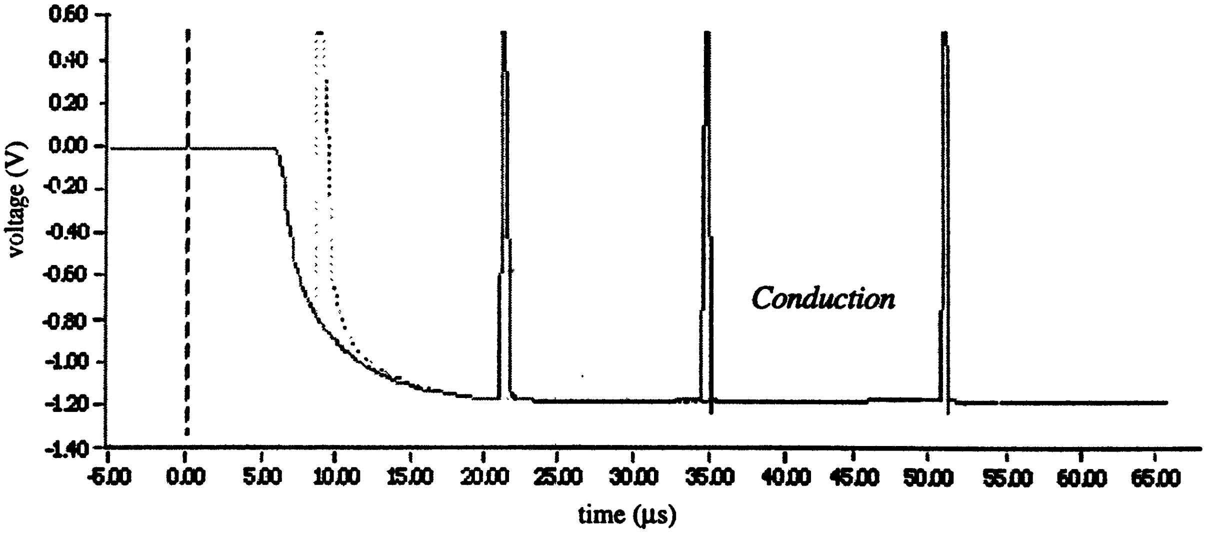


Figure 4.8 Circuit Isolation to Conduction State Pulse Transmission with UM4002 diodes

Figure 4.9 provides an evaluation of the raw data of figure 4.7 by interpreting the circuit transfer function gain between V_{out} (at the sensor) and V_S (at the pulse source) as a time varying function. The plot shows how the circuit gain , which can be thought of as the isolation provided by the two diode circuit, varies during the circuit transition to from conduction state to the isolation state. The measurements were performed with the circuit using UM4002 diodes,a bias of 47mA for D_1, and a 5V 1μs pulse. In the figure the gain is expressed in decibels (dB) units defined as

$$\mathrm{Gain}_{dB} = 20\log(\mathrm{Gain}) \tag{4.6}$$

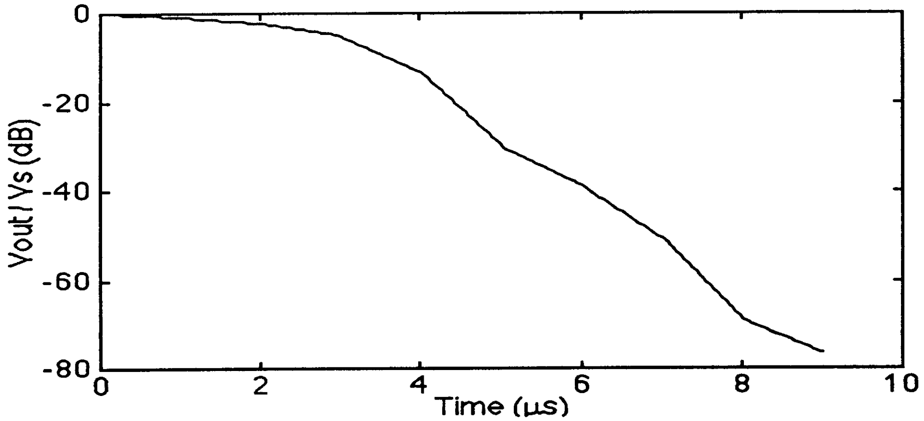


Figure 4.9 Circuit Isolation variation with Time during transition to the Isolation State

Chapter 5 Conclusions

5.1 General Problem

The purpose of this project was to investigate the protection of a sensor from transient pulses. The goal was to establish a technique to isolate the sensor during the time of a short time power pulse, and yet still allow the sensor to be active when the pulse is absent. The power pulse (100ns, -500V) comes from a series connected source and is necessary for the system operation.

The approach used to protect the sensor was a series-shunt circuit configuration. This circuit employs a series isolation switch and a shunt switch parallel to the sensor. PIN diodes are the active elements used to implement the series and shunt switches. Two distinct issues were investigated; the PIN diode as a device, and the series-shunt circuit configuration for protection of the sensor.

The electric characteristics of three PIN diode families (made by Microsemi Corp.) were studied in order to assess their capabilities to perform as solid state switches for short time pulses. The PIN diode high frequency resistance, power handling capability and switching speed were used in the selection criteria for choosing the diode to be used in the sensor protection circuit. The design included trade-offs between high power handling, low series resistance and moderately fast switching speed. The series-shunt circuit was selected to maximize the protection of the sensor.

5.2 PIN Diodes

The behavior of a PIN diode is determined by the device parameters and the nature of the signals applied to it. From the diode operation point of view, signals are cataloged as high or low frequency signals referenced to the diode transit-time frequency, which is inversely proportional to the intrinsic region carrier lifetime.

For low frequency signals, PIN diodes act as normal PN junction diodes. The forward bias resistance being the dynamic resistance from the forward I-V curve at a given quiescent point. This behavior was confirmed for the diodes investigated.

The distinctive characteristic of PIN diodes is that in the forward bias region they behave as current controlled linear resistor for high frequency signals. This resistance value varies with the inverse of the bias current. The higher the bias current, the lower the resistance. However, a constraint is imposed on the high frequency signal applied to the diode in order for this diode behavior to persist: the amount of charge that might be removed from the diode by the non-bias signal should not exceed the stored charge induced by the bias current.

For the PIN diodes studied, it was shown that higher bias currents resulted in lower resistance values, in both high and low frequency conditions. However the high frequency resistance was generally smaller than the low frequency resistance at the same bias point. Among different devices, the diodes with longer carrier lifetimes displayed the higher high frequency resistances.

Under reverse bias, charge in the intrinsic region is removed and the PIN diode can be modelled as a parallel plate capacitor. Capacitance value depends on the reverse voltage applied and the signal frequency. For high frequencies, however, the PIN diode behave as a low value linear capacitor independent of reverse bias.

The switching performance of PIN diodes was investigated. A voltage pulse was applied to a PIN diode at both forward (on) and reverse (off) biases. In forward bias, the applied pulse resulted in a high diode current and minor change in the diode voltage. This was because the forward biased diode was in a low impedance state. In contrast, when the diode was in reverse bias the same applied pulse resulted in a very small diode current and a hugh change in the diode voltage (comparable to the pulse magnitude). This was because the diode was in a high impedance state.

The dynamic conditon poses a different problem. The turn-on and turn-off times of a particular PIN diode are governed by its recombination time, and the currents and voltages applied to the diode. Under fixed drive conditions, devices with longer carrier lifetimes had longer turn-on and turn-off times. For all diodes studied the turn-off time was much longer than the turn-on time. In PIN diodes, the turn-off time, or forward to reverse transition time, is the longer switching time and hence the important consideration while evaluating the switching speed of the device.

5.3 Two Diode Protection Circuit.

The series-shunt protection circuit chosen for this work has two clearly distinguished states relative to the protected sensor: a conduction state and an isolation state. During the conduction state a series diode is forward bias while the shunt diode is reverse bias so that current is allowed to flow through the sensor. Alternately, when the circuit is driven into the isolation state (when a triggering pulse is applied) the shunt diode is in forward bias and the series diode in reverse bias so that then no signal shows at the sensor, thus protecting and isolating the sensor.

