Defining Diode Data Sheet Parameters

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When consulting a data sheet for specifications of a part, it is, of course, important to take the meaning intended by the authors of the data sheet. The importance of this obvious idea plays itself out in the ability to make wise part selections in the course of a new design or in the search for a replacement part.

This application note will take the reader on a tour of parameters used by Advanced Power Technology in their diode data sheets. In most cases the intent will be to define and explain. In a few cases more discussion will be provided to clarify the usage of data sheet information. The note will be divided into sections corresponding to the sections of the data sheets. It is recommended that the reader refer to the data sheet for the APT15D60B while reading this application note. This data sheet is referred to at several points in the note and is available on APT's website:

http://www.advancedpower.com/.

Nomenclature

In this document lower case letters will be used for instantaneous values of signals, and upper case letters will be used for limits, averages, and D.C. values. Consequently, i_R is the instantaneous value of the diode reverse current, whereas I_R is the specified D.C. reverse current under certain conditions of reverse voltage, V_R, and case temperature T_C. In data sheets this distinction is sometimes not made. An example of using a capital letter two different ways is found in the data sheets in the sections dealing with maximum D.C. reverse voltage, V_R, and junction ca-

pacitance, C_T. The voltage at which the junction capacitance C_T is measured is 200 V. That voltage is called V_R to designate it as the applied D.C. reverse voltage. It is left therefore to the reader to discern from the context whether V_R is the maximum D.C. reverse voltage or the applied D.C. reverse voltage.

Glossary

A Glossary is provided at the end of this note for the reader's reference. It contains definitions pertinent to the content of the

note and to the information contained in APT's diode data sheets.

Maximum Ratings

The three voltage ratings discussed below, V_R, V_{RRM}, and V_{RWM}, are equal. In principle they could have different values, but in APT's data sheets they are equal. Thus the designer must ensure that all voltages, intended or otherwise, regardless of the conditions, must be kept within this single value to comply with the specification and maintain reliable operation of the diode. The reader will observe that the three voltage ratings presented below do not address isolated transients. The designer must keep in mind that any transients exceeding the diode's own breakdown voltage will probably destroy the diode.

V_R, Maximum D.C. Reverse Voltage

V_R is the maximum allowable D.C. reverse voltage that may be applied to the diode. This rating does not apply to repetitive and non-repetitive transient reverse voltages, and it is valid across the full allowable operating temperature range of the diode. The actual breakdown voltage of the diode is greater than V_R by about five to ten percent. Good design practice keeps the voltage within the rating.

The diode must be operated at or below V_R, since, if the actual breakdown voltage is exceeded, the diode will be destroyed. In some cases diodes are manufactured with a ruggedness rating that specifies how much avalanche energy the diode can withstand. In the case of rugged diodes it is still recommended that they not be avalanched by design, but rather that their ruggedness, i.e., their avalanche capability, be used as a

safety for those few times when transients are big enough to put the diode into breakdown.

V_{RRM}, Maximum Peak Repetitive Reverse Voltage

V_{RRM} is the maximum allowable repetitive instantaneous value of the diode's reverse voltage. This rating does not apply to non-repetitive transients or to D.C. conditions. It is a periodic voltage that includes commutation spikes, inductive kicks, and any other transients that occur in every cycle. These transients are the result of circuit and diode properties and are somewhat under the control of the system designer. The key word is "repetitive."

The diode must be operated at or below V_{RRM}, since, if the actual breakdown voltage is exceeded, the diode will be destroyed. Again, even if the diode has a ruggedness rating, it should not be avalanched by design. Rather the avalanche capability of a rugged diode should be used as a safety for those rare occasions when a transient exceeds the actual breakdown voltage of the diode.

V_{RWM}, Maximum Working Peak Reverse Voltage

V_{RWM} is the maximum allowable working peak reverse voltage of the diode. This rating does not apply to repetitive or non-repetitive transient voltages. It is the maximum value of the reverse operating (working) voltage when transient aberrations from the intended waveform are not considered.

The diode must be operated in this way at or below V_{RWM}, since, if the actual breakdown voltage is exceeded the diode will be de-

stroyed. Again, even if the diode has a ruggedness rating, it should not be avalanched by design.

$I_{F(AV)}$, Maximum Average Forward Current

$I_{F(AV)}$ is the maximum allowable average forward current when the case temperature is maintained at a specified value between 25ºC and 75ºC below the maximum allowable junction temperature. The case temperature specified for this parameter is usually different for every diode. As long as the specified case temperature falls between 25ºC and 75ºC below the maximum allowable junction temperature, $I_{F(AV)}$ agrees with the definition. Note too that this parameter specifies an average current.

