By Rick Cory, Skyworks Solutions Inc

LIMITERS SHIELD SENSITIVE FRONT-END SEMICONDUCTOR COMPONENTS FROM TRANSMITTER-SIGNAL DAMAGE.

PIN-limiter diodes effectively protect receivers

Limiters are necessary in situations in which a transmitter delivers signals of peak power on the order of kilowatts or megawatts to an antenna that also connects to the receiver. Receivers, however, must reliably detect and process weak incoming signals, so they have a sensitive low-noise amplifier at their input, although some receivers apply the received signal directly to the input of a downconverter mixer. A limiter can protect these sensitive front-end semiconductor components, which even a small portion of the transmitter signal is likely to damage, whether the transmitter signal couples to the receiver input by reflection from the antenna or by another means.

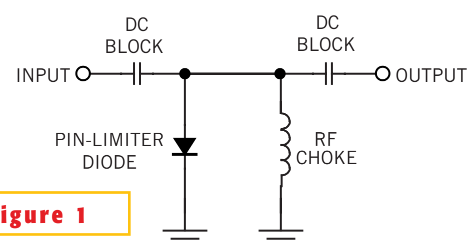


Figure 1

A single-stage limiter is a relatively simple topology, but PIN-diode parameters are critical.

A SIMPLE LIMITER CIRCUIT

A simple, passive receiver-protection limiter comprises a PIN (positive-intrinsic-negative) diode and an RF choke inductor, both of which are in shunt with the main signal path (**Figure 1**). In most limiter circuits, the input and the output of the circuit include dc blocking capacitors. A single-stage limiter can typically reduce the amplitude of a large input signal by 20 to 30 dB.

A limiter PIN diode is a three-layer device whose middle I layer is doped with gold to reduce the minority carrier lifetime. The design of the diode, specifically I-layer thickness, I-layer resistivity, and P-to-I-layer junction area is an exercise in trade-offs to produce the desired resistance, capacitance, recovery time, and threshold level. The diode can act as an input-power-controlled RF variable resistance to produce attenuation that is a function of the diode characteristics as well as the incident signal amplitude. The limiter circuit can consist of a single diode or multiple cascaded diodes separated by one-quarter wavelength, $\lambda/4$. Adding a directional coupler and a Schottky detector diode to the system can lower the threshold level.

The PIN-limiter diode functions as an incident-power-controlled, variable resistor. Without a large input signal, the impedance of the limiter diode is at its maximum, resulting in insertion loss of typically less than 0.5 dB. Any large input signal temporarily forces the impedance of the diode to a much lower value, producing an impedance mismatch that reflects most of the input signal power back toward its source. Below the threshold level, the transfer function for the limiter stage is linear; above the threshold, the transfer function shows an increasing insertion loss as signal amplitude increases until the diode is forced to its minimum impedance (**Figure 2**). Without the large signal and after a brief delay whose duration depends on the diode used, thermal factors, and other elements of the circuit, the impedance of the diode reverts from a low value to its maximum value.

In a properly designed circuit, a limiter diode that can safely dissipate only a few hundred milliwatts can also protect a receiver from signals many orders

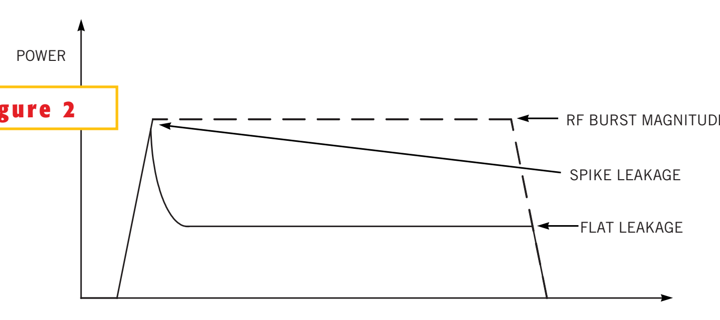


Figure 2

The typical profile of limiter input and output power versus time shows the impact of spike-leakage- and flat-leakage-induced power.

of magnitude larger without damage to itself. When a large input signal is present, the limiter diode reflects, rather than dissipates, most of the input signal power, if you assume that the reflected signal is either reradiated from the system antenna or directed by a nonreciprocal device, such as a circulator or an isolator, to a resistive load that can dissipate the reflected signal power.

