

# AN5001

## Use of $V_{T0}$ , $r_T$ On-state Characteristic Mode

### Application Note

Replaces AN5001-7

AN5001-8 August 2016 (LN33745)

#### The use of the $V_{T0}$ , $r_T$ on-state model and a more accurate alternative

The inclusion of the theoretical terms  $V_{T0}$  and  $r_T$  in power semiconductor datasheets allows a simple means of calculating power loss, but this can lead to many incorrect assumptions. The terms in question are the two coefficient of a straight line model of the device on-state characteristics curve. To calculate the power the following formula is used:

$$P = V_{T0} \cdot I_{T(AV)} + r_T \cdot k^2 \cdot I_{T(AV)}^2 \quad [1]$$

Where  $k$  is the current waveform form factor, eg 1.57 for half sine wave.

The use of  $V_0$  and  $r_T$  to approximate the forward volt drop curve of a power semiconductor originates from pre-computer days when engineers used slide rules, calculators or even log tables for their calculations. The use of modern computers and spreadsheets means that better approximations to the characteristics can easily be used. The most popular of these models is that proposed by General Electric:

$$V_{TM} = A + B \cdot \ln(I) + C \cdot I + D \cdot \sqrt{I} \quad [2]$$

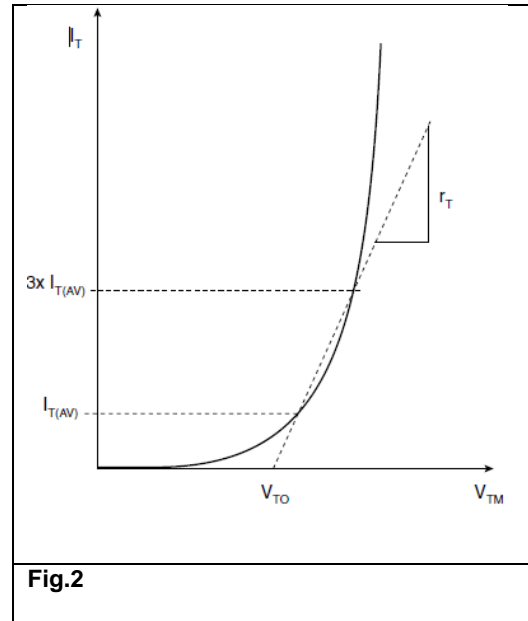
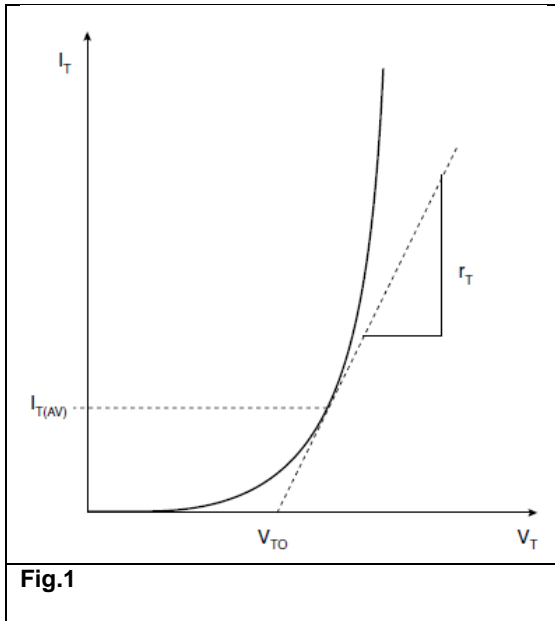
Where  $A, B, C$  and  $D$  are constants with values specific to the device in question. The use of this model is described later.

#### $V_{T0}$ , $r_T$ definitions

Although the straight-line model is basically simple, variations in definition can lead to significant differences in calculated powers.