Obviously it has to be an average of something, and, in the APT diode data sheets, the basis for the average is a train of square pulses with 50% duty cycle. In such a train of pulses, the average current is half of the peak current. Therefore, a 15 A rating implies a train of square, 30 A pulses with a 50% duty cycle.

Historically, the basis for the average was a train of half sine wave pulses such as would be the output of a half-wave bridge. In other words, the time between the pulses was equal to the duration of the pulses. Because fast power diodes are called on today to handle square or trapezoidal pulses, the basis for the average is no longer the train of half-sine wave pulses.

The specified case temperature is determined from the following relationship:

$$P = \frac{T_J - T_C}{R_{\theta JC}},$$ (1)

where, P is the average power dissipation, T_J is the junction temperature, T_C is the case temperature, and $R_{\theta JC}$ is the thermal resistance maximum junction-to-case.

The average power P is determined as follows. Recall that the basis for the numbers is square pulses with 50% duty cycle and that the peak current of the pulse is 30 A for an $I_{F(AV)}$ of 15 A. That is, the peak current is twice the average current precisely because the duty cycle is 50%. For the same reason, the peak power is twice the average power. Therefore, P, the average power, is taken as half of the product of the forward voltage maximum for the peak current and the peak current itself. This is shown in equation 2.

$$P = \frac{V_F(I_{F(PK)}) \cdot I_{F(PK)}}{2}.$$ (2)

However, since

$$I_{F(AV)} = \frac{I_{F(PK)}}{2},$$ (3)

the average power may be expressed as follows:

$$P = V_F(I_{F(PK)}) \cdot I_{F(AV)}.$$ (4)

This makes the calculation of T_C consistent with the definition of $I_{F(AV)}$ and average power. The forward voltage maximum is used for worst-case analysis.

Consider a diode rated at $I_{F(AV)}$ = 15 A. This is a design specification. For it to be a valid design specification, the calculated case temperature must be between 75°C and 125°C, that is, between 75°C and 25°C below the maximum junction temperature. One such diode has a maximum junction temperature of 150°C. In the same data sheet, the case temperature for the $I_{F(AV)}$ specifica-

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tion is found using equation 1 to be 94°C. This case temperature is in the right range; therefore it is correct to speak of this diode as a 15 A diode.

Note that this rating does not mean the diode will only handle 15 A. For values of T_C < 94°C, the diode will handle more current, and for values of T_C > 94°C, it will handle less current. Keep in mind that this rating is based on a duty cycle of 50%. Obviously, changing the duty cycle also changes the current. This functionality is shown in the data sheet figure entitled Maximum Average Forward Current *vs*. Case Temperature (Figure 1 in this note). See the discussion of that figure for more on this topic. Only the newer data sheets present this figure.
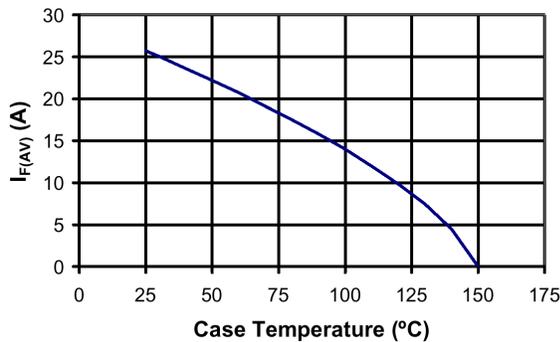

Figure 2. Maximum Average Forward Current vs. Case Temperature

Figure 1 shows that the diode is indeed a 15 A diode at 94°C. However, the allowable range of case temperatures is 75°C to 125°C. In that range, it would be acceptable to call the diode anything from and 18 A diode to an 8 A diode. It simply depends on which case temperature is specified in the data sheet. It is called a 15 A diode because the design target was 15 A. In this case Figure 1 shows that the goal was achieved.

This allowable range becomes important when comparing diodes offered by different manufacturers. If one manufacturer specifies $I_{F(AV)}$ at 30 A and another specifies it at 32

A, the two diodes may actually be equivalent. It is important to compare the case temperatures and, if available, the above figure, Maximum Average Forward Current *vs*. Case Temperature.

$I_{F(RMS)}$, RMS Forward Current

$I_{F(RMS)}$ is the maximum allowable RMS current when the case temperature is maintained at 25°C. The basis for the calculation is the same square wave current used in the calculations for $I_{F(AV)}$. For a periodic square wave with duty cycle δ,

$$I_{F(RMS)} = I_{F(PK)} \cdot \sqrt{\delta} . \qquad (5)$$

Equation 5 is in common use and can be verified by integrating the square wave appropriately to get the RMS current. For all diode data sheets, δ is taken as 50%. The $I_{F(PK)}$ in equation 5 is not of the same value as the peak current for the $I_{F(AV)}$ rating, because the two ratings are given for different case temperatures. The rated $I_{F(AV)}$ for the diode discussed above is valid at a case temperature of 94°C. $I_{F(RMS)}$ is given for a case temperature of 25°C. Nevertheless, for both current ratings the junction temperature maximum is taken to be 150°C for this diode.

