APPENDIX - B

A COMPARISON OF PIN DIODE & RECTIFIER DIODE CHARACTEISTICS

NOTES

RF Application Note MPD - 101A
A Comparison of PIN Diodes & Rectifier Diodes

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Introduction
Many RF circuit designers are unclear about how a PIN diode works in an RF circuit and how it differs fundamentally from the circuit performance of a rectifier diode. This Application Note compares the physical properties and electrical behavior of two classes of Silicon semiconductor diodes: those that rectify an a-c signal (Silicon pn-junctions and Silicon Schottky junctions) and those that do not rectify an a-c signal (Silicon PIN diodes). We begin with a discussion of the various electrical properties of Silicon rectifier diodes because the reader is most likely familiar with them already. We then continue with a discussion of unique electrical properties of Silicon PIN diodes and make a comparison of the applications of both classes of diodes.

I Rectifier Diodes
Rectification [1] is generally defined as the process of converting an alternating current to a unidirectional current. A rectifier device conducts current substantially in one direction only. An ideal rectifier diode would be an open circuit in one direction and a short circuit in the other direction. It also would not dissipate power during the rectification process.

Pn junctions and Schottky junctions rectify RF current. The current flow in a pn junction is comprised of minority carriers (holes and electrons), whereas the current flow in a Schottky junction consists only of majority carriers (electrons). The reader not familiar with these types of junctions and the various mechanisms for current flow across semiconductor junctions is referred to reference [2].

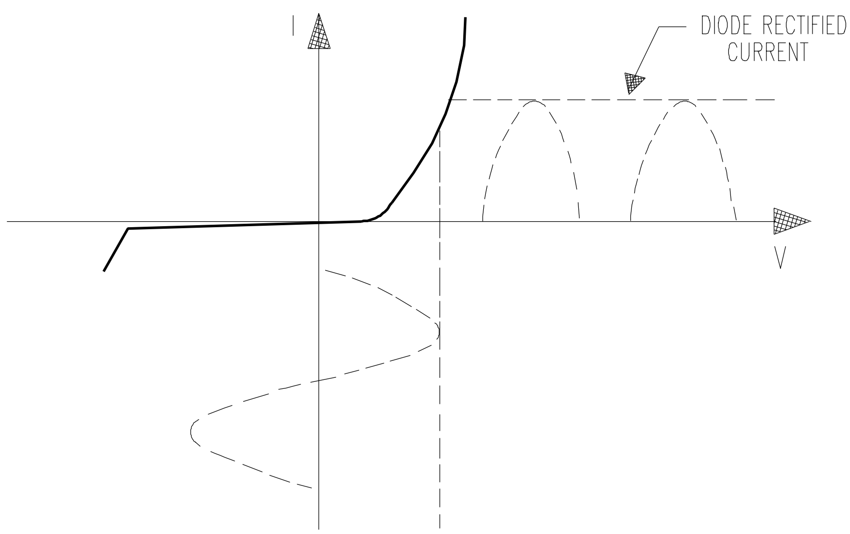

Figure 1. Half-wave Rectification Waveform

The rectifier presents a non-linear resistance (Figure 1) to an a-c current source. The rectifier diode's I V characteristic shows an exponential forward bias curve given by equation 1.

$$I = I_s \left(e^{qv/nkt} - 1 \right) \qquad (1)$$

I_s = Saturation Current
n = Ideality Factor, $1 < n < 2$

The reverse bias "blocking " state, for values of reverse voltage less than the reverse breakdown voltage (VBR), removes the negative half cycles of the input signal. The equation for the reverse bias characteristic is quite complex [2]. Empirically, the reverse bias current increases gradually with reverse voltage until VBR occurs. The breakdown current consists of both avalanche and Zener components and depends mainly on the surface conditions along the periphery of the junction.

The full sine wave signal is shown on the negative vertical axis of Figure 1. The peak voltage of the sine wave is less than VBR. The output current flows in the forward direction only and consists of the forward positive half cycles of the input current wave as shown on the horizontal axis of Figure1. The negative half cycles are blocked from the output by the rectifier's high reverse bias resistance. The current output from the rectifier is unidirectional but it must be filtered to be useful as a d-c bias source.

II Rectification - Non-linear Effects

Equation 1 is the defining relationship for rectifier diodes. The relationship between I and V is exponential and therefore highly non-linear. Heuristically, we observe that a device is linear if the output signal is a faithful replica of the input signal. The input signal's amplitude may increase (gain) or decrease (attenuation) but the shape of the waveform does not change. If the shape of the waveform changes, the device has had a non-linear effect on the input signal. In the case of Figure 1, only the positive half cycles appear in the output of the rectifier. The rectifier has performed a non-linear transformation on the input signal and the output has some added harmonics of the input frequency that the input signal did not have. The subject of non-linearity and signal distortion is discussed in detail in reference [3].

Non-linear devices are highly useful for frequency conversion processes. Frequency up-converters (modulators) and frequency down-converters (mixers) depend on the non-linear devices for their performance characteristics. A rectifier diode is an a-c to d-c converter. However, when non-linear devices are used to switch or attenuate RF power, they will seriously distort the input signal unless biased properly.

III PIN Diode - A Current Controlled Linear Resistor

A PIN diode is a pn-junction with a doping profile tailored in such a way that an intrinsic layer (I-region) is sandwiched between the p-layer and the n-layer. A p-π -n diode has a p-π junction and a π-n junction in series (separated by the length of the I-region).

Microwave PIN diodes are manufactured using an epitaxial process. The π or η layer is nominally a 100 Ohm-cm layer, grown on a heavily doped p+ or n+ type substrate. These diodes provide adequate switching performance above 2 GHz.

