The Influence of I-Region Width Modulation on PIN Diode Attenuator Design

Robert H. Caverly and Zhi Wen Tang

Department of Electrical and Computer Engineering
University of Massachusetts Dartmouth
N. Dartmouth, MA 02747-2300

Abstract

This paper discusses the effects of I-region width modulation on PIN diode attenuator performance. The work shows that the I-region thickness becomes thinner as the dc bias current decreases, and that over-estimates of PIN diode forward resistance can be the result.

Introduction

PIN diodes are widely used in microwave and RF control circuits such as switches and attenuators. In attenuator applications, such as a reflective attenuator using a series connected PIN diode (a series reflective attenuator), the diode can be operated at low bias currents to provide high resistance and hence attenuation

The forward bias resistance of the PIN diode is usually defined using the formula [1,2]:

$$R_s = \frac{W^2}{2\mu I_o \tau} \qquad (1)$$

where W is the I-region width and I_0 is the dc forward current. A common assumption used in resistance prediction is that this I-region width is constant independent of dc forward bias current. The work described in this paper will show that W is not constant with forward bias current, but rather starts at a smaller value and increases to its final value with increasing forward current. The smaller than expected resistance caused by so-called I-region width modulation may lead to overestimates of resistance at fixed forward current levels, leading to errors in expected attenuator response.

Background

At zero bias, the PIN diode I-region is either partially or completely depleted. Under reverse bias voltages beyond a certain level, the I-region becomes completely depleted and the corresponding I-region thickness is called the punch-through thickness, W_{PT}. Under low levels of forward bias (where many attenuator diodes are operated), some of the I-region may still be depleted (Figure 1). Simulations using a numerical technique [3] have shown that the region of stored charge (where conductivity modulation in the PIN diode occurs) changes with the applied forward bias current, giving rise to an effective I-region width that varies with forward voltage. Figure 2 presents the results of one set of these simulations and shows that the effective I-region width is small at low bias currents and approaches its final value as the bias current increases.

This effect can be explained by defining an effective I-region width W_{eff} as the difference between the punch-through width and the depleted portion of the I-region:

$$W_{eff} = W_{PT} - \sqrt{\frac{2\varepsilon}{qN_I}(V_{bi} - V_A)} \qquad (2)$$

where the second term is the definition of the depletion width of a junction [4], V_A is the applied forward voltage and N_I is the background impurity concentration in the I-region. The dc forward voltage and dc forward current are related by the well-known diode I-V law. As indicated by both Figure 2 and Eqn. 2, the effective I-region width can be small at low dc bias current levels, and will approach W_{PT} as the applied bias increases. This reduction in I-region width can lead to an overestimate of the PIN diode resistance at low bias levels, giving rise to errors in attenuator design. This effect is more pronounced in thinner I-region diodes than thick ones since there can be greater incursion of the depletion region in thin devices.

Experimental

In an effort to validate the phenomenon described above, detailed measurements of PIN diode resistance and stored charge ($Q = I_0\tau$) were carried out to calculate W_{eff} for several PIN diodes. Resistance measurements were made at 100 MHz using HP4191A and HP4291A impedance analyzers. Stored charge measurements (Q) were made using Bermar Corp. stored charge meters QS-65 and QS-85. The results of these calculations (using Eqn. 1) are presented in Figure 3, which shows that the I-region thicknesses approach a constant value that remains unchanged at higher dc bias currents. For low bias levels, there is a significant decrease in the I-region thickness, which may give rise to lower than expected resistance. Note that these measurements agree qualitatively with the model results explained by Eqn. 2.

Application

The effect of I-region width modulation will cause an overestimate in resistance if a microwave circuit designer assumes that the I-region width is constant with bias. This overestimate will be most pronounced at high values of resistance, where bias currents are low and the stored charge region is a smaller portion of the total I-region width. Measurements of resistance (above) were used to compute the error in attenuation for the series reflective attenuator circuit. Diodes of 20 and 40 microns (nominally measured at a high bias current of 1 mA) were used in these measurements. Figures 4 and 5 illustrate the degree of overestimate in the series reflective attenuators, where a constant I-region thickness based on its high bias current value has been assumed. Note that the attenuation variation can be greater than 7 dB for the smaller I-region width diode at low dc forward currents (Figure 5). This effect is more pronounced in thinner PIN diodes than thick ones (compare Figure 4 and Figure 5) since there is greater incursion of the depletion region in thin devices.