Thus the rated $I_{F(RMS)}$ for the diode is 37 A. To see how this number is calculated go to the point in figure 2 where the case temperature equals 25°C. The corresponding average forward current maximum is 26 A. Now recall that a 50% duty cycle means that the peak current is twice the average forward current maximum. Therefore, at $T_C = 25°C$, the peak current is 52 A or 26 A times 2. Again, this rating is for a case temperature of 25°C. Therefore, $I_{F(RMS)}$ is found as follows:

$$I_{F(RMS)} = 52 \cdot \sqrt{0.5} = 37\,A \qquad (6)$$

It is also possible to determine the allowable RMS current at 94°C, the case temperature at which the rated $I_{F(AV)}$ is specified. Once again, the peak current is $I_{F(AV)}$ times 2. Therefore, the peak current is 30 A, and the RMS current at $T_C = 94°C$ is:

$$I_{F(RMS)} = 30 \cdot \sqrt{0.5} = 21\,A. \qquad (7)$$

Equations 5-7 are a special case of the more general expression,

$$I_{F(RMS)} = \frac{I_{F(AV)}}{\sqrt{\delta}}. \qquad (8)$$

This can be seen from the general relationship

$$I_{F(PK)} = \frac{I_{F(AV)}}{\delta}. \qquad (9)$$

Equation 9 shows us that for a 50% duty cycle $I_{F(PK)}$ is $I_{F(AV)}$ times 2, for a 20% duty cycle $I_{F(PK)}$ is $I_{F(AV)}$ times 5, and for an 80% duty cycle, $I_{F(PK)}$ is $I_{F(AV)}$ times 1.25. Now recall equation 5 and substitute the right hand side of equation 9 for $I_{F(PK)}$:

$$I_{F(RMS)} = \frac{I_{F(AV)}}{\delta} \cdot \sqrt{\delta}. \qquad (10)$$

Equation 10 reduces to equation 8, and thus at any point along the curve in figure 2 the maximum RMS current for that case temperature can be calculated from the maximum average forward current by dividing by the square root of δ.

I_{FSM}, Non-Repetitive Forward Surge Current

I_{FSM} is the maximum allowable non-repetitive half-sine wave surge current under the following conditions: $T_J = 45°C$ and the base-width of the half-sine wave surge pulse is 8.3 ms. A sample of diodes is selected and one-by-one the diodes are tested to destruction. This is done by hitting the DUT with a single surge pulse and checking to see whether the diode was destroyed. If so, the peak value of the surge is recorded as that diode's pulse-height capability, and the next diode is tested. If not, the junction temperature is allowed to return to 45°C, the peak value of the surge is increased, and the DUT is hit again. This process is repeated until all of the diodes in the sample have been destroyed. Then the pulse-height capabilities are averaged and I_{FSM} is set equal to half of the average.

T_J, T_{STG}, Operating and Storage Temperature Range

The T_J in this section is the allowable *range* of operating junction temperatures, namely, from –55°C to +150°C. In like manner, T_{STG} is the *range* of allowable storage temperatures. As shown in the various diode data sheets, both ranges are usually the same. Operation or storage outside this range is not recommended.

T_L, Lead Temperature: 0.063" from Case for 10 Sec.

T_L is the maximum allowable lead temperature when soldering 0.063 inches from the case for a duration of 10 seconds. This parameter informs assemblers of the safe conditions for soldering the diode into a through-hole board. The 0.063 inches might

seem peculiar, but that is given in the specification, because it is a common standard thickness for printed circuit boards.

Normally, the case of a through-hole part does not contact the board. Rather the pin shoulder contacts the through-hole barrel, leaving the case even farther away from the point on the backside of the board where the soldering is done. If the part is being flow-soldered, so that the solder wicks up into the barrel, the shoulder is still longer than 0.063 inch. So, although the specification works for all through-hole situations, in most instances the soldering is not actually being done 0.063 inches from the case.

Static Electrical Characteristics

Whereas the ratings presented above are maximum ratings, the ratings to follow are presented as typical or maximum, depending on the parameter or conditions. Note that these are static or D.C. ratings for the particular conditions stated in the data sheet.

