

Temperature Insensitive PIN Diode Attenuators

The authors studied the temperature dependence of PIN diode resistance for various PIN geometries and discovered that for a particular PIN diode the resistance is essentially temperature invariant, and is an attractive choice for attenuators to operate over wide temperature extremes.

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Since PIN diodes behave like current controlled resistors at microwave frequencies, they are widely used in analog attenuators. When an attenuator is required to operate over a broad temperature range, a feedback loop or temperature compensated current source may be included to maintain constant attenuation with temperature. In most designs, however, such complications to the circuitry are not employed and the PIN diode is biased with a constant current with no attempt at temperature compensation. As a consequence, the attenuators's performance with temperature often is unknown a priori and is subjective to the characteristics of the particular PIN diode selected.

Although microwave circuits using PIN diodes have been designed for more than 25 years, there is nothing reported in the literature, to our knowledge, on the effect of temperature on PIN diode resistance. In this paper we show the results of just such a study and how it can be applied to PIN diode attenuators that are virtually temperature insensitive.

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]:

$$\text{Equation (1)} \quad R = \frac{W^2}{2\mu I_o \tau}$$

where W is the I-region thickness, μ is the I-region ambipolar mobility, I_o is the dc forward current and τ is the ambipolar carrier lifetime. The stored charge Q of the PIN diode is the product of the dc forward current and the carrier lifetime. Of these factors, only the mobility and carrier lifetime are functions of temperature and contribute to the dependence of the resistance on temperature. Mobility is the proportionality constant relating the average carrier velocity to the applied electric field.

Carrier lifetime is the recombination time constant of the holes and electrons, equal to the time in which a given number of them will recombine to 37% ($1/e$) of their initial value. Recombination is equivalent to carrier death in that once an electron recombines with a hole, neither is available as a mobile charge to carry current in the I region of the PIN diode. Replenishment of mobile charge is provided by the “dc” bias current to the PIN diode.

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 “ambipolar” mobility is the effective average mobility of electrons, which move faster, and holes, which move slower, to an applied electric field. This temperature dependence can be approximated by

$$\text{Equation (2)} \quad \mu(T) = \mu(T_o) \left(\frac{T}{T_o} \right)^{-n}$$

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. Figure 1 shows a plot based on fits to experimental data [2]. Also plotted is the mobility variation for $n=2$, indicating that the mobility decreases at nearly the same square law rate.

The temperature dependence of the carrier lifetime is not as well understood, with most investigators relying on measurements and analysis on gold doped devices. It is known that the carrier lifetime is influenced by several factors, outlined in the following expression [3]:

$$\text{Equation (3)} \quad \tau^{-1}(T) = (\tau_B^{-1} + A_{SHR}) \left(\frac{T_o}{T} \right)^m + B_{AUG} \left(\frac{T}{T_o} \right)^k$$

where the first term is the intrinsic lifetime, the term A_{SHR} is the lifetime determined by the Shockley-Hall-Read process, the third term is the lifetime contribution due to Auger recombination, and the temperature exponents are empirical fits to measured data [3]. In silicon PIN diodes, Auger recombination is several orders of magnitude less than that due to SHR recombination and so this term can be neglected under normal operating conditions.

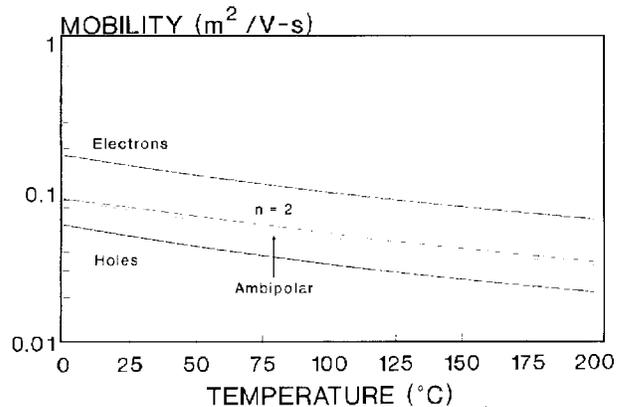


Figure 1. The charge carrier mobility decreases within the normal operating temperature range of PIN diodes. Both the electron and hole mobility decrease with increasing temperature, and the ambipolar mobility decreases at a rate that is nearly inverse square law.

The intrinsic lifetime is quite large (on the order of milliseconds) and is also a minor contributor to the overall lifetime in silicon PIN diodes. This leaves only the SHR term that influences PIN diode carrier lifetime. The stored charge Q of the PIN diode is the product of the dc forward current and the carrier lifetime.

Based on these measurements and work performed by other investigators on silicon devices [3-7], carrier lifetime has been found to increase with increasing temperature. The temperature dependence of carrier lifetime may be modeled by the following expression:

$$\text{Equation (4)} \quad \tau(T) = \tau(T_o) \left(\frac{T}{T_o} \right)^m$$

Combining Equations 2 and 4 and assuming a value of n equal to 2, the resistance temperature dependence of a PIN diode may be approximated as follows:

$$\text{Equation (5)} \quad \frac{R(T)}{R(T_o)} = \left(\frac{T}{T_o} \right)^{2-m}$$

Figure 2 shows the resistance ratio described by Equation 5 plotted versus temperature using simulated values of 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 temperature range. A value of m equal 2 would result in no change in resistance with temperature.