The protection circuit was implemented using two type UM4002 diodes in a series-shunt configuration. These were selected on the basis of the earlier device test and represent the medium switching speed case with low forward bias impedance. The first diode is in series with sensor to be protected and the second diode is connected across the sensor and series diode.

Three attributes of the circuit were investigated; the transition speed (switching) between conduction and isolation states, the amount of isolation provided when fully in the isolation state, and the dynamic isolation during transition between states.

State transition times in the circuit are dominated by the turn-off characteristic of the diodes used. The conduction to isolation state transition is governed by the series diode. The isolation to conduction state transition is controlled by the shunt diode. On the circuit tested, the state transition times were similar to the turn-off times observed for the type UM4002 diodes individually under similar applied forward and reverse switching currents.

The amount of isolation provided by the circuit was quantified by applying a pulse voltage at the circuit input and measuring the response at the sensor position. This was done for the circuit in both the conduction and isolation states. During the conduction state, a pulse at the input generated a response at the sensor position of about half the pulse size. During isolation, the same input pulse generated a greatly reduced response pulse, indicating high isolation. A reduction by a factor of approximately 4000 was observed for the response between the conduction and isolation states.

Pulses were applied to the circuit at different times during the transition between states to investigate the dynamic circuit isolation behavior.The isolation increased smoothly following the circuit transition from conduction to isolation, but decreased sharply during the isolation to conduction transition. This sharp decline in isolation while going into conduction mode is due the faster tun-on time of the series diode compared to its turn-off time.

A succsessful isolation and protection of the sensor was achieved for the case of the series-shunt PIN circuit when biasing provided good turn-on and turn-off responses.

Appendix A: Microsemi Diodes Experimental Characterization

The diode characterization was done by measuring the diode voltage for different levels of bias current. The forward bias I-V characteristic was obtained by fitting a curve of the form

$$\log_{10}(I_D)=K_1V_D+K_2 \tag{A.1}$$

to the dc diode voltage (V_D) and current (I_D) points measured. Three other parameters are used besides the forward bias I-V curve to characterize the PIN diodes. These are the DC resistance (R_{dc}), the ac resistance (R_{ac}) and the high frequency resistance (R_F). The first two are based on the I-V curve by the following relationships,

$$R_{dc}=\frac{V_D}{I_D} \tag{A.2}$$

$$R_{ac}=\frac{dV_D}{dI_D}=\frac{1}{K_1I_D} \tag{A.3}$$

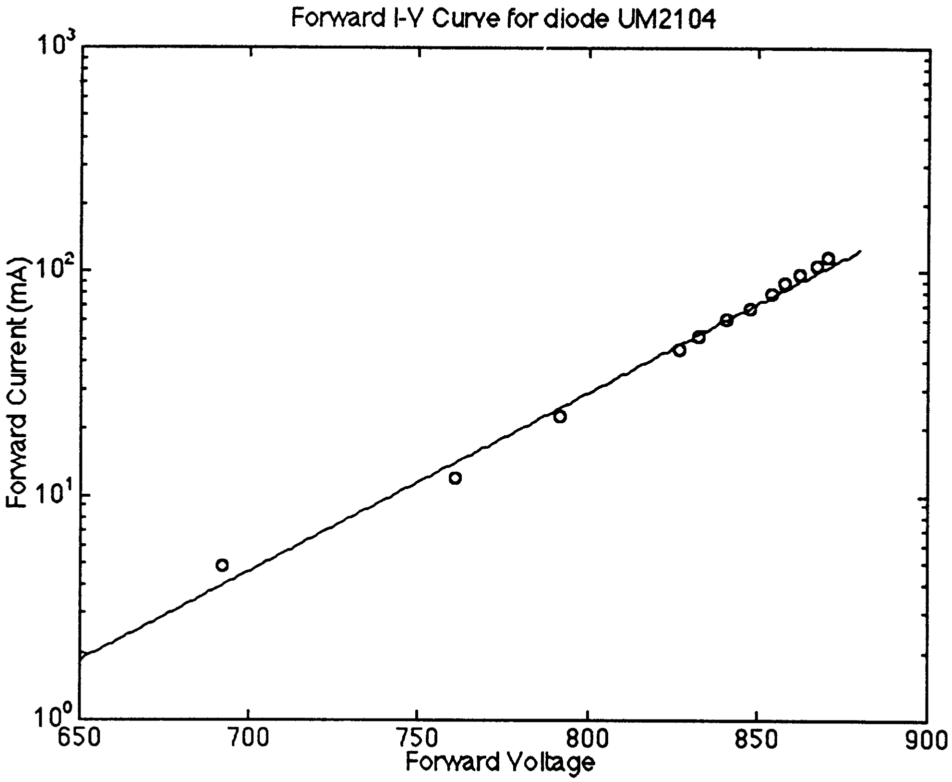
The ac resistance corresponds to the small signal (dynamic) resistance at the bias point. In contrast, the high frequency resistance depends on the amount of stored charge in the diode intrinsic region instead of its I-V characteristic.This resistance can be expressed as,

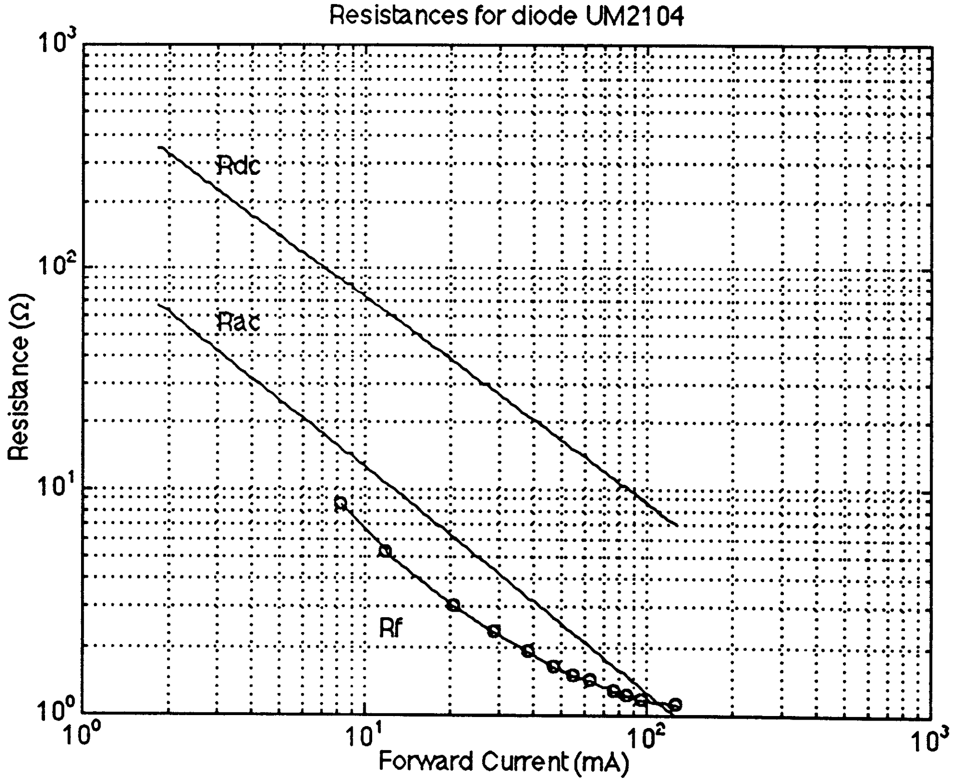
$$R_f=\frac{W^2}{2\mu\tau I_F} \tag{A.4}$$