V_F, Forward Voltage

V_F is the diode's forward voltage. In APT's data sheets a MAX value (maximum) of V_F is published for the conditions $T_J = 25°C$, $T_C = 25°C$, and I_F = rated current; a TYP value (typical) of V_F is given for the conditions $T_J = 25°C$, $T_C = 25°C$, and I_F = twice rated current; and a TYP value of V_F is also presented for the conditions $T_J = 150°C$, $T_C = 25°C$, and I_F = rated current. Sometimes a TYP value (typical) for the first set of conditions ($T_J = 25°C$, $T_C = 25°C$, I_F = rated current) is also published.

In general, there is a tradeoff among diodes between V_F and the switching speed. For diodes of the same current rating or die size,

a diode that is designed to switch off faster will tend to have a higher forward voltage than a diode designed to switch off slower.

I_{RM}, Maximum Reverse Leakage Current

I_{RM} is the specified maximum reverse leakage current given the specified V_R. A diode whose reverse leakage so measured exceeds the rating in the data sheet fails to meet the specification. Leakage maxima are published for two junction temperatures: $T_J = 25°C$ and $T_J = 125°C$. In APT's diode data sheets I_{RM} is given for two sets of conditions only one of which shows the junction temperature ($T_J = 125°C$). The other one is not not showing the junction temperature is for the condition $T_J = 25°C$.

C_T, Junction Capacitance

C_T is the junction capacitance of the diode at a specified reverse voltage. In APT's data sheets this reverse voltage is 200 V. Actually C_T is a monotonically decreasing function of V_R, as can be seen in the diode data sheet figure entitled "Junction Capacitance *vs*. Reverse Voltage."

L_S, Series Inductance

L_S is the series inductance measured from one lead to another lead. The measurement is performed at a distance of 5 mm from the case on each lead. This inductance is typically on the order of 10 nH.

Dynamic Characteristics

All of the parameters in this dynamic characteristics section are associated with for-

ward or reverse recovery of the diode. Usually TYP values are given instead of MAX.

t_{rr}, Reverse Recovery Time

The diode data sheet figure entitled, "Diode Reverse Recovery Waveform and Definitions" is presented near the end as Figure 2 for this note. This figure is presented only in the newer data sheets. In the older data sheets a different figure is presented showing a different measurement for t_{rr}. In the older figure the points at 0.75 I_{RRM} and at 0.5 I_{RRM} on the right half of the reverse recovery waveform are used to define the line drawn through the abscissa that in turn defines t_{rr}. The newer measurement depicted in Figure 2 will be discussed below.

As the reader can see, the first peak in the reverse recovery waveform is found—under some conditions it is the only peak—and a line is drawn from that peak through the point on the second half of the reverse recovery waveform where i_{RR} = 0.25 I_{RRM} (one-fourth of the first peak). When the first peak is the only peak, as shown in the figure, it is rightly called I_{RRM}. If a second larger peak exists, technically that second peak is I_{RRM}, but the measurement is still done from the first peak. See below for the definition of I_{RRM}.

As this line is extended up through the abscissa, the time from the zero-crossing of the current to that intersection of the straight line with the axis is t_{rr}. APT's diode data sheets give two or three reverse recovery times, depending on when the data sheet was generated.

Older data sheets show three. T_{rr1} is the reverse recovery time for low-injection conditions: I_F = 1 A, di_F/dt = -15 A/μs, V_R = 30V, and T_J = 25°C. t_{rr2} is the reverse recovery

time for high injection conditions: I_F = 15 A, di_F/dt = -200 A/μs, V_R = 400 V, and T_J = 25°C. These conditions are more like the conditions actually encountered in today's switchmode circuits. In fact, di_F/dt is often greater in magnitude than 200 A/μs. t_{rr3} is the reverse recovery time for the same conditions, except that T_J = 100°C.

Newer diode data sheets from APT give only two reverse recovery times. In these newer data sheets, t_{rr1} is the same as t_{rr2} in the older data sheets, and t_{rr2} is the same as the older t_{rr3}.

This description of t_{rr} makes the issue seem very simple when it is not. The reality is that real circuits produce other effects in the reverse recovery waveform that do not appear in the above drawing, such as ringing due to snap-off, second bumps in the current waveform, and long tails in the trailing part of the current waveform. All of these features affect trr and are often hidden from view when one reads a trr number in a data sheet. Historically the older slow diodes subjected to slower circuit conditions exhibited the waveform shape depicted in the figure. Today's fast diodes under today's fast conditions exhibit many of these other features just mentioned.

The point of this discussion is that t_{rr} depends not only on the conditions specified in the data sheet but also on the drive electronics, any snubbers that may be present, and the parasitics in the power circuit. If two designers design and build test circuits and use the same forward current, current rate of decrease, and applied reverse voltage, they will get different values of t_{rr}. Why? The device used for the switch won't be the same; the parasitics won't be the same; one will use a snubber and the other will not; one will add a capacitor across the switch's gate and source or gate and emitter and the other will

not. The other designer might use a different capacitor. t_{rr} depends on all of these actions or effects.