THERMAL IMPEDANCE

The thermal impedance of a limiter diode is important, because the life of a semiconductor decreases as operating junction temperature increases. Even though in normal operation a limiter diode dissipates only a small portion of the RF power incident upon it, that small portion can be appreciable. Joule heating converts this power from electrical energy to heat in the diode, primarily in the diode's I and N layers, which contain most of its resistance. The analysis of the diode's thermal model can be complex (see **sidebar** "Structure and material determine thermal characteristics" on the Web version of this article at www.edn.com). A special class of limiter circuit is the clipper circuit. Although the two designations overlap, the topology and action of the clipper differ (see **sidebar** "Will that be clipped or limited?")

When a small signal is incident on the diode of the basic limiter circuit, the electric field of this signal is too small to force carriers into the I layer of the diode. Therefore, its resistance remains high. The insertion loss of the diode in this state is primarily the mismatch loss produced by the capacitive reactance of the diode's junction capacitance. Choose an inductor, which completes the required dc circuit path, with a sufficiently large reactance and out-of-band series resonance, so that it also produces negligible in-band reflection loss.

Consider the events at the leading edge of a large-signal RF burst incident upon the diode. The electric fields that this signal produces force charge carriers into the I layer of the diode, reducing its series resistance. The series resistance of the I-layer changes from its maximum value to its minimum value, assuming that the amplitude of the input RF signal is sufficiently large. The low impedance of the limiter diode causes a large impedance mismatch to the transmission line, thereby reflecting almost all of the input signal power back toward the source.

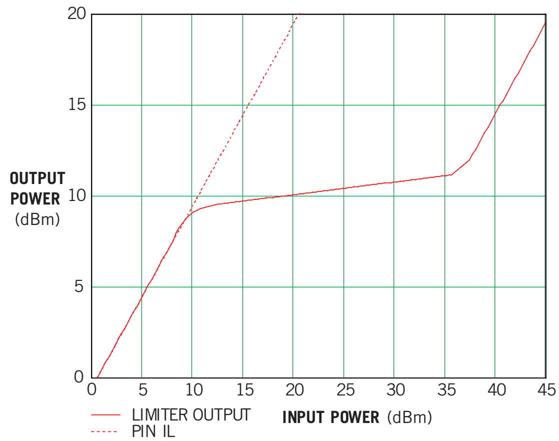


Figure 3 The transfer function for a single-stage limiter shows the performance at which limiting action begins and the diode saturates.

Initially, when the diode is still in its high-impedance state, virtually all of the input signal power passes by the diode limiter and is attenuated only by the small mismatch loss from the diode's capacitance. After sufficient time has passed for the impedance of the diode to reduce to its minimum, which is approximately the carrier transit time across the I layer, the input power is attenuated by the isolation produced by the diode's low impedance. **Equation 1** defines the isolation produced by a shunt resistance:

$$\text{ISOLATION} = 20\log\left(1+\frac{Z_0}{2\times R}\right).$$

The output power that initially propagates past the diode is called spike leakage (**Figure 2**). The power level coming from the diode, after it changes to its low impedance, is flat leakage. It is important to select a limiter diode such that the energy that propagates past the limiter during the output spike is sufficiently small that no damage to the following receiver stages occurs.

Even after the limiter diode has reached its low impedance state, a small portion of the input signal does not reflect back to its source. Some of this energy propagates past the limiter stage to the limiter circuit's load. The diode dissipates the balance of the input energy, due to the joule heating that the RF signal voltage across the diode's resistance produces. The amount of power that propagates to the load is typically 2 to 4 dB larger than the threshold level of the diode, again assuming that the incident signal is much larger than the input threshold level.