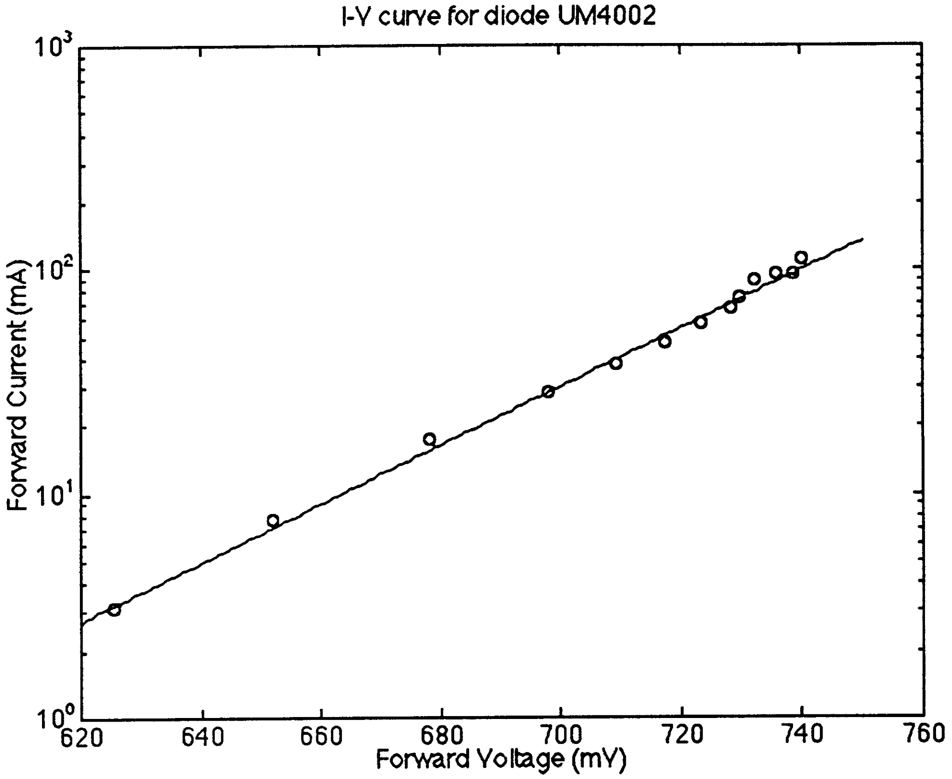
where μ is the mobility of carriers in the intrinsic region, W is the I-region width, τ is the carrier lifetime and I_F is the forward bias current. Experimentally it was determined by superposition of a high frequency (2MHz) signal to the diode bias, and taking the ratio of the high frequency components of the measured diode voltage and current,

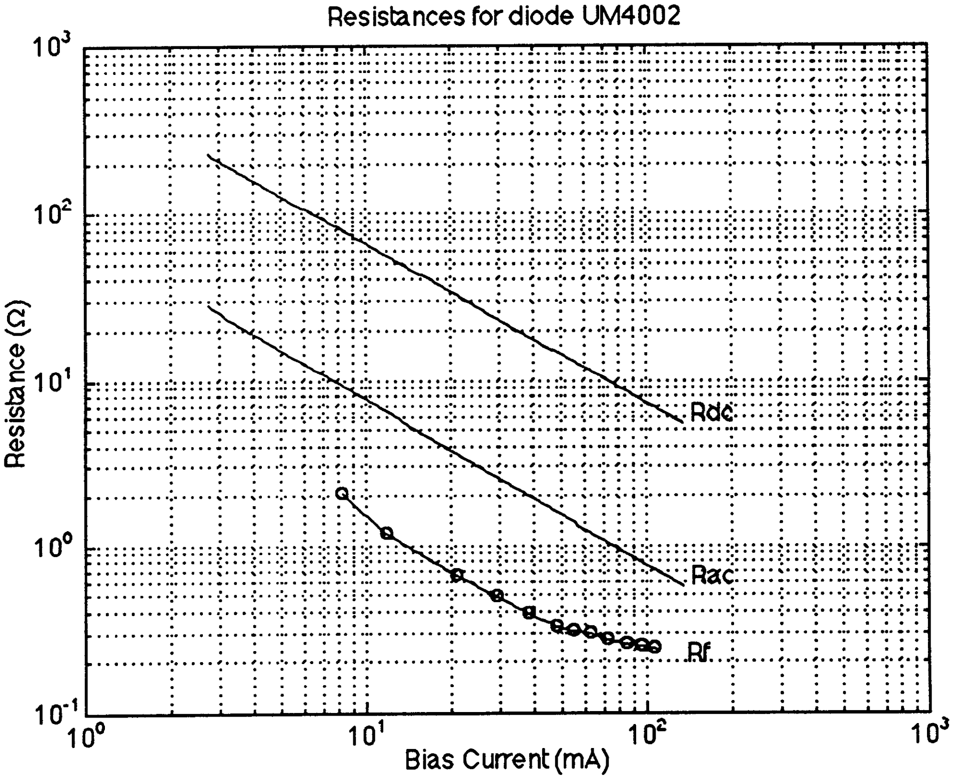
$$R_F=\frac{v_d}{i_d}\text{, high frequency} \tag{A.5}$$

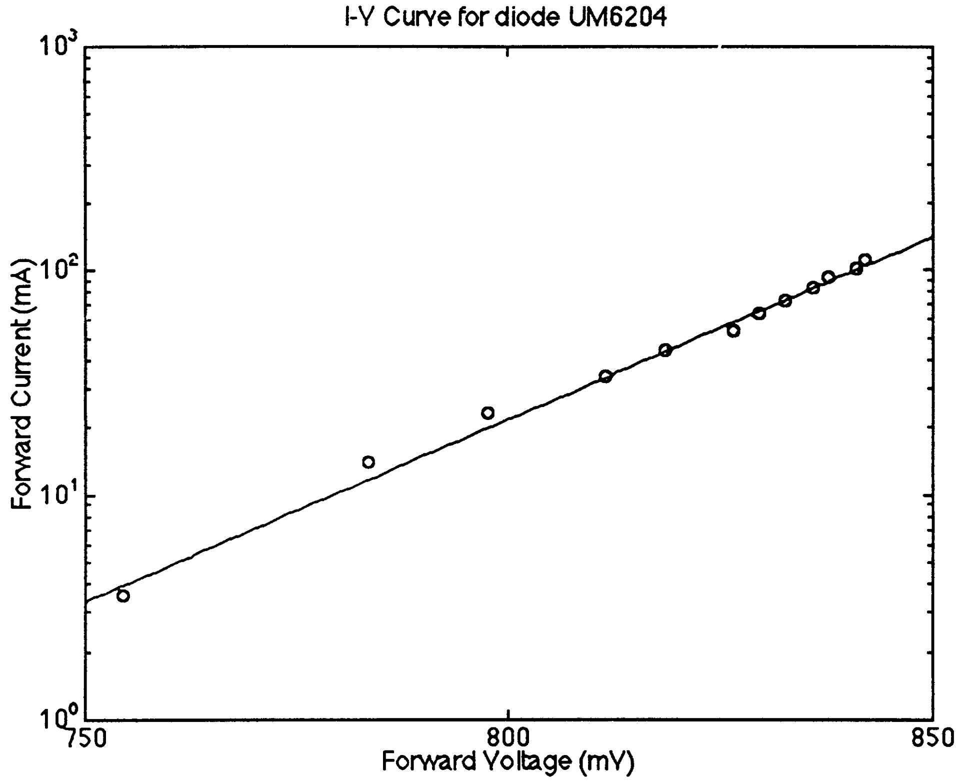
The following pages show the experimental diode characteristic (I-V curves, R_{dc},R_{ac} and R_F) obtained for three Microsemi PIN diodes: UM2104, UM4002 and UM6204.