Therefore, of what value is the t_{rr} in the data sheet? Is it a good way to compare competing diodes? If the respective values are of the same order of magnitude, the designer must perform a test to find out which diode is actually faster in the particular circuit under design. Why? The competing companies did not use the same test circuits to do the measurement, even though the basic schematic is for all intents and purposes the same. Also, they did not in general do the measurement the same way. The only way to know for sure which device will perform better in a user's circuit is to test both devices in that circuit.

t_{fr}, Forward Recovery Time

When the voltage polarity on a diode is inverted from reverse to forward, it takes a non-zero amount of time for the forward voltage, v_F, to equilibrate to a value that corresponds to the amount of forward current, i_F, flowing in the diode. Until enough stored charge builds up in the base region of the diode to increase the diode's conductivity, the anode-to-cathode voltage overshoots the value it will eventually equilibrate to. The time it takes v_F to do this is t_{fr}. In APT's diode data sheets, two values of t_{fr} are published. t_{fr1} is the forward recovery time at $T_J = 25°C$, and t_{fr2} is the forward recovery time at $T_J = 100°C$.

I_{RRM}, Maximum Reverse Recovery Current

I_{RRM} is the maximum reverse recovery current for a specified set of conditions. As such it is the peak value of the diode's re-

verse current. In APT's diode data sheets, I_{RRM} is measured for given forward current, I_F, current rate of decrease, di_F/dt, and applied reverse voltage, V_R. In the data sheets, I_{RRM1} is the maximum reverse recovery current at $T_J = 25°C$, and I_{RRM2} is the maximum reverse recovery current at $T_J = 100°C$.

Like trr, this parameter depends on the elements in the power circuit. It can be larger or smaller depending on how the switch that reverse biases the diode is driven and there can be a second "bump" whose magnitude can sometimes exceed the magnitude of the first "bump." The waveshape in the figure entitled "Diode Reverse Recovery Waveform and Definitions" is not always realized in practical circuits.

Q_{rr}, Reverse Recovery Charge

Q_{rr} is the area under the reverse current curve measured from the zero crossing to the point at which t_{rr} is measured. It is the area designated as item 5 in the "Diode Reverse Recovery Waveform and Definitions" figure. The reader should observe that this is not all of the charge stored in the diode under forward conduction, because some of the stored charge is not represented in the area under the reverse current curve.

When the diode is subject to forward current, stored charge builds up in the base region. When the diode's voltage polarity is inverted from forward to reverse, the accumulated stored charge must be removed before the diode can recover to its "off" state. There are two ways the stored charge can be removed: one is recombination and the other is drift. When electrons and holes recombine inside the diode, they will not participate in the terminal current. Consequently, all of the current detected at the terminals is net drift current inside the diode plus the small

amount of current it takes to deplete the base region enough to withstand the applied reverse voltage. By far, the net drift current makes the greater contribution to the terminal current. The point to understand here is that Q_{rr} represents the sum of the charges passing out of the diode at the terminals when the diode is in reverse recovery.

V_{fr}, Forward Recovery Voltage

When the polarity of the diode voltage, anode-to-cathode, is inverted from reverse to forward, the initial resistance in the diode is high due to the comparative lack of carriers in the device. As the forward current builds up and levels off and as the number of carriers in the base region builds up, the resistance goes down. The initial higher value of resistance brings about an overshoot in the forward voltage from which the voltage settles to a steady-state value. This change in resistance (conductivity modulation) is brought about by the buildup of charge carriers in the base region of the diode. V_{fr} is the peak value of the voltage overshoot. In some diodes this voltage can be very high, on the order of 30 V or more.

di_M/dt, Maximum di/dt During t_b

Since the recovery current is negative, this rate of "fall" is the rate of increase of the reverse current from its peak negative value to values less and less negative as it moves toward zero. Referring to the "Diode Reverse Recovery Waveform and Definitions," Figure 2, di_M/dt is measured on the right side of the recovery waveform, not the left.

When the maximum is near I_{RRM}, the diode is probably soft, and when the maximum is near zero, the diode is probably "snappy." In the figure di_M/dt is near the peak reverse current. In some diodes it is definitely near zero. Near zero, a high di_M/dt can bring about undesireable ringing in the power circuit. The value of di_M/dt by itself does not say anything about whether the reverse recovery is soft. Snappiness usually indicates a lack of softness, but more particularly, if ringing does not occur, the recovery is soft enough. Again, this means a test in the circuit under design is important.

Thermal and Mechanical Characteristics

The following parameters are thermal and mechanical–not electrical. Some are maximum; some are typical.