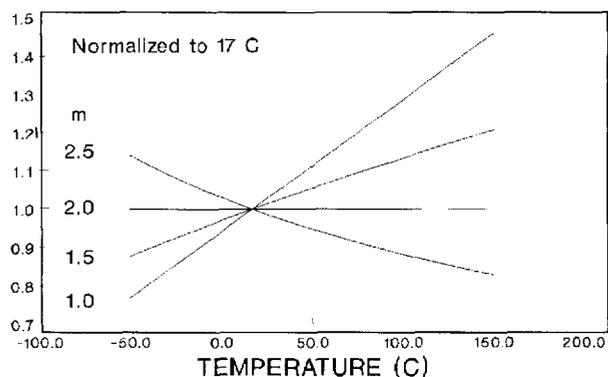


Figure 2. The resistance of a PIN diode may increase or decrease with increasing temperature, depending on the rate of increase of the carrier lifetime with temperature. A linear increase in the carrier lifetime with temperature causes an increase in resistance with temperature. A quadratic increase causes a nearly constant resistance-temperature characteristic.

A variety of factors influence 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 that we performed.

Experimental Results

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

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 diode designs. 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 (the voltage at which the low frequency measured capacitance of the junction ceases to decrease) is directly proportional to this ratio, and was used as its measure. Figure 3 shows the measured dependence of carrier lifetime factor m with respect to capacitance for the three different passivations. The curves in Figure 3 are least square fits to the experimental data. For large capacitance, nitride passivated diodes, carrier lifetime increases approximately linearly with temperature ($m=1$).

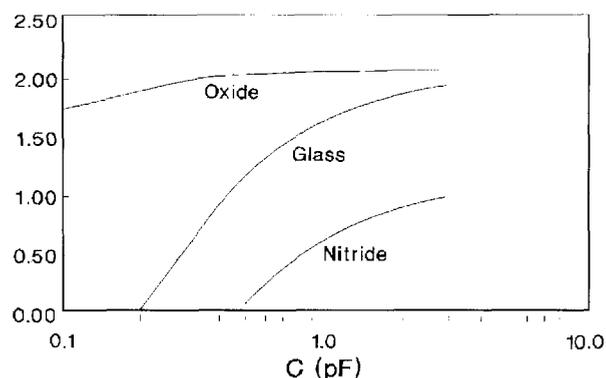


Figure 3. The carrier lifetime temperature coefficient m is a function of diode capacitance as well as diode passivation.

The typical PIN diode used in microwave attenuators is a silicon dioxide passivated device with capacitance of the order of 0.10 pF. Figure 3 shows that this device has an m factor of approximately 1.7, which can be expected 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 an HP 4191A Impedance Analyzer. The measurement frequency was high enough so that carrier lifetime effects on the diode impedance were minimized [8,9]. Figure 4 displays normalized resistance versus temperature for selected PIN diodes of different calculated values of carrier lifetime temperature coefficient (m). This figure is an experimental validation of Figure 2 and shows a range of resistance-temperature characteristics with devices exhibiting a slight reduction of resistance with temperature and others showing an increase of resistance with temperature at a rate of 0.2% to 0.3% per degree C, as predicted by Equation 5.

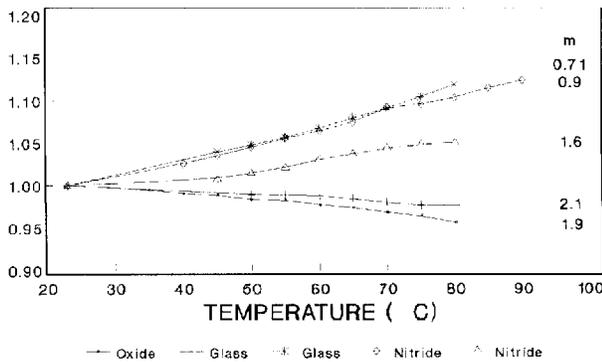


Figure 4. Measurements of resistance versus temperature show variability over a wide temperature range that is dependent on the carrier lifetime coefficient as well as passivation material.

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 5 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 5. The values of m are taken from Figure 2 for the oxide passivated device.

Microwave attenuator measurements were also performed on these PIN diode specimens installed 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 6 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.