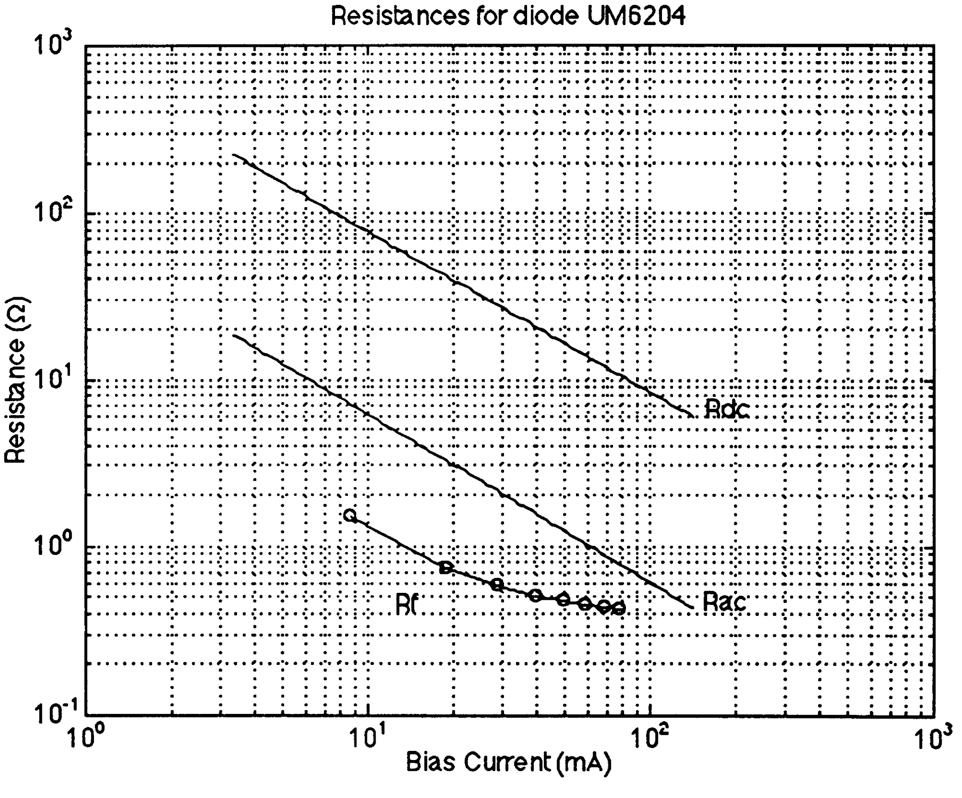

Forward I-V Curve for diode UM2104
10^3
10^2
10^1
10^0
Forward Current (mA)
650
700
750
800
850
900
Forward Voltage


Resistances for diode UM2104
10^3
10^2
10^1
10^0
Resistance (Ω)
Rdc
Rac
Rf
10^0
10^1
10^2
10^3
Forward Current (mA)


I-V curve for diode UM4002
Forward Current (mA)
Forward Voltage (mV)
10^0
10^1
10^2
10^3
620
640
660
680
700
720
740
760

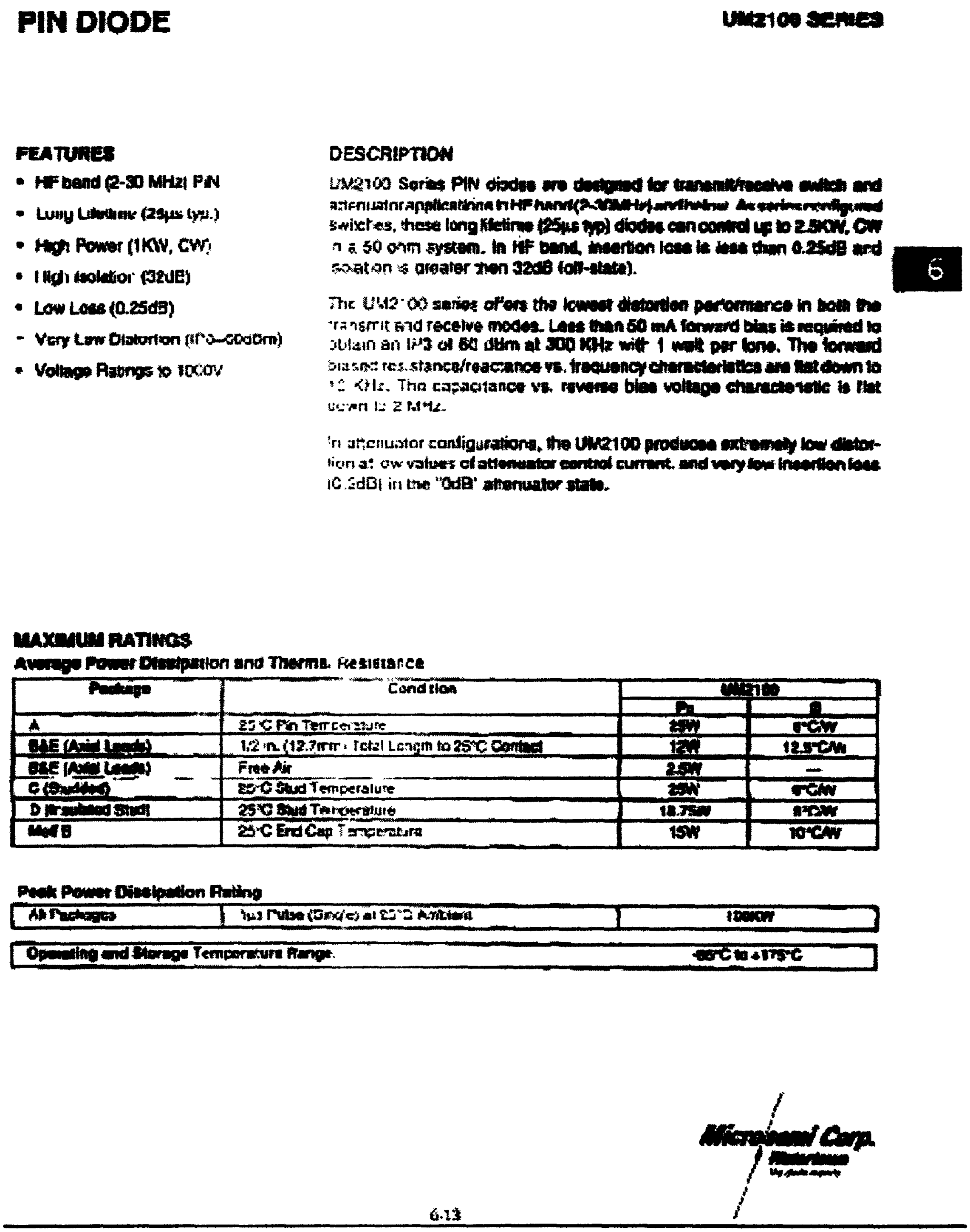

Resistances for diode UM4002
Resistance (Ω)
Bias Current (mA)
10^{-1}
10^0
10^1
10^2
10^3
Rdc
Rac
Rf


I-V Curve for diode UM6204
Forward Current (mA)
Forward Voltage (mV)
10^0
10^1
10^2
10^3
750
800
850


Resistances for diode UM6204
Resistance (Ω)
Bias Current (mA)
10^{-1}
10^0
10^1
10^2
10^3
Rdc
Rac
Rf

Appendix B: Microsemi Diodes Data Sheets

B.1 UM2104



PIN DIODE

UM2100 SERIES

6

FEATURES

- HF band (2-30 MHz) PIN
- Long Lifetime (25µs typ.)
- High Power (1KW, CW)
- High Isolation (32dB)
- Low Loss (0.25dB)
- Very Low Distortion (IP3—60dBm)
- Voltage Ratings to 1000V

DESCRIPTION

UM2100 Series PIN diodes are designed for transmit/receive switch and attenuator applications in HF band (2-30MHz) and below. As series configured switches, these long lifetime (25µs typ) diodes can control up to 2.5KW, CW in a 50 ohm system. In HF band, insertion loss is less than 0.25dB and isolation is greater than 32dB (off-state).

The UM2100 series offers the lowest distortion performance in both the transmit and receive modes. Less than 50 mA forward bias is required to obtain an IP3 of 60 dBm at 300 KHz with 1 watt per tone. The forward biased resistance/reactance vs. frequency characteristics are flat down to 10 KHz. The capacitance vs. reverse bias voltage characteristic is flat down to 2 MHz.

In attenuator configurations, the UM2100 produces extremely low distortion at low values of attenuator control current, and very low insertion loss (0.2dB) in the "0dB" attenuator state.