$R_{\theta JC}$, Junction-to-Case Thermal Resistance

$R_{\theta JC}$ is the resistance to heat flow as measured from the diode's junction to the baseplate of the diode's case. The path from the junction to the baseplate is the path of least resistance. The thermal resistance junction-to-case is given in the data sheet instead of the thermal resistance junction-to-ambient through a heatsink, because the choice of heatsink and interface material to be made by the designer is not known. The $R_{\theta JA}$ given in the data sheet does not apply here, because it is based on the assumption that a heatsink is not in use. It is up to the designer to calculate the total thermal resistance, given the particular design selections of heat sink and case-to-heatsink interface material.

The steady-state analysis of heat flow involves the following equation:

$$\Delta T = R_{\theta}P, \qquad (11)$$

where ΔT is the temperature difference between two points (for example, between

junction and case) in ºC, R_θ is the thermal resistance in ºC/W, and P is the power dissipated in watts. Notice that this expression has the same form as Ohm's law with ΔT analogous to voltage and P analogous to current. This, of course, is where the name "thermal resistance" comes from. Note that equation (2) is just a rearrangement of equation (1). Dynamic analysis of heat flow will be addressed later in the discussion of the transient thermal impedance model.

$R_{\theta JA}$, Junction-to-Ambient Thermal Resistance

$R_{\theta JA}$ is the resistance to heat flow as measured from the diode's junction to the ambient with no heat sink between the case and the ambient. In some circumstances a diode may be operated without a heat sink. $R_{\theta JA}$ represents the limit imposed on operating frequency and pulse width by the device itself on that kind of operation. See the discussion of $R_{\theta JC}$. The same principles apply to $R_{\theta JA}$.

W_T, Package Weight

W_T is the package weight expressed in ounces and grams.

Torque, Maximum Mounting Torque

Torque is the maximum allowable mounting torque to be applied to the mounting screw(s) for the given package. The units are lb·in and N·m.

Figures

The final section of the data sheet presents figures showing maximum or typical per-formance curves, a test circuit, some definitions, a thermal model and a package outline. Two of the figures present maxima, whereas seven of them present typical values. One depicts the test circuit used for reverse recovery testing, and one presents a reverse recovery waveform and definitions of the various parts of the waveform. Also included are the transient thermal impedance model and the package outline.

The typical performance curves discussed in this last section are produced from measurements of a typical diode. It is eminently possible to buy a diode that does not obey the curves exactly. The curves are intended to show in general how the devices will perform. Results for any particular diode may vary slightly from the values given in the curves.

Because there are older data sheets and newer ones, the figure numbers are not always the same between the two generations for a given figure. Therefore, the figure should be identified by its caption. In other words, to see the correspondence between a given data sheet and this application note, match the data sheet's caption to the corresponding header here in the note.

Several of the figures in the older data sheets refer to a variable called "Current Slew Rate." In the newer data sheets this has been changed to "Current Rate of Decrease" to make it clear that the slope in view is that of the falling edge of the diode current waveform.

Maximum Effective Transient Thermal Impedance, Junction-to-Case *vs*. Pulse Duration

Thermal impedance is a combination of thermal resistance and thermal capacitance.

Thermal resistance has already been defined above in the section on Junction-to-Case Thermal Resistance. Thermal capacitance can be understood using equation 12:

$$C_\theta = m \cdot S, \qquad (12)$$

where C_θ is the thermal capacitance in W·s/°C, m is the mass of the solid (usually calculated as the product of volume and density), and S is the specific heat in W·s/g·°C. To work then from the units involved, it is seen that thermal capacitance is the amount of energy (heat) a piece of material can hold per °C. This again is simply the product of mass and specific heat. Since R_θ has units of °C/W and C_θ has units of W·s/°C, it can be seen that $R_\theta C_\theta$ has units of time and may be taken as the thermal time constant. As such it gives an indication of the rate of temperature rise in the material. The one-dimensional thermal impedance, then, for a piece of material is the parallel combination of R_θ and C_θ. More rigorous modelling will make use of a three-dimensional model and finite element analysis, but the one-dimensional model is adequate for many cases.

The curves in the figure are based on this concept of a thermal time constant. For a square wave of power having specified height and duty cycle, the transient thermal impedance, junction-to-case, $Z_{\theta JC}$, is some amount smaller than the steady-state thermal resistance, depending on the thermal time constant, the duty cycle and the height of the power pulse.

The data for the curves are measured, not calculated. The instrument used to take the data is able to generate a one-dimensional $R_\theta C_\theta$ model that can be used in a simulator to reproduce the information in the curves. This model is presented in the data sheet and is called the "Transient Thermal Impedance Model." In the model the units for the resistance values are °C/W, and the units for the capacitance values are W·s/°C.