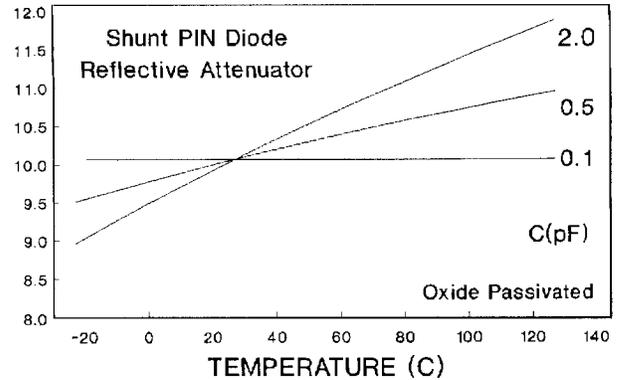


Figure 5. A theoretical curve showing that a shunt PIN diode reflective attenuator containing a silicon oxide passivated diode may exhibit a nearly constant attenuation-temperature characteristic for small capacitance diodes (0.1 pF) or an increasing level of attenuation for large capacitance diodes.

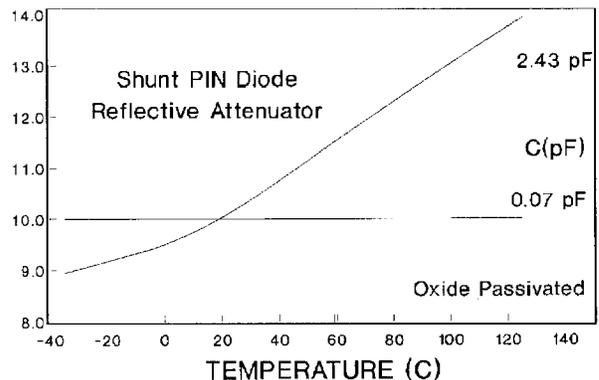


Figure 6. Measurements of attenuation versus temperature show that low capacitance silicon dioxide passivated PIN diodes exhibit nearly constant attenuation over a range of temperatures, whereas larger capacitance diodes exhibit increasing attenuation over this same temperature range.

The results show that device passivation and geometry play a major role in governing the resistance-temperature coefficient in PIN diodes. Large capacitance diodes, regardless of their passivation, tend toward negative resistance coefficients, indicating that shunt attenuators constructed with these devices will have attenuation which increases 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.

It can be seen 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. Thus, the resistance-temperature characteristic of any PIN diode may be experimentally determined by independently measuring stored charge Q or carrier lifetime versus temperature. The value of m determined by this method is a good predictor of the temperature sensitivity of the attenuator circuit.

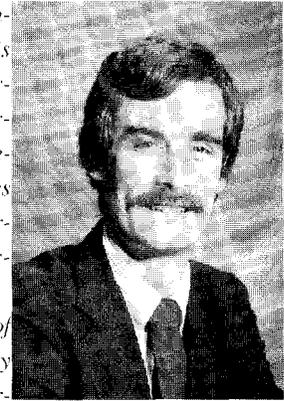
Acknowledgment

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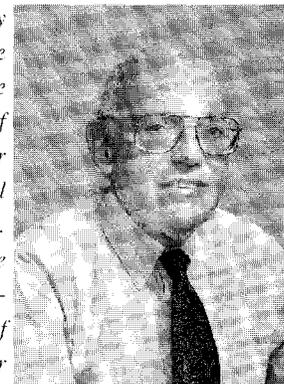
Robert H. Caverly was born in Cincinnati, Ohio in 1954. He received his Ph.D. Degree in Electrical Engineering from The Johns Hopkins University, Baltimore, MD, in 1983. He received the MSEE and BSEE degrees from the North Carolina State University, Raleigh in 1978 and 1976 respectively.



He has been with the University of Massachusetts Dartmouth (formerly Southeastern Massachusetts University) and is currently a Professor. Concurrently he has been a consultant for M/A-COM, Inc., Burlington, MA., engaged in various microwave control element projects. In 1990, with support from The National Science Foundation, he was a Visiting Research Fellow with the Microwave Solid-State Group at the University of Leeds in the United Kingdom. His research interests lie in characterizing PIN diodes and MESFETs in the microwave and RF control environment, an area in which he has published over twenty technical papers. Besides microwave semiconductor electronics, his interests include analog and digital CMOS VLSI design.

Dr. Caverly is a reviewer for the *IEEE Transactions on Microwave Theory and Techniques*, a Senior Member of the IEEE, and a member and local chapter advisor of Eta Kappa Nu. He is also a recipient of the Dow Outstanding Young Faculty Award from The American Society of Engineering Education.

Gerald Hiller was born in New York City and received the BEE degree from the City College of New York in 1958 and the MSEE degree from the University of Pennsylvania in 1963. He is a Senior Member of IEEE and on the editorial board of the *IEEE MTT Transactions*.



In 1984 he joined MACOM where he is Senior Principal Engineer and Manager of Applications Engineering of MACOM's Burlington Semiconductor Operations. From 1972 to 1984 he was Director of Microwave Engineering at Unitrode Corp. and from 1962 to 1972 he was Applications Manager of Raytheon's Micro State Electronics Operation.

Mr. Hiller has authored many articles on the subject of PIN diodes and their applications in RF and microwave circuits. Also, in collaboration with Dr. Robert Caverly, additional contributions to PIN diode technology were developed and published. Of particular importance is their development of the distortion model for PIN diodes, the PIN diode impedance-frequency characteristic and the reverse bias requirement for PIN diodes in high power switches.