MAXIMUM RATINGS

Average Power Dissipation and Thermal Resistance

Package	Condition	UM2100	
		P_D	θ
A	25°C Pin Temperature	25W	6°C/W
B&E (Axial Leads)	1/2 in. (12.7mm) Total Length to 25°C Contact	12W	12.5°C/W
B&E (Axial Leads)	Free Air	2.5W	—
C (Studded)	25°C Stud Temperature	25W	6°C/W
D (Insulated Stud)	25°C Stud Temperature	18.75W	8°C/W
Melf B	25°C End Cap Temperature	15W	10°C/W

Peak Power Dissipation Rating

All Packages	1µs Pulse (Single) at 25°C Ambient	100KW

Operating and Storage Temperature Range	-65°C to +175°C

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Watertown

6-13

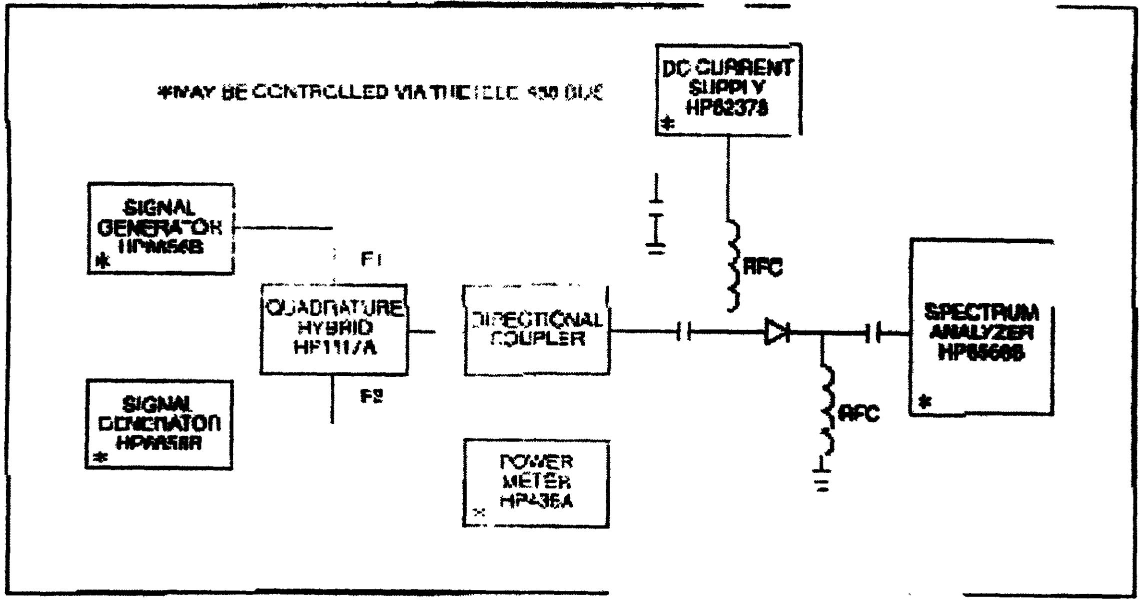
VOLTAGE RATINGS (25°C)

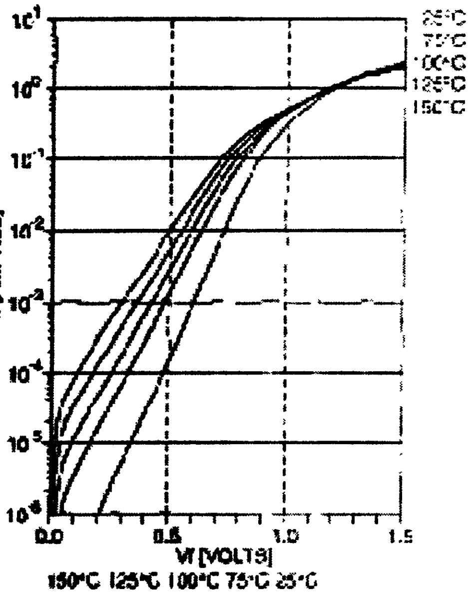
Reverse Voltage (VR) – Volts IR = 10µA	Part type
100V	UM2101
200V	UM2102
400V	UM2104
600V	UM2106
800V	UM2108
1000V	UM2110

ELECTRICAL SPECIFICATIONS (25°C)

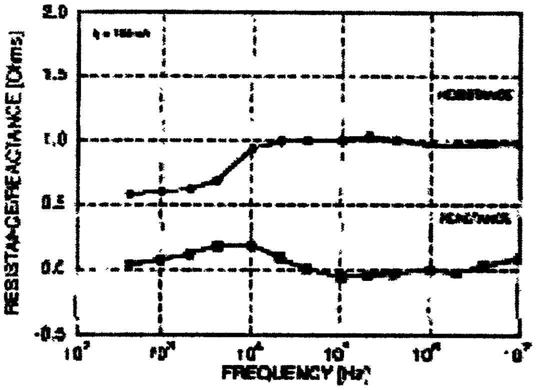
Test	Min.	Typ.	Max.	Units	Conditions
Diode Resistance R_S		1.0	2.0	Ω	2MHz, 100mA
Capacitance C_T		1.9	2.5	pF	1MHz, 100V
Reverse Current I_R			10	µA	@ Rated Voltage
Carrier Lifetime τ	20	25		µs	I = 10 mA/100V
IP3	50	60		dBm	2W total, If = 25mA F1 – 1.999 MHz F2 – 2.001 MHz 1.0 W/tone

FORWARD BIAS DISTORTION TEST

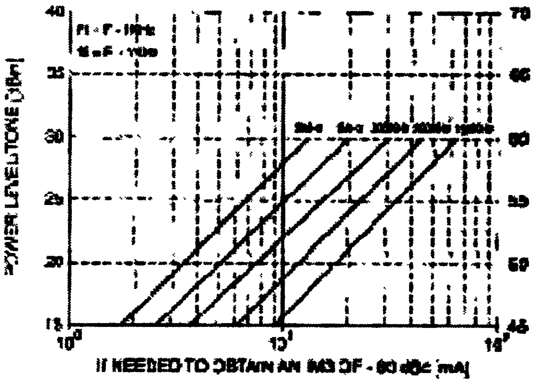




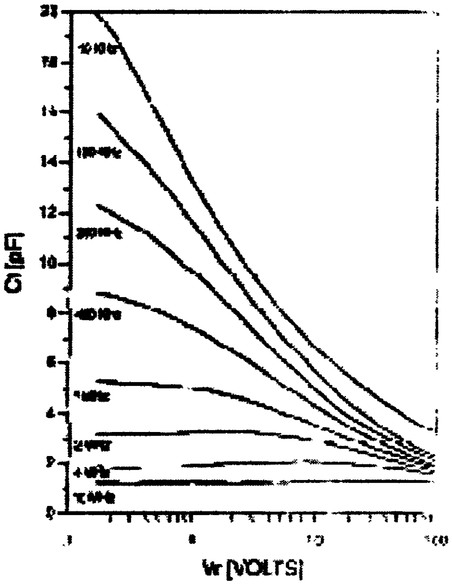
MEAN I-V CURVE



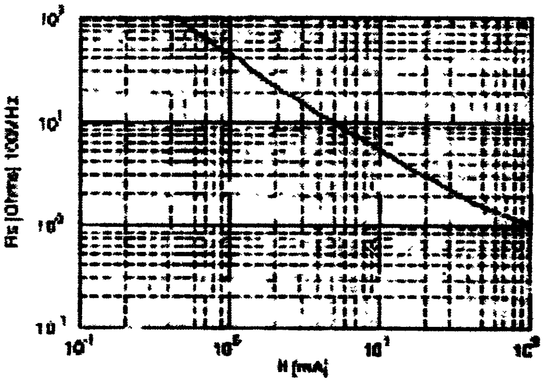
RESISTANCE/REACTANCE vs FREQUENCY



POWER LEVEL vs FORWARD BIAS CURRENT



CAPACITANCE vs REVERSE VOLTAGE



SERIES RESISTANCE vs FORWARD BIAS CURRENT

B.2 UM4002

PIN DIODE

UM4000 SERIES
UM4900 SERIES

Features

- **Power dissipation** to 37.5W
- **Voltage ratings** to 1000V
- **Series resistance** rated at 0.5Ω
- **Carrier lifetime** greater than 5μs

Description

The **UM4000** and UM4900 series feature **high power PIN** diodes with long carrier lifetimes and thick I-regions. They are especially suitable for use in low distortion switches and attenuators, in the HF through S band frequencies. While both series are electrically equivalent, the UM4900 series have higher power ratings due to a shorter thermal path between chip and package. High charge storage and long carrier lifetime enable high RF levels to be controlled with relatively low bias current. Similarly, peak RF voltages can be handled well in excess of applied reverse bias voltage.