In a simulator R_θ is treated as resistance (ohms), C_θ is treated as capacitance (farads), P is treated as current (amps), and ΔT is treated as voltage (volts). Ohms, farads, amps, and volts are, of course, the units the simulator works with. Therefore, to make use of the simulation results, the current is read as watts and every node voltage is a temperature (°C) referenced to the ground node, which is the case temperature. Whatever voltage is measured at one of the nodes other than the ground node is a temperature of that value (whatever the voltage is) above the case temperature (whatever it happens to be).

Remember that the voltage (ΔT), current (P), impedance (Z_θ) relationship leads to differences in temperature, not raw values of temperature. Having a model for the junction-to-case parameters, the designer can then provide the model for the case-to-heatsink interface and for the heatsink itself. This, then, is everything needed to model (in one dimension) the dynamic thermal behavior of the diode in the designer's particular application.

One might wonder whether the various $R_\theta C_\theta$ pairs in the Transient Thermal Impedance Model represent the various layers in the part: die, attach, baseplate, for example. In general they do not. The pairs the instrument sets forth are just the pairs it needs to model the data, and the number of pairs is not always the same from part to part, even when the number of physical layers for a given package type is the same. Nevertheless, the top voltage in the model, the voltage across the power source, does represent the number of degrees above the case temperature at which the junction is operating. Therefore,

the case temperature plus the voltage across the power source (in ºC—in the simulation, voltage is the difference in temperature) is the junction temperature.

Transient Thermal Impedance Model

In the newer data sheets only, a one-dimensional "Transient Thermal Impedance Model" is presented for use in simulations of the thermal behavior of the diode in the user's assembly. To use the model the user must supply the R_θ and C_θ for the case-to-heatsink interface material as well as the R_θ and C_θ for the heatsink. These must be added to the model in the same fashion as the existing R_θ and C_θ elements, making it possible then to simulate the entire system from junction to ambient.

Forward Voltage *vs*. Forward Current

The curves in this figure are taken on a curve tracer and represent the transfer characteristic of the diode. If you run a certain number of amps through the diode at a certain temperature, the voltage across the device, measured from anode-to-cathode will be given by the curves. For the same forward current, as the temperature increases, the forward voltage decreases. This negative temperature coefficient is shown by the curves and can be a disadvantage when attempting to use diodes in parallel.

Reverse Recovery Charge *vs*. Current Rate of Decrease

This figure shows how the reverse recovery charge varies as a function of di_F/dt. As stated before, in the older data sheets "Current Rate of Decrease" was called "Current Slew Rate." The data sheet for the

APT15D60B shows for this figure that as di_F/dt increases for a given I_F, the reverse recovery charge, Q_{rr}, also increases. The same figure also shows that for a given di_F/dt, as the forward current, I_F, increases, the reverse recovery charge increases.

Reverse Recovery Current Maximum *vs*. Current Rate of Decrease

This figure shows how the reverse recovery current maximum varies as a function of di_F/dt. In the older data sheets "Current Rate of Decrease" was called "Current Slew Rate." This figure in the data sheet for the APT15D60B shows that as di_F/dt increases for a given I_F, the reverse recovery current maximum, I_{RRM}, also increases. The same figure also shows that for a given di_F/dt, as the forward current, I_F, increases, the reverse recovery current maximum increases.

Dynamic Parameters *vs*. Junction Temperature

One would also like to know how the parameters vary with junction temperature. This figure shows this variation for t_{rr}, Q_{rr}, and I_{RRM}. In the data sheet for the APT15D60B, all three increase as the junction temperature increases from -50ºC to 150ºC. I_{RRM} increases by about a factor of 2.4, t_{rr} increases by about a factor of 3, and Q_{rr} increases by almost a factor of 7.

Reverse Recovery Time vs Current Rate of Decrease

This figure shows how the reverse recovery time varies as a function of di_F/dt. In the older data sheets "Current Rate of Decrease" was called "Current Slew Rate." In the data sheet for the APT15D60B, as di_F/dt in-

creases, trr decreases. Also in the same figure, for a given di_F/dt, as the forward current I_F increases, t_{rr} increases.

Forward Recovery Voltage/Time *vs.* Current Rate of Decrease

This figure shows how the forward recovery voltage and forward recovery time vary with di_F/dt. In the older data sheets "Current Rate of Decrease" was called "Current Slew Rate." In the data sheet for the APT15D60B this figure shows that V_{fr} increases linearly with di_F/dt and that t_{fr} decreases as di_F/dt increases.

Junction Capacitance *vs.* Reverse Voltage

This figure shows how the junction capacitance varies as a function of reverse voltage V_R. The capital "V" is used here, because the voltage in view is D.C. In the data sheet for the APT15D60B this figure shows that as V_R increases C_J decreases. In fact, as V_R varies from 0 to 200 V, C_T decreases by a factor of 10 or more.

