THE TEMPERATURE DEPENDENCE OF PIN DIODE ATTENUATORS

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ABSTRACT

This paper presents the results of a study of the effect of temperature on PIN diode resistance whose knowledge will allow designers of microwave PIN diode attenuators to predict attenuation changes with temperature. A theoretical and experimental study of PIN diodes of different geometries and passivations indicates that the resistance-temperature coefficient of low capacitance silicon dioxide passivated PIN diodes is in the range of -0.1% to + 0.1% per degree C. Microwave attenuation measurements were taken that validate this approximation.

INTRODUCTION

PIN diode attenuators are commonly used as microwave control devices. The attenuation level is dependent on the value of the PIN diode resistance which is primarily established by the forward bias current at room temperature. PIN diode attenuators are generally required to work over a wide temperature range and the attenuation level is affected by the temperature of the PIN diode. This paper describes the temperature dependence of the resistance of PIN diodes and its affect on attenuator performance.

The study of the effects of temperature on PIN diode resistance consisted of a theoretical analysis of the behavior of mobility and carrier lifetime with temperature. PIN diodes of different geometries and passivations were fabricated and evaluated over temperature. Measurements of I-region stored charge versus temperature and resistance versus temperature were performed on these devices This data showed a marked contrast on the thermal behavior of PIN diode resistance that is dependent on both diode passivation and geometry. Measurements over temperature of these PIN diodes in a single-diode shunt attenuator configuration were also performed to compare with the previous resistance data. From these measurements, a temperature coefficient of resistance is now suggested for typical PIN diodes utilized in many microwave attenuators. Consequently, the temperature performance of a PIN diode attenuator may now be predicted.

ANALYSIS

The relationship for the microwave resistance of a PIN diode contains terms that are related to the forward current, device geometry, and electronic properties of its semiconductor material. These parameters are related to the PIN diode resistance by the following simple expression [1]:

$$R = \frac{W^2}{2\mu I_0 \tau} \qquad (1)$$

where W is the I-region thickness, μ is the I-region ambipolar mobility, I_0 is the dc forward current and τ is the ambipolar carrier lifetime Of these factors, only the mobility and lifetime are functions of temperature and contribute to the dependence of the resistance on temperature.

The temperature dependence of the mobility in silicon has been extensively studied [2] and it has been established that mobility decreases with increasing temperature in the temperature range of interest This temperature dependence can be approximated by

$$\mu(T) = \mu(T_0)\left(\frac{T}{T_0}\right)^{-n} \qquad (2)$$

in the temperature range of 223 to 473 Kelvin (-50 to 200 C) and with a value of n in the narrow range of approximately 2 to 2.2.

The temperature dependence of the carrier lifetime is not as well understood, with most investigators relying on measurements and analysis on gold doped devices. Based on these measurements and work performed by other investigators on silicon devices [3-6], carrier lifetime has been found to increase with increasing temperature. The temperature dependence of carrier lifetime may be modeled by the following exponential expression:

1993 IEEE MTT-S Digest

$$\tau(T) = \tau(T_o)\left(\frac{T}{T_o}\right)^m \qquad (3)$$

Combining Equations 2 and 3 and assuming a value of n equal to 2, the resistance temperature dependence of a PIN diode may be approximated as follows:

$$\frac{R(T)}{R(T_o)} = \left(\frac{T}{T_o}\right)^{2-m} \qquad (4)$$

Figure 1 shows the resistance ratio described by Equation 4 plotted versus temperature using the carrier lifetime coefficient m as a parameter. The figure illustrates that, depending on the temperature dependence of the carrier lifetime, the resistance of the PIN diode may increase, decrease or remain constant over a wide variation in temperature The value of m equal 2 would indicate no change in resistance with temperature.

The value of m appears to vary over a wide range, and a variety of factors influences the carrier lifetime temperature characteristic. Some of the important ones are the diode geometry (specifically the I-region width and diameter), the type of material used to passivate the diode surface, and whether impurities have been intentionally introduced into the intrinsic layer in order to reduce carrier lifetime. Of these three factors, the first two are typical of PIN diodes most commonly used in microwave attenuator design, and are the focus of the experimental measurements reported in this work.

EXPERIMENTAL

Measurements were performed to independently determine the temperature dependence of resistance, carrier lifetime and microwave attenuation The specimens used were PIN diodes fabricated with different geometries and surface passivation materials· silicon dioxide, silicon nitride on silicon dioxide and M/A-COM CERMACHIP glass.