Microsemi Corp's RF PIN diodes are based on high voltage rectifier technology. In these P+πN+ and P+ η N+ structures, only the high resistivity layer contributes series resistance (R_s).

Under forward bias conditions, the I-region resistance is given by equation (2).

$$R_s = W^2 / (2\,\mu\tau I_f) \qquad (2)$$

where: μ = ambipolar mobility of minority carriers

τ = effective lifetime of minority carriers

W = effective width of the I-region

I_f = forward bias current

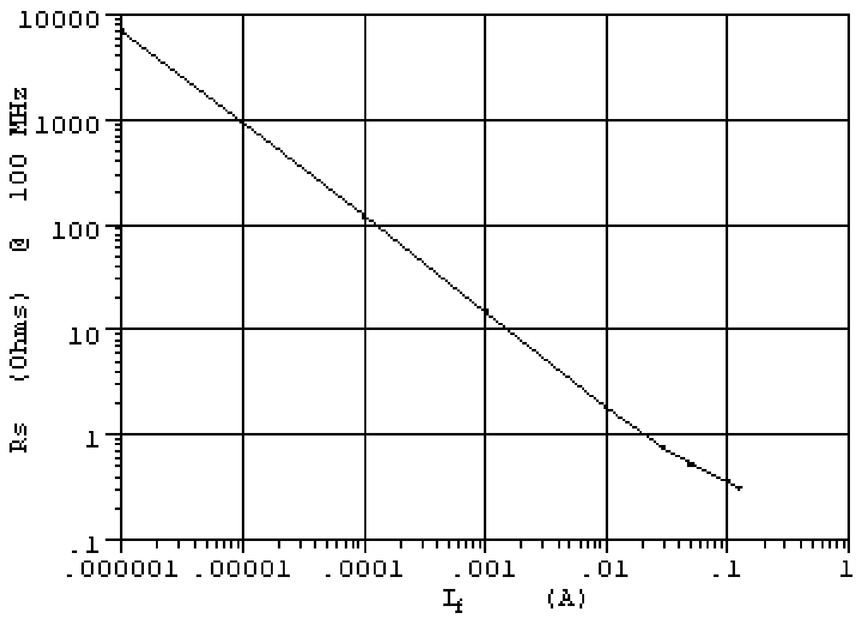

Figure 2. PIN Diode Series Resistance vs Forward Bias Current - UM 9401

This relationship between R_s and I_f is shown in Figure 2 for a UPP 9401. When the PIN diode is forward biased, it is a current controlled resistor that presents a linear resistance to the flow of RF current. Above 50 mA, R_s begins to approach the parasitic resistance of the p+ , the n+ layer, and the Ohmic contact layers. The range of linear operation occurs above a lower cut-off frequency given by equation (3).

$$f_c = 10 / \tau \qquad (3)$$

The RF power that can be controlled depends on the frequency of operation and the peak RF current [3]. PIN diodes can control a relatively large amount of RF current with a small amount of d-c bias current if the frequency of operation satisfies equation (3).

The bias current condition for linear operation is given by equation (4).

$$I_f > I_{rf} / (\pi f_o \tau) \qquad (4)$$

where I_{rf} is the peak value of the RF current waveform. Optimum bias conditions for high power operation in HF band are discussed in detail in references [3,5]. As a lower bound on equation (4),

$$I_f > I_{rf} / 20 \tag{5}$$

IV Non-linear Effects In PIN Diodes

PIN diodes are designed and manufactured to enhance the linearity of the forward biased resistance vs forward bias current characteristic of equation (2) and Figure 2. But as the operating frequency approaches the cutoff frequency defined by equation (3) and /or the d-c forward bias current is inadequate to control the RF current, the PIN diode will begin to rectify and non-linear distortion effects will be evident. This effect can be seen experimentally and is discussed in reference [4].

If the RF induced charge (in the I-region) is nearly equal to the d-c induced charge, the forward bias resistance is not only controlled by the d-c bias, but is modulated also by the RF current. Equations (3) & (4) define the conditions for linear operation of PIN diodes.

V Comparison of Rectifier & PIN Diode Applications

So far, the PIN diode discussion has focused on its forward bias characteristic and that implies that the PIN diode is being used in an RF power attenuator circuit. Rectifiers are entirely unsuitable for this application if signal distortion is an issue.

The differences in electrical performance of either the rectifier or PIN diode are most apparent in the RF switch application. Within the constraints of equations (3) & (4), the PIN diode can switch large values of RF current with a small amount of d-c bias current. In VHF band, a d-c bias of 50 mA can control 1 Ampere of RF current if the minority carrier lifetime is adequate (2us). A rectifier diode can be used toswitch 1 Ampere of RF current, but the d-c bias current must be at least 1 Ampere also!

VI Conclusions

RF PIN diodes perform a unique function for RF switch and RF attenuator designers that pn-junction and Schottky junction devices cannot perform. In the switch application, small levels of d-c bias control can control large amounts of RF line current and not distort the input signal waveform. Their unique forward bias R_s vs I_f characteristic provides nearly distortion free RF signal attenuation when biased over the proper current ranges. Longer lifetime PIN diodes are becoming available which will provide the devices needed to switch or attenuate large levels of RF power from MF band through VHF band.

REFERENCES

[1] IEEE Standard Dictionary of Electrical and Electronic Terms, Wiley-Interscience, New York, 1981

[2] S.M. Sze, Modern Semiconductor Device Physics, John Wiley & Sons, New York, 1988

[3] The PIN Diode Circuit Designers' Handbook, Microsemi Corp, 1998, Appendix E

[4] "PIN Diodes Offer High-Power HF Band Switching", W.E. Doherty, Jr. And R.D. Joos, Microwaves & RF, Vol 32, No 12, 1993, pp 119-128