An RF signal level forces the series resistance of the limiter PIN to its minimum value. If the input-signal amplitude increases further, the output power from the limiter also increases on a decibel-for-decibel basis, because the finite, nonzero minimum impedance of the diode remains fixed at approximately R_{SAT}. Consequently, the reflection loss caused by the impedance mismatch also remains constant. **Figure 3** shows the transfer function for a single stage limiter. For a practical limiter, the RF currents in the limiter diode operating in its saturated mode can approach or exceed the value that damages the diode, so avoid operating with input signal levels that force the diode into hard saturation.

At the end of the RF-input-signal burst and briefly afterward, free charge carriers are present in the diode I layer, so its resistance remains low. During this interval, the limiter is still operating in its isolation state. In a radar transceiver, therefore, the receiver is essentially "blind" during this interval, even though the transmitter is no longer producing its high-power RF burst. The sensitivity of the receiver temporarily degrades during this interval, because the mismatch loss of the diode's low impedance would attenuate reflected signals that might arrive from a target during this interval. Clearly, the operators of radar systems would like to see this condition end as quickly as possible.

After completion of the RF burst, no externally applied electric field exists to force these charge carriers to be conducted from the I layer. Therefore, the only mechanism to eliminate them and thereby allow the diode to revert to its high-impedance, low-insertion-loss state is recombination of the negatively charged electrons with the positively charged holes. The time that this process requires is proportional to the minority carrier lifetime of the diode, so limiter PIN diodes are treated during wafer fabrication to reduce that duration without adjusting I-layer thickness or junction area. In most cases, this treatment consists of the addition of gold doping to the I layer by thermal diffusion. The minority carrier lifetime of a gold-doped limiter diode with a 2-micron-thick I layer and a junction capacitance of 0.1 pF is approximately 5 nsec. The same diode without Au doping would have minority carrier lifetime of 20 to 40 nsec.

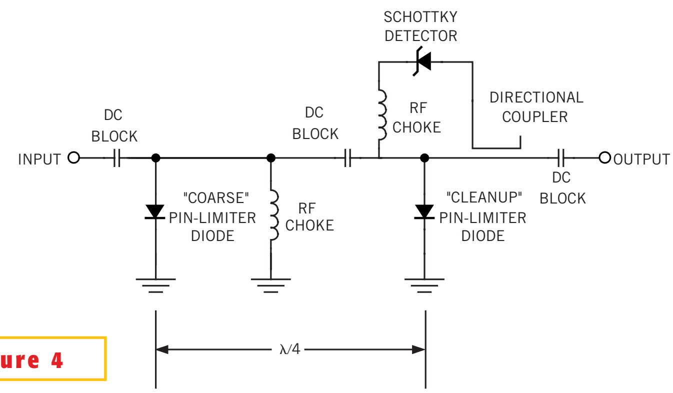


Figure 4

A two-stage limiter can increase the achievable isolation beyond what one-stage version; the capacitor, Schottky diode, and directional coupler further lower the threshold of the circuit.

MULTISTAGE LIMITERS

The geometry of a PIN-limiter diode and the composition of its layers determine its electrical characteristics. A single-stage limiter can typically produce 20 to 30 dB of isolation, depending on the input signal frequency and the characteristics of the diode. In most cases, much more isolation is required to protect sensitive receiver components. Such applications use multistage limiters, such as the two stage-limiter of **Figure 4.**

The PIN-limiter diode at the output, commonly referred to as the cleanup stage, is the diode with the thinner I layer. The threshold level of the circuit must be low enough to protect the remainder of the receiver components. The limiter diode at the input, often called the coarse limiter, has a thicker I layer for several reasons. The P-layer diameter can be larger for a diode with a thicker I layer and can maintain a capacitance value that produces low insertion loss under small-input-signal conditions. This approach produces a diode series resistance that is often smaller than that of the cleanup diode, so the isolation of the coarse limiter can be larger than that of the cleanup stage. Thermal resistance of diodes typically used as coarse limiters can also be lower than that of cleanup-type diodes.