Both series have been fully qualified in high power UHF phase shifters and megawatt peak-power duplexers, accumulating thousands of hours of proven performance. Both types have been used in the design of antenna selectors and couplers, where inductive and capacitive elements are switched in and out of filter or cavity networks.

MAXIMUM RATINGS

Average Power Dissipation and Thermal Resistance Ratings

Package	Condition	UM4000		UM4900	
		P_D	θ	P_D	θ
A ·	25 °C Pin Temperature	25W	6 °C/W	37.5W	4 °C/W
B&E (Axial Leads)	½ in. (12.7mm) Total Length to 25 °C Contact	12W	12.5 °C/W	12W	12.5 °C/W
B&E (Axial Leads)	Free Air	2.5W	—	2.5W	—
C (Studded)	25 °C Stud Temperature	25W	6 °C/W	37.5W	4 °C/W
D (Insulated Stud)	25 °C Stud Temperature	18.75W	8 °C/W	25W	6 °C/W

Peak Power Dissipation Rating

All Packages	1 μs Pulse (Single) at 25 °C Ambient	**100 KW**

Operating and Storage Temperature Range: −65 °C to +175 °C

Microsemi Corp.
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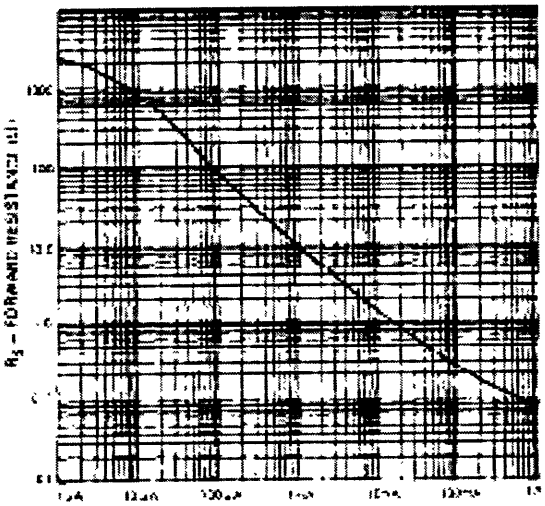
Voltage Ratings (25°C)

Reverse Voltage (V_R) — Volts (I_R = 10 μ Amps)	Types	
100	UM4001	UM4901
200	UM4002	UM4902
400	—	—
600	UM4006	UM4906
1000	UM4010	—

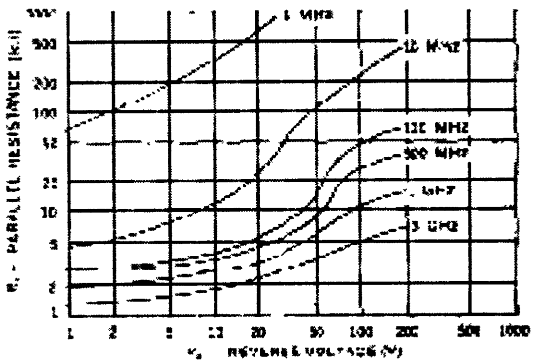
Electrical Specifications (25°C)

Test	Symbol	UM4000 UM4900	Conditions
Total Capacitance (Max)	C_T	3 pF	100V, 1MHz
Series Resistance (Max)	R_S	0.5Ω	100mA, 100MHz
Parallel Resistance (Min)	R_P	10 KΩ	100V, 100MHz
Carrier Lifetime (Min)	τ	5μs	I_F = 10mA
Reverse Current (Max)	I_R	10μA	V_R = Rating
I-Region Width (Min)	W	150μm	—

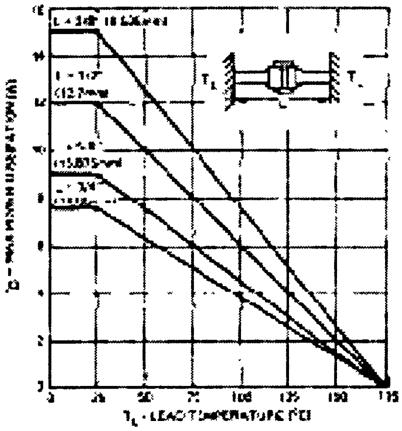
TYPICAL FORWARD RESISTANCE
VS
FORWARD CURRENT
(F = 100 MHz)



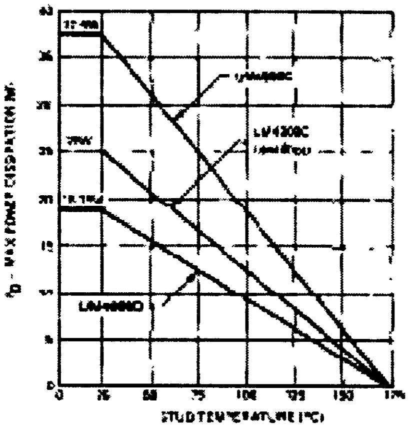
TYPICAL PARALLEL RESISTANCE CHARACTERISTIC



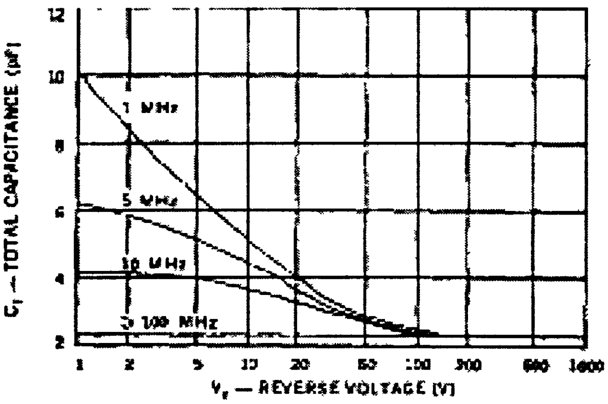
POWER RATING
AXIAL LEADED DIODE



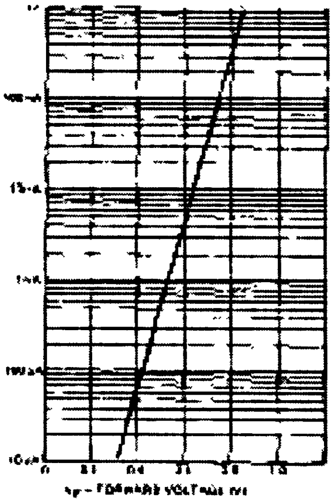
POWER RATING
STUD MOUNTED DIODES



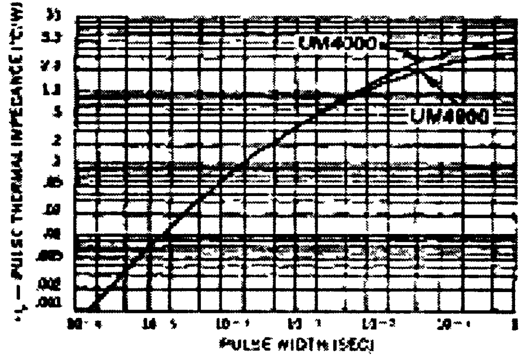
TYPICAL CAPACITANCE CHARACTERISTIC



DC CHARACTERISTICS
FORWARD VOLTAGE
VS
FORWARD CURRENT (TYPICAL)



THERMAL IMPEDANCE



ORDERING INSTRUCTIONS

Part numbers of Microsemi PIN Diodes consist of the letters UM followed by four digits and one or two letters. The first two digits indicate the diode series, the next two digits specify the minimum breakdown voltage in hundreds of volts. The remaining letters denote the package style. Reverse polarity (anode large end cap) is available for the C style and denoted by adding second letter R.