A. Carrier Lifetime and Resistance Measurements

Measurements of stored charge versus temperature over the temperature range of 20 to 90 C were performed on a variety of diodes from each lot. Carrier lifetime was calculated from stored charge measured using one of several stored charge meters, Bermar models QS-65, QS-85 and QS-63. A test fixture was constructed to fit directly on the meter's measurement port This was necessary to minimize lead lengths and ensure more accurate measurements of stored charge, especially in short carrier lifetime diodes. The temperature was monitored using either a thermocouple or thermistor assembly. The data taken indicated that, in addition to the expected dependence of lifetime with passivation, there was also noticed a dependence on the ratio of I-region area to I-region width. Junction capacitance at punch-through is directly proportional to this ratio, and was used as its measure. Figure 2 shows the measured dependence of carrier lifetime factor m with respect to capacitance for the three different passivations. The curves in Figure 2 are least square fits to the experimental data. For large capacitance, nitride passivated diodes, carrier lifetime will increase approximately linearly with temperature (m=1).

The typical PIN diode used in microwave attenuators is a silicon dioxide passivated device with capacitance of the order of 0.10 pF Figure 2 shows that this device will have an m factor of approximately 1.7, which is predicted to result in a minor resistance change with temperature.

Resistance measurements as a function of temperature were also performed on the PIN diode specimens. These measurements were performed at 100 MHz using a HP 4191A Impedance Analyzer Figure 3 displays normalized resistance (R_T / R_{To}) versus temperature for selected PIN diodes of different calculated values of carrier lifetime temperature coefficient (m). This figure is an experimental validation of Figure 1 and shows a range of resistance-temperature characteristics with devices $(m \approx 2)$ exhibiting a slight reduction of resistance with temperature and others $(m \approx 1)$ showing an increase of resistance with temperature at a rate of 0 2% to 0.3% per degree C as predicted by Equation 4.

B. Microwave Attenuator Measurements

These results indicate that the temperature dependence of carrier lifetime is a good predictor of the temperature coefficient of PIN diode resistance and therefore microwave attenuation. Figure 4 shows the expected performance of a shunt connected PIN diode attenuator biased at 10dB at room temperature. The figure shows predicted attenuation versus temperature for oxide passivated PIN diodes of capacitances between 0.1 and 2.0 pF The figure shows that the attenuation varies with temperature depending on the resistance temperature coefficient, as predicted by Equation 4. The values of m are taken from Figure 2 for the oxide passivated device.

Microwave attenuator measurements were also performed on PIN diodes in a single diode shunt reflective attenuator fixture. Attenuator data were taken at frequencies between 1.0 and 2.0 GHz using an HP 8510A Network Analyzer. The temperature was varied between -35 to +125°C. Figure 5 shows the results of the measurements on silicon dioxide passivated devices with capacitance of 0.07 pF and 2.4 pF. The lower capacitance device shows little attenuation variation over the temperature range indicated, agreeing with the best-fit curves shown in Figure 2. The large capacitance device exhibits a negative temperature coefficient with a corresponding increase in the attenuation. This is consistent with independent stored charge and resistance measurements.

CONCLUSION

This paper presented the results of a study investigating PIN diode electrical parameters that ultimately affect the temperature dependence of PIN diode attenuators. The results show that device passivation and geometry play a major role in governing the resistance-temperature coefficient in PIN diodes. The study has shown that large capacitance diodes of any passivation tend toward negative resistance coefficients, indicating that shunt attenuators constructed with these devices will show attenuation levels increasing with temperature. Low capacitance silicon dioxide passivated diodes (0.1 pF and smaller) typically exhibit resistance-temperature coefficients in the range of -0.1% to +0.1% per degree C, corresponding to very small changes of attenuation with temperature.

The study showed that the variation of stored charge with temperature is a good predictor of the temperature dependence of the PIN diode resistance, and ultimately its performance in attenuator applications.

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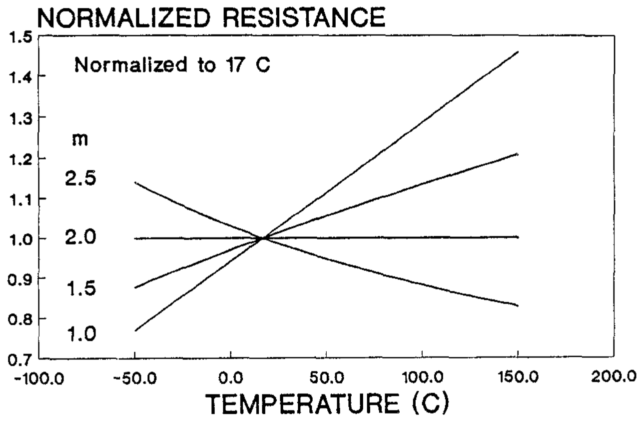

FIGURE 1. Plot of normalized PIN diode resistance versus temperature using the carrier lifetime coefficient m as a parameter.