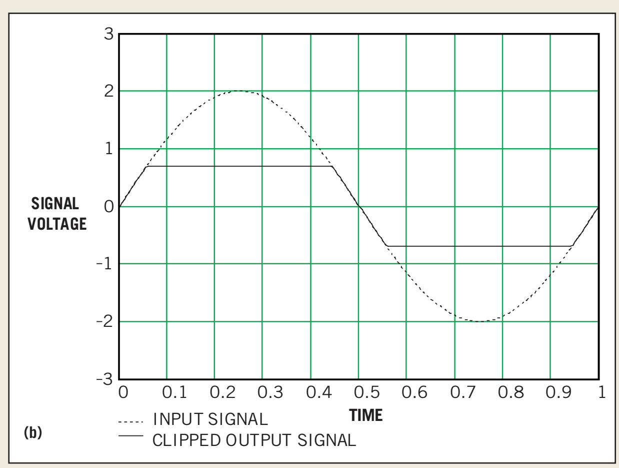
Placement of these stages is important. You normally place the coarse limiter one-quarter wavelength (λ/4) or an odd multiple of one-quarter wavelength, from the cleanup stage toward the signal source. Under small-signal conditions, both diodes are in their high-impedance states, so the total insertion loss is a result of each diode's capacitance and the small mismatch loss they create.

At the leading edge of a large RF-signal burst, both diodes are initially in their high-impedance state. Consequently and briefly, the entire input-signal amplitude, less the small insertion loss, propagates past the limiter. The impedance of the cleanup stage changes first, because the carrier transit time across its thinner I layer is less than that of the coarse diode. This change establishes a standing wave on the transmission line, with a voltage

WILL THAT BE CLIPPED OR LIMITED?

The PIN (positive-intrinsic-negative) limiter circuit operates differently from another class of limiter, known as a clipper (**Figure Aa)**, in which two rectifying diodes (which could be Schottky or pn-junction diodes) limit the peak voltage of the positive and negative signal alternations, either referenced to ground or to some arbitrarily selected dc level. This circuit allows signals whose amplitudes are less than the cut-in voltage of the rectifier diodes to pass unchanged, and signals with larger voltage amplitudes force the diode into conduction. In this case, the voltage drop across the diode is approximately 0.7V for a silicon pn diode, so the peak voltage of the alternation that forward-biases the diode is clamped to within a forward voltage drop of the potential to which the diode is connected. The transfer function (**Figure Ab**) shows that the output signal is no longer purely sinusoidal; instead, it contains numerous harmonics.

Applications requiring low frequency typically use clipper circuits, nominally at VHF ranges and below, because the stored charge of the rectifier diodes limits their rectification efficiency at higher frequencies. Frequency- or phase-modulation-receiver IF-amplifier sections often employ this type of limiting circuit.



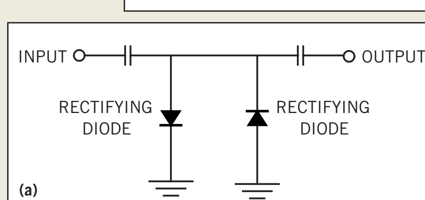


Figure A

A clipping circuit (a) is similar in some ways to a limiter, but it uses antiparallel diodes and has a different transfer function (b).

minimum at the low-impedance cleanup stage. Because the coarse limiter stage is spaced λ/4 away, a voltage maximum occurs across it. This large voltage forces charge carriers into the coarse limiter I layer, thereby reducing its impedance. Consequently, the lower impedance of the coarse diode ultimately produces most of the overall limiting, and the cleanup stage determines the threshold level and spike leakage of the circuit.

For example, you could implement this circuit with a 1.5-micron cleanup diode, such as CLA4603-000, and a 7-micron coarse limiter, such as CLA4607-000. The maximum capacitance for each of these diodes is 0.2 pF, and the maximum resistance specified with a 10-mA forward bias current is 2Ω. Because the coarse diode has a substantially thicker I layer, it can have a junction diameter twice that of the cleanup stage and still maintain low capacitance. This ability results in a much lower thermal resistance for the coarse stage (40°C/W) than for the cleanup stage (100°C/W), allowing it to handle larger input signals.