Maximum Average Forward Current *vs.* Case Temperature

In contrast to most of the other figures, this figure presents a curve of maximum values. It also appears only in the newer data sheets. This figure reveals the actual currents possible with the diode, depending on how efficient the heat sinking is. If the case temperature is specified as the independent variable in equation (1) and the equation is solved for current, the result is this figure, given the data in the Forward Voltage *vs.* Forward Current figure corrected for maximum values.

Diode Reverse Recovery Test Circuit and Waveforms

This shows the test circuit in use for measuring t_{rr}, but it does not show the details of the drive for the MOSFET. The figure appears only in the newer data sheets. A double pulse turns the MOSFET on and off. The first pulse turns the MOSFET on when the current in the inductor is zero. This inductor is the 30µH inductor in the figure. This is done to show which inductor is under consideration. The actual value may not be 30 µH. The duration of the pulse determines the amount of current developed in the inductor. When the pulse goes off the MOSFET is turned off and the current in the inductor free wheels through the diode (the DUT). The second pulse turns the MOSFET on again and the diode (DUT) is forced to undergo reverse recovery. The reverse recovery of the diode takes place during the second pulse.

The shape of the reverse recovery waveform depends on the diode's own properties, the properties of the switch, the nature of the gate drive circuit, and the parasitic elements in the power circuit. The switch is not always a MOSFET. It may instead be an IGBT.

Diode Reverse Recovery Waveform and Definitions

This figure is considered to be self-explanatory, except that the waveform in a user's circuit may have features not depicted in the figure. The figure for the older data sheets differs from the figure for the newer data sheets, reflecting a change in the way t_{rr} and Q_{rr} are measured. Refer to the figures for this information. There can be oscillations and second peaks that depend, as already stated, on the components and stray

elements in the circuit. Also, di_M/dt may or may not occur next to I_{RRM}. It could equally well occur near the zero current axis.

Package Outlines

Depending on the data sheet there will be one or two drawings showing the outlines of the package(s) covered by the data sheet along with dimensions of the package and pins.

1 I_F - Forward Conduction Current

2 di_F/dt - Current Rate of Decrease, Rate of Diode Current Change Through Zero Crossing From Positive to Negative.

3 I_{RRM} - Maximum Reverse Recovery Current.

4 t_{rr} - Reverse Recovery Time, measured from zero crossing where diode current goes from positive to negative, to the point at which the straight line through I_{RRM} and $0.25 \cdot I_{RRM}$ passes through zero.

5 Q_{rr} - Area Under the Curve Defined by I_{RRM} and t_{rr}.

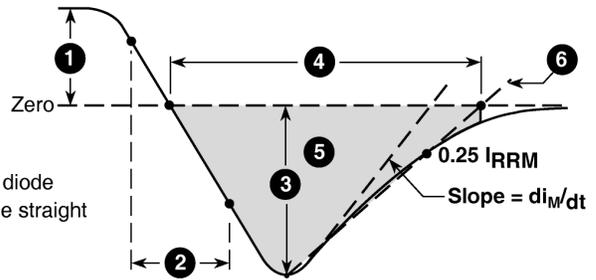**6** di_M/dt - Maximum Rate of Current Increase During the Trailing Portion of t_{rr}.

Figure 2. Diode Reverse Recovery Waveform and Definitions

Glossary

Item	Definition
Avalanche	Carrier multiplication due to impact ionization—see also "breakdown"
Base region	In a PIN diode, which is the basic structure of power diodes, the lightly doped region between the P+ and the N+ regions—designated "I" in the name PIN, which stands for "intrinsic," but is usually a lightly doped N or P region
Breakdown	Condition in which more than a specified amount of reverse leakage current is present during avalanche—the mechanism of breakdown in power diodes—specified as the voltage at which this occurs
Current Rate of Decrease	The rate at which the diode current is decreasing at turn-off measured in A/µs at the zero-crossing from forward to reverse current
Forward current	The terminal current flowing through the diode from anode to cathode
Forward voltage	Positive voltage at the diode's terminals measured from anode to cathode
i_{RR}	Instantaneous reverse recovery current
I_{RR}	Average reverse recovery current
I_{RRM}	Peak reverse recovery current
Junction capacitance	Designated C_T, it is the capacitance of the diode measured at the terminals and depending on the depletion width—depletion occurring primarily in the base region in power diodes—reported for given values of V_R
Reverse voltage	Negative voltage at the diode's terminals measured from anode to cathode
Switching speed	For a diode, designates the time it takes for reverse recovery to be completed—often indicated by t_{rr}