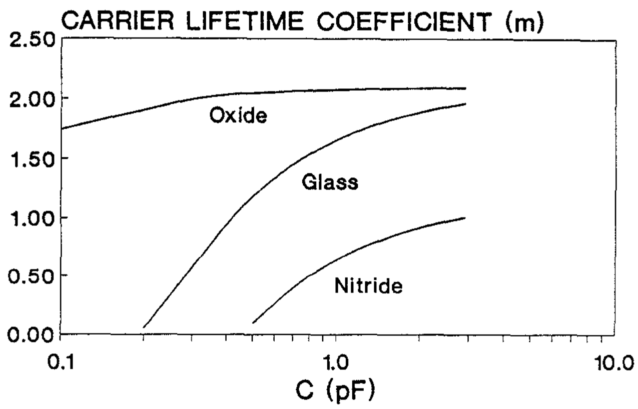

FIGURE 2. Plot of carrier lifetime coefficient versus PIN diode capacitance for three different surface passivations.

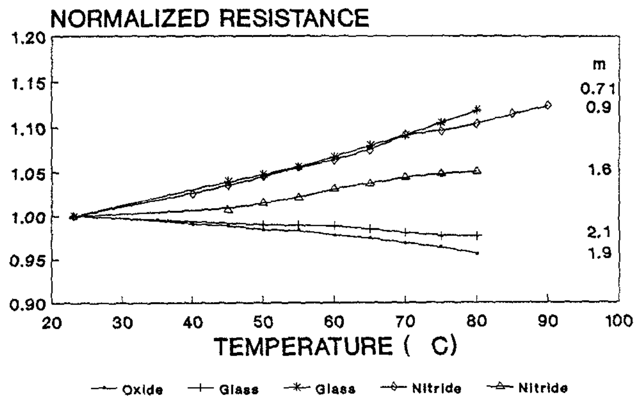

FIGURE 3. Plot of measured resistance for diodes in the three passivation groups as a function of the measured carrier lifetime coefficient m. The resistances are normalized to their 23 C resistance.

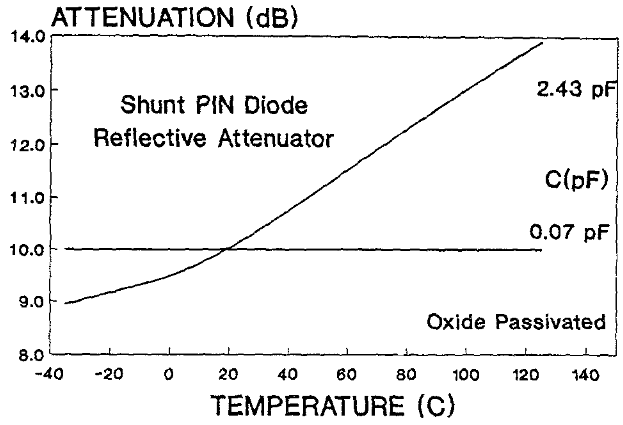

FIGURE 5. Measured variation of attenuation with temperature in a shunt connected PIN diode attenuator. The room temperature attenuation is set to 10 dB.

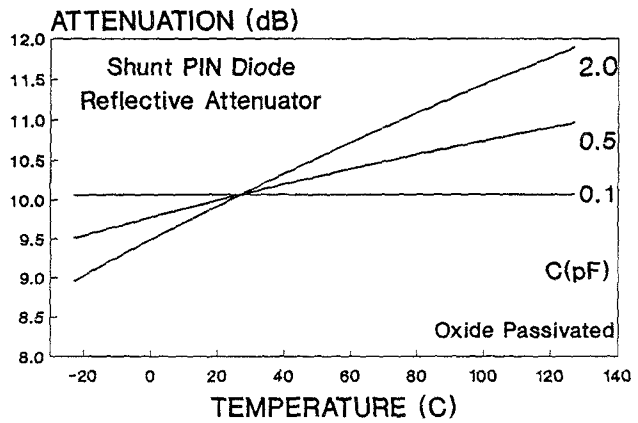

FIGURE 4. Predicted variation of attenuation with temperature in a shunt connected PIN diode attenuator using PIN diode capacitance as a parameter.