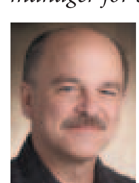
If the limiter must handle large input signals, you may need to add a third stage at the limiter input, spaced another λ/4 from the second diode, which now is called the intermediate limiter. The new coarse limiter diode has a thicker I-layer than the intermediate-stage limiter. The spike and flat leakage remain functions of the cleanup-limiter I-layer thickness, and the power handling and overall isolation remains a function of the characteristics of the three-diode cascade. You can add more stages with increasingly thick I layers at the input of the limiter to handle extremely large signals, spaced at λ/4, but most practical limiters use three stages or fewer.

DETECTOR LIMITERS OFFER ANOTHER OPTION

The threshold level for the thinnest I-layer diode available is approximately 7 dBm. The spike-leakage energy, even at this level, may damage some extremely sensitive receiver components. You can arbitrarily lower the threshold level of the limiter circuit by adding a Schottky detector diode and some passive components to the circuit (**Figure 4**).

The Schottky diode acts as a peak or an envelope detector. It couples to the output of the limiter circuit, often through a directional coupler. The current produced by the Schottky detector is applied as a bias current to the cleanup stage, via an RF choke. The combination of the coupling factor of the directional coupler and the barrier height of the Schottky diode determines the threshold level of this circuit, which is typically around 0 dBm, but could be lower.□

Author's biography



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STRUCTURE AND MATERIAL DETERMINE THERMAL CHARACTERISTICS

Heat flows from regions of high temperature to regions of lower temperature via convection, radiation, or conduction. Convection and radiation of heat from a diode die are negligible and rarely contribute to the removal of heat from the diode.

Conduction of the heat generated in the I layer of a PIN (positive-intrinsic-negative) limiter diode and at the pn junction (the interface between the heavily doped, p-type P layer and the lightly doped, n-type I layer) is through the cathode layer, which is typically the thickest layer of the diode. Designers typically make the electrical connection to the anode of the diode using a circular-cross-section wire (typically 0.0007 in., or 17.8 microns, in diameter) or a rectangular-cross-section ribbon of typically 0.00025×0.003 in., or 6.35×76.2 microns (**Figure A**). The cross-sectional area of each of these conductors is sufficiently small that conduction of heat through this path is also considered negligible (**Reference A**).

Rigorously calculating the thermal impedance of a diode can be involved. However, some simplifying assumptions can reduce the calculation to a more manageable problem. Heat flows from a point source in conical section whose major angle is roughly 60°. Assuming nominal dimensions for a limiter PIN diode with a mesa and that the heat is generated at the interface between the P and the I layers, then as long as a 60° conical section whose minor diameter is the circumference of the P-I interface is completely contained within the diode, you can simplify the analysis to assume that all heat flows from the diode through a right cylindrical section whose diameter is also equal to the diameter of the P-I interface (**Figure B**). This assumption is valid for virtually all commercially available limiter diodes.

This analysis predicts a thermal resistance somewhat larger than what the entire volume of the conic section actually produces. However, overly optimistic assumptions about other thermal impedances within the system often offset this overestimation.

The thermal resistance from junction to heat sink, θ_{jc}, is given by:

$$\theta_{jc} = \frac{L}{G_{THERMAL} \times A},$$

where θ_{jc} is the thermal resistance from junction to heat sink; L is the length of the thermal conduction path (approximately the combined thickness of the I and N layers of a PIN-limiter diode); $G_{THERMAL}$ is the thermal conductivity of the material in the thermal path (for silicon, 0.84 W/(cm°C)); and A is the cross-sectional area of the right cylindrical section assumed to be the path for the heat flow.