For Example: UM4010CR

(Series 4000) (100 Volts) (Style C Reverse Polarity)

B.3 UM6204

PIN DIODE

UM6000 SERIES
UM6200 SERIES
UM6600 SERIES

Features

- Capacitance specified as low as 0.4 pF (UM6600)
- Resistance specified as low as 0.4Ω (UM6200)
- Voltage ratings to 1000V
- Power dissipation to 6W

Description

These series of PIN diodes are designed for applications requiring small package size and moderate average power handling capability. The low capacitance of the UM6000 and UM6600 allows them to be used as series switching elements to 1 GHz. The low resistance of the UM6200 is useful in applications where forward bias current must be minimized.

Because of its thick I-region width and long lifetime the UM6000 and UM6600 have been used in distortion sensitive and high peak power applications, including receiver protectors, TACAN, and IFF equipment. Their low capacitance allows them to be useful as attenuator diodes at frequencies greater than 1 GHz. The UM6200 has been used successfully in switches in which low insertion loss at low bias current is required.

The "A" style package for this series is the smallest Microsemi PIN diode package. It has been used successfully in many microwave applications using coaxial, microstrip, and stripline techniques at frequencies beyond X-Band. The "B" and "E" style, leaded packages offer the highest available power dissipation for a package this small. They have been used extensively as series switch elements in microstrip circuits. The "C" style package duplicates the physical outline available in conventional ceramic-metal packages but incorporates the many reliability advantages of the Microsemi construction.

MAXIMUM RATINGS

Average Power Dissipation and Thermal Resistance Ratings

Package	Condition	UM6000 UM6600		UM6200	
		P_d	θ	P_d	θ
A&C	25°C Pin Temperature	6W	25°C/W	4W	37.5°C/W
B&E (Axial Leads)	½ in. (12.7mm) Total Lead Length to 25°C Contact	2.5W	60°C/W	2.0W	75°C/W
B&E (Axial Leads)	Free Air	0.5W	—	0.5W	—

Peak Power Dissipation Rating

All Packages	1 μs Pulse (Single) at 25°C Ambient	UM6000 - 25 KW UM6200 - 10 KW	UM6600 - 13 KW

Operating and Storage Temperature Range: −65°C to +175°C

Microsemi Corp.
Watertown

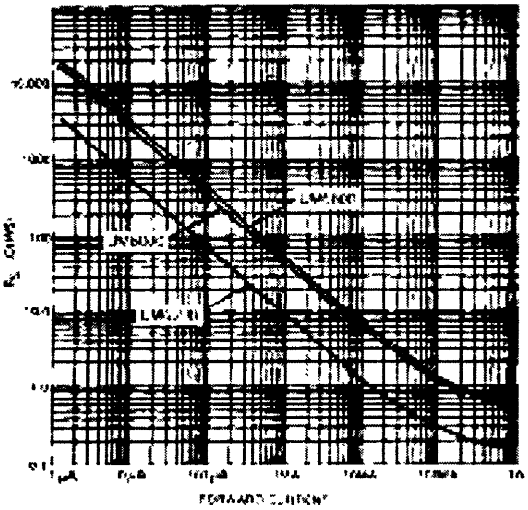
Voltage Ratings (25 °C)

Reverse Voltage (V_R) — Volts (I_R = 10 µA)	Types		
100V	UM6001	UM6201	UM6601
200V	UM6002	UM6202	UM6602
400V	—	UM6204	—
600V	UM6006	—	UM6606
1000V	UM6010	—	UM6610

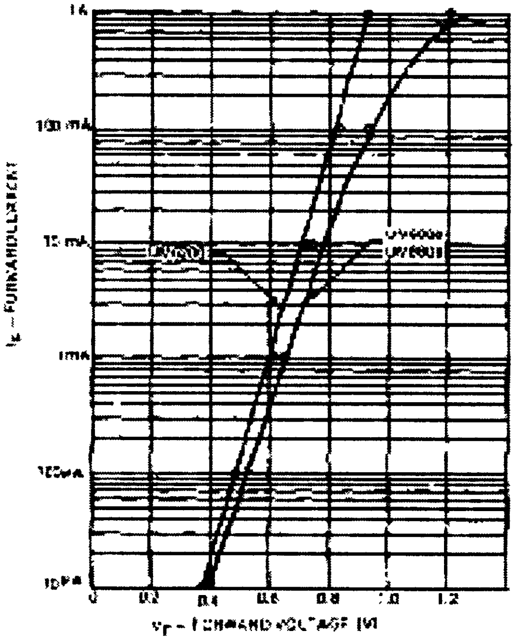
Electrical Specifications (25 °C)

Test	Symbol	UM6600	UM6000	UM6200	Conditions
Total Capacitance (Max)	C_T	0.4 pF	0.5 pF	1.1 pF	100V, 1MHz
Series Resistance (Max)	R_S	2.5Ω	1.7Ω	0.4Ω	100mA, 100MHz
Parallel Resistance (Min)	R_P	300 KΩ	300 KΩ	350 KΩ	100V, 100MHz
Carrier Lifetime (Min)	τ	1.0 µs	1.0 µs	0.6 µs	I_F = 10 mA
Reverse Current (Max)	I_R	10 µA	10 µA	10 µA	V_R = Rating
I-Region Width (Min)	W	150 µm	150 µm	40 µm	—

TYPICAL SERIES RESISTANCE
VS
FORWARD CURRENT
(F = 100MHz)