Conclusion

In summary, microwave and RF circuit designers should determine the complete resistance-current characteristic of the PIN diode over the range of operating resistances to ensure that I-region width modulation does not negatively influence expected attenuation performance.

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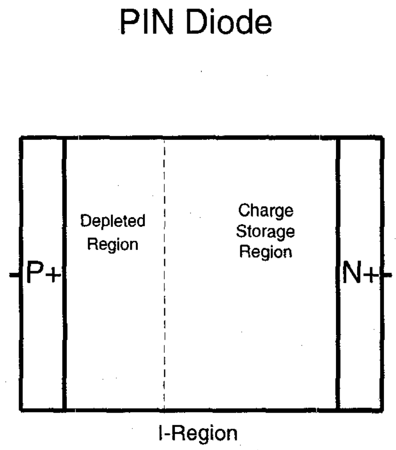

Figure 1: A sketch of a PIN diode showing depleted and charge storage regions. In this figure, a slightly n-type impurity concentration in the I-region (a p-ν-n diode) has been assumed.

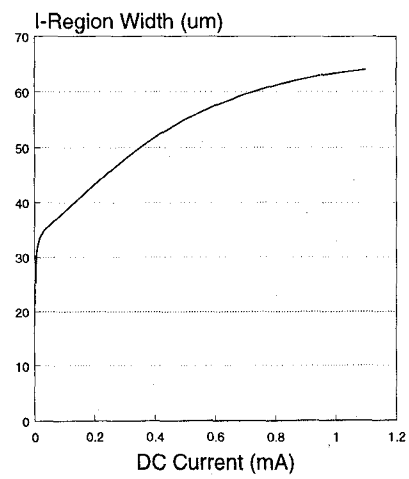

Figure 2. Effective I-region thickness versus dc bias current computed from numerical simulation.

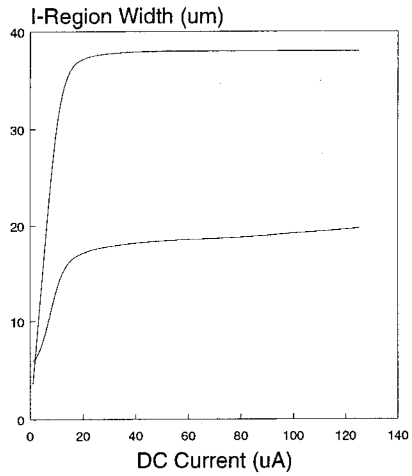

Figure 3. Effective I-region thickness versus forward dc current for two PIN diodes of nominal thickness 20 microns and 40 microns. The I-region width was computed using experimental data.

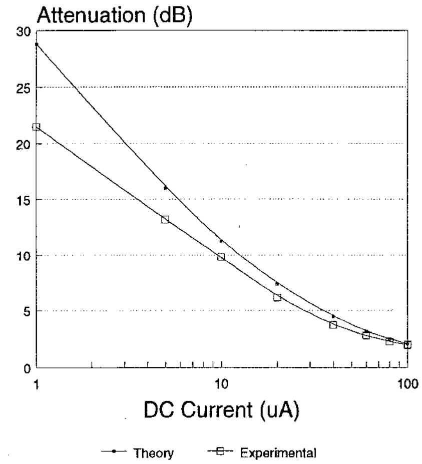

Figure 5. Plot of attenuation for a series reflective attenuator versus forward dc current for a 20 micron wide PIN diode. Note that the measured level of attenuation is significantly different from the theoretical value based on a constant I-region and use of Eqn. 1.

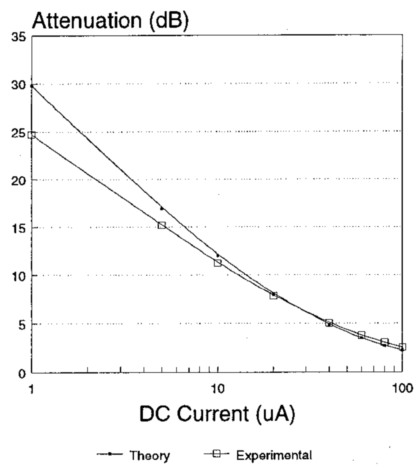

Figure 4. Plot of attenuation for a series reflective attenuator versus forward dc current for a 40 micron wide PIN diode. Note that the measured level of attenuation is significantly different from the theoretical value based on a constant I-region and use of Eqn. 1.