THERMAL CAPACITANCE

A finite period is required for heat to flow from the diode. During this time, the temperature of the diode increases as the heat propagates from the junction, to the die-attach interface, to the heat sink. Thermal capacitance, $C_{THERMAL}$, or heat capacity, is the amount of energy required to raise the temperature of the diode I layer by 1°C in the absence of heat flow from the diode (**Reference B**). Thermal capacitance is given by:

$$C_{THERMAL} = \frac{(SPECIFIC\_HEAT \times DENSITY)}{VOLUME},$$

where $C_{THERMAL}$ is the thermal capacitance; specific heat is the specific heat of silicon, or 0.176 calories/(g °C); density is the density of silicon, or 2.43g/cm^3; and volume is the I- and N-layer volumes, or $(\pi \times radius_{I\ LAYER}^2)/(thickness - thickness_{N\ LAYER})$.

THERMAL TIME CONSTANT

Designers can use the thermal time constant of a limiter diode to analyze how the junction temperature of a limiter diode changes over time. It is important because the diode does not reach its final, steady-state temperature until approximately six thermal time constants, $\tau_{THERMAL}$, have elapsed, assuming a constant-amplitude input signal. For brief signal bursts, junction temperature reaches a lower peak value than for much longer bursts.

The thermal time constant is the analog of the electrical time constant. It is the product of thermal resistance and thermal capacitance:

$$\tau_{THERMAL} = \theta_{jc} \times C_{THEMRAL}.$$

The junction temperature of a limiter diode versus time is given by:

$$T_j = T_{HEAT\ SINK} + \Delta T_j,$$

where

$$\Delta T_j = P_{DISSIPATED} \times \theta_{jc}\left(1 - e^{\frac{-t}{\tau THERMAL}}\right).$$

Because the heat sink in a typical system is not infinite, rigorous analysis should include the thermal resistances and capacitances of the remainder of the system, such as the die-attach medium, system ground plane, and system housing.

T_J VERSUS TIME

Consider a series of RF bursts incident upon a typical limiter diode, such as CLA4606-000. The thermal resistance of the diode is 80°C/W. The diode's P layer diameter is 63.5 microns, its I layer is 2.5 microns thick, and its N layer is 100 microns thick. Also assume that the peak dissipated power in the diode is 2W, the duration of each RF burst (sometimes called the "pulse width") is 25 μsec at 2.5% duty cycle, and the die-attach surface is maintained at 40°C.

If the input signal were a continuous wave, the junction temperature would seriously exceed the maximum rated temperature, destroying the diode. The thermal capacitance of this diode is 57.6 μJ/°C, so the thermal time constant is $\tau_{THERMAL}$=46 μsec. Because 6*$\tau_{THERMAL}$ is substantially longer than the burst duration, you can expect that the junction temperature of the diode will not reach the maximum possible temperature, which is the product of the power dissipation and the thermal resistance.

Figure C shows the simulated junction temperature versus time for this set of conditions. The peak diode temperature is approximately 107°C, which is much less than the rated maximum junction temperature of 175°C. Notice that after each RF burst, T_J has ample time to recover to the die-attach surface temperature before the next burst. Under these signal conditions, the diode is not subjected to overstress.

Assume that the duty cycle decreases to 40% but the burst duration increases to 50 μsec. In this case, the diode can handle peak power dissipation of only 2W, in which case the peak T_J climbs alarmingly close to that maximum rated temperature. **Figure D** shows that the junction temperature does not recover to the temperature of the die-attach surface before the start of the next burst. Therefore, the T_J for the diode follows a stair-step-like curve, until the peak T_J finally reaches its steady-state value of approximately 172°C at the end of the third RF burst. At that point, the average T_J is approximately 120°C.

Finally, consider the case in which the RF burst duration exceeds 6$\tau_{THERMAL}$. **Figure E** shows the junction temperature versus

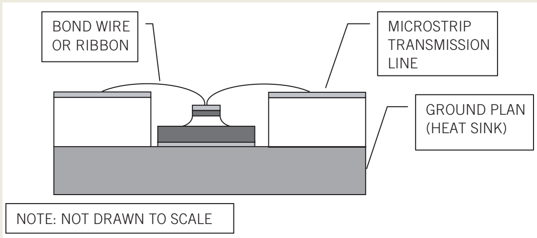

Figure A The cross-section of a shunt PIN-limiter diode in a microstrip system is the basis for thermal modeling.