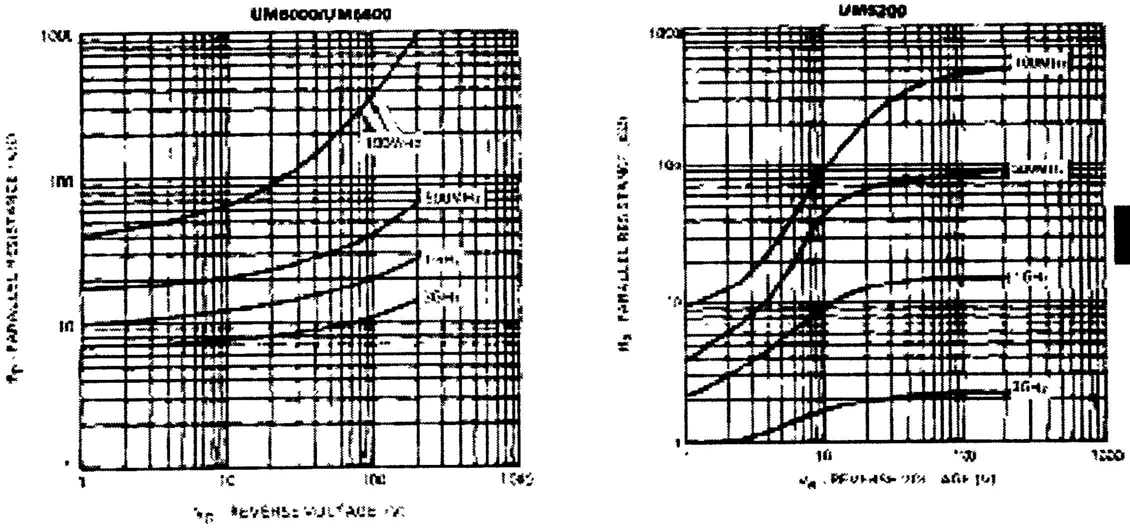


DC CHARACTERISTICS
FORWARD VOLTAGE VS CURRENT

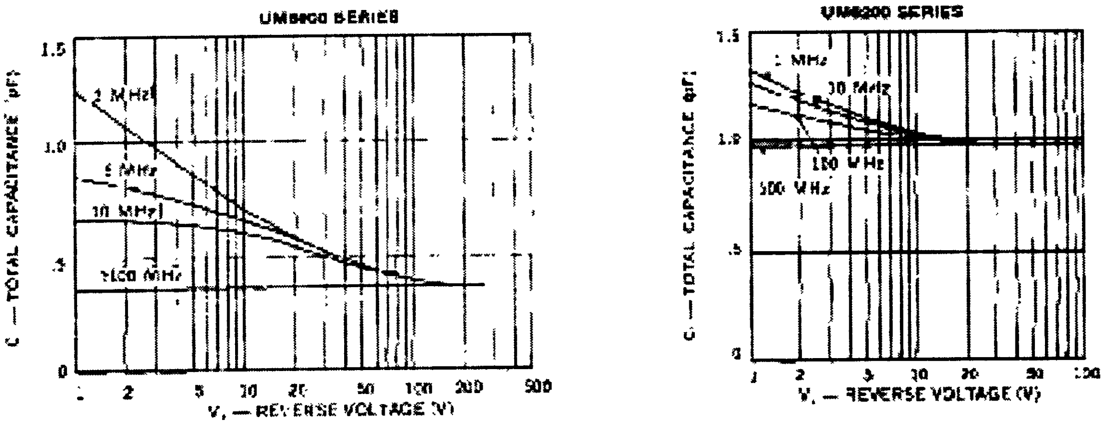


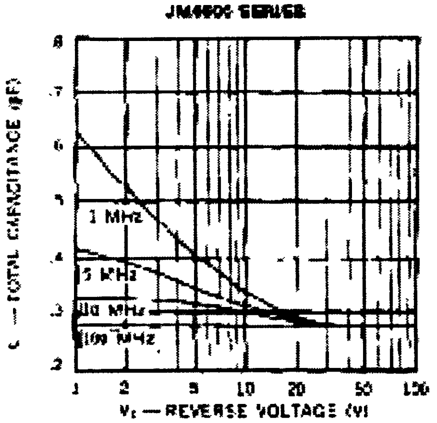
UM6000 UM6200 UM6600

TYPICAL R_p VS VOLTAGE & FREQUENCY



TYPICAL CAPACITANCE VS VOLTAGE AND FREQUENCY





ORDERING INSTRUCTIONS

Part numbers of Microsemi PIN Diodes consist of the letters UM followed by four digits and one or two letters. The first two digits indicate the diode series, the next two digits specify the minimum breakdown voltage in hundreds of volts. The remaining letters denote the package style. Reverse polarity (anode large end cap) is available for the C style and denoted by adding second letter R.

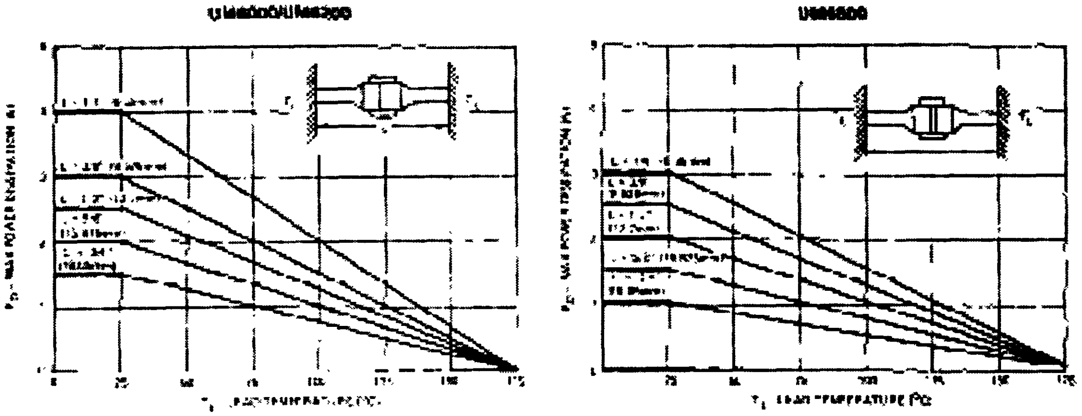
For Example UM|62|06|CR

Series 6200

600 Volts

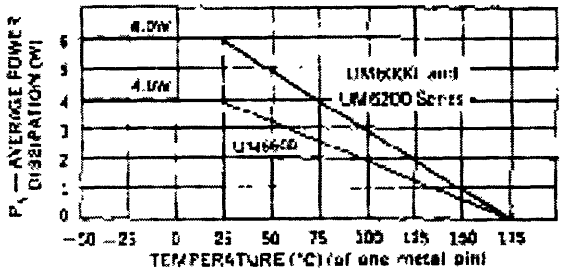
Style C, Reverse Polarity

POWER RATING — AXIAL LEADED DIODE

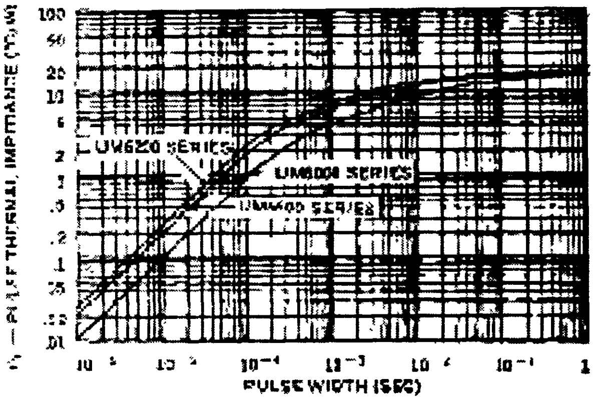

UM6000/UM6200

UM6600

POWER RATING



PULSE THERMAL IMPEDANCE VS PULSE WIDTH



Appendix C: Two Diode Circuit Matlab Scripts for Steady State Computations

C.1 Shunt Diode Operation Point

A Matlab script was created to compute the operation point of the shunt diode (D_1) when the circuit is in the isolation mode. The script provides a numeric and graphic solution to equations (4.4).

```
% Shunt Diode Operation Point Script
% Bias conditions for Microsemi's PIN diode UM4002
vd=linspace(.2,.85,1200);
% Diode i-v curve from data sheet
y=[60e-6 4e-3 300e-3];
x=[.4 .6 .8];
m=polyfit(x,log10(y),1);
id=10.^(polyval(m,vd));
% Circuit component values
Vbb=3;
Rl=50;
Rb=50;
Rs=50;
% Diode load line equation
id2=(Vbb-vd)/Rb;
% Ploting load line on diode i-v
curveplot(vd,id,vd,id2)
grid
xlabel('Forward voltage')
ylabel('Forward current')
% Finding diode DC operation point
[ipt,ind]=min(abs(id-id2));
disp('Operation point')
Id=id(ind)
Vd=vd(ind)
```

C.2 Series Diode Operation Point

A Matlab script was created to compute the operation point of the series diode (D_2) when the circuit is in the conduction mode. The script provides a numeric and graphic solution to equations (4.1).

```
% Series Diode Operation Point Script
% Bias conditions for Microsemi's PIN diode UM4002
vd=linspace(.2,.85,1200);
% Diode i-v curve
y=[60e-6 4e-3 300e-3];
x=[.4 .6 .8];
m=polyfit(x,log10(y),1);
id=10.^(polyval(m,vd));
% Circuit component values
Vbb=3;
Rl=50;
```

```
Rb=50;
Rs=50;
% Diode load line equation
id2=(Vbb-vd)/(Rl+Rb);
% Ploting load line on diode i-v curve
plot(vd,id,vd,id2)
grid
xlabel('Forward voltage')
ylabel('Forward current')
% Finding diode DC operation point
[ipt,ind]=min(abs(id-id2));
disp('Operation point')
Id=id(ind)
Vd=vd(ind)
```

C.3 Transfer Function Computation

The following Matlab script evaluates equation (4.5) for different bias currents using UM4002 forward resistance and reverse bias capacitance from data sheets. The values are computed for a 2MHz signal.

```
% Output Voltage Data Points
vout=[2.68e-3 2.12e-3 1.2e-3 .96e-3 .76e-3
.60e-3];
isole=vout/5;
ibias=[10 20 30 40 50 60];
% Circuit Components
Rl=50;
Rb=50;
Rs=50;
f=2e6;
% Reverse Capacitance and Forward
Resistance from
% UM4002 Data Sheets
C0=11e-12:-1e-12/6:10e-12;
Zt=1./(2*pi*i*f*C0(2:7));
rf=[1.3 .8 .6 .5 .4 .32];
% Transfer Fct Computation
isol=Rl./((Rl+Zt)+Rs*(Rl+Zt+rf)./rf);
loglog(ibias,isole,ibias,isole,'o',ibias,abs
(isol))
```

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