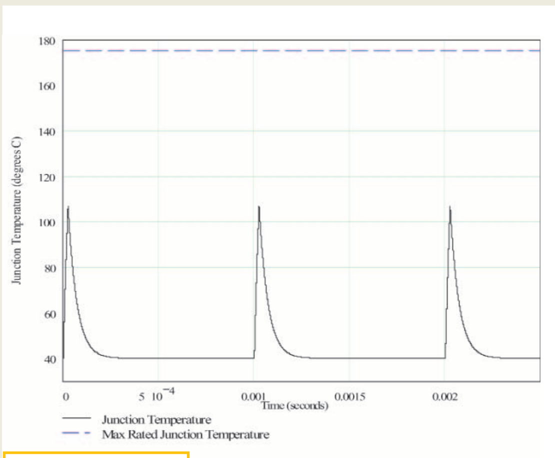

Figure C Diode junction temperature relates closely to duty cycle; the temperature here is shown for a 10% duty cycle.

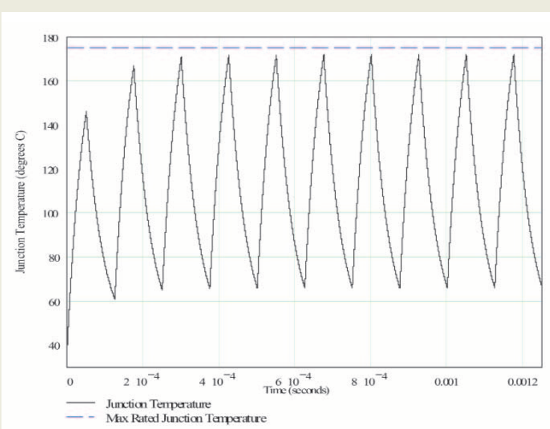

Figure D The diode-junction-temperature profile changes dramatically at a duty cycle of 50%.

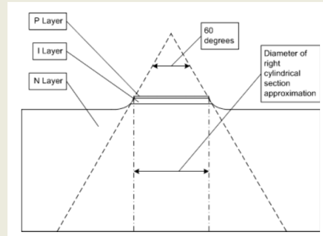

Figure B The mechanical cross-section leads to the right-cylindrical section approximation used for thermal analysis.

time for an input RF burst duration of 1.5 msec and a 10% duty cycle but with the diode dissipating 750 mW peak. Notice that the diode reaches its peak junction temperature and remains there for a substantial interval, so the fact that the signal is burst rather than continuous-wave is insignificant. Analyze the thermal conditions for this case as if the input signal were a continuous wave, rather than a sequence of bursts.

The physical properties of the diode determine its thermal time constant (the product of thermal resistance and thermal capacitance), which you compare with the duration of the pulse that heats the diode to determine how much power the diode can safely dissipate without overheating.

Reference

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B. White, JF, *Microwave Semiconductor Engineering*, JF White Publications, 1995, pg 106.

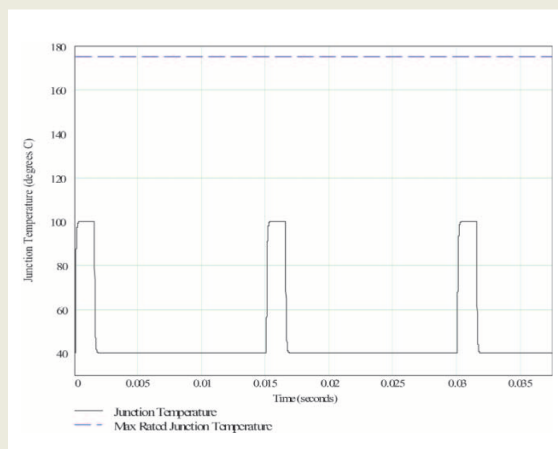

Figure E At a 10% duty cycle and burst width of 1.5 msec, junction temperature does not exceed 100°C for the sample parameters.