Different manufacturers of power semiconductors have defined  $V_0$  and  $r_T$  in different ways. Here are 4 variations:

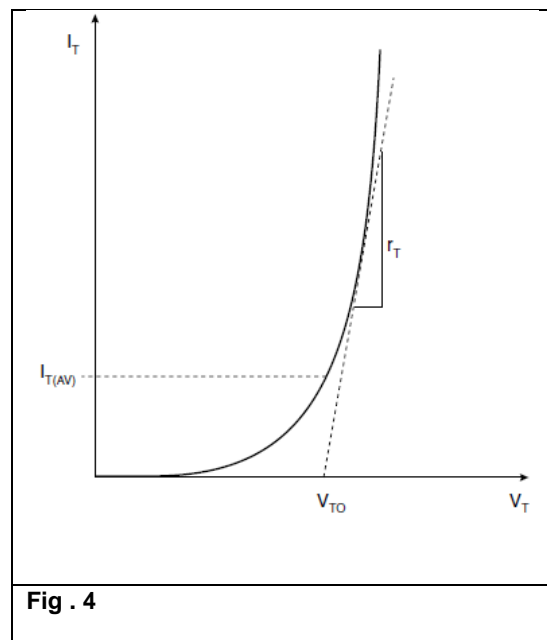
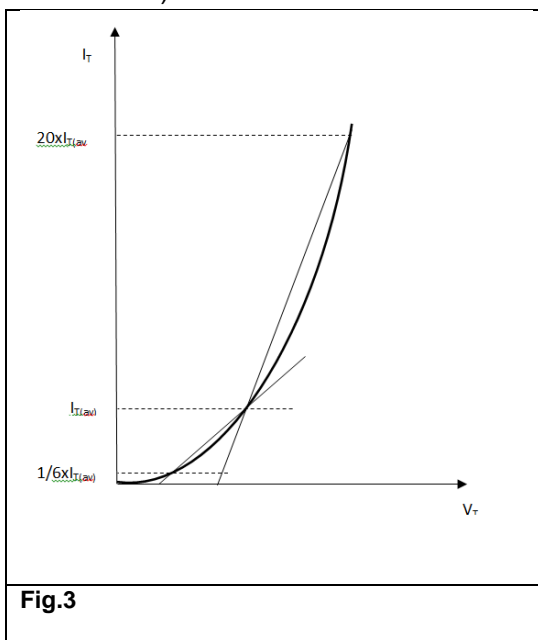
- 1) As fig1, where the line is a tangent to the  $V_{TM}$  vs  $I_T$  curve at the average current rating.
- 2) As fig 2, where a chord is drawn through  $I_{T(AV)}$  and  $3I_{T(AV)}$ . For rectifier diodes a chord through  $3I_{T(AV)}$  and  $5I_{T(AV)}$  sometimes gives a better result.



Similarly, if the thermal resistance junction to heat-sink is used then the corresponding de-rate curve of junction temperature against heat-sink temperature is calculated.

A more rigorous derivation can be performed numerically using the ABCD coefficients to define the forward voltage drop curve:  $V_{TM}=A+B \times \ln I_T + C \times I_T + D \times \sqrt{I_T}$ . See Application Note AN5001 “Use Of The VTO, rT On-state Characteristic Model”

- 3) A variant of 2 which uses two straight lines instead of one to approximate to the true curve. In this version the lines pass through  $1/6 \cdot I_{T(AV)}$  and  $20 \cdot I_{T(AV)}$  and also  $I_{T(AV)}$  and  $20 \cdot I_{T(AV)}$
- 4) As fig 3, A tangential point constructed such that the value of  $I_{T(AV)}$  calculated from:  $I_{T(AV)} = (-V_{TO} \pm \sqrt{V_{TO}^2 + 4 \cdot k^2 \cdot r_T \cdot P}) / 2 \cdot k^2 \cdot r_T$  [3] is the same as that calculated by more exacting methods. This method is a variation of method 1).



**Limitations of the  $V_{T0}$ ,  $r_T$  model**

Using any one of the four definitions gives the correct losses at one or at most two points on the  $V_{TM}$  vs  $I_T$  curve. It can be seen that depending on where a point is taken on the curve the answer will be optimistic or pessimistic. Definitions 1, 2 1nd 4 give adequate accuracy up to 3 x  $I_{T(AV)}$ .

For improved accuracy a mathematical model is needed which is a better fit to the true curve.

**A Four Coefficient Model**

The GE four term curve-fit equation given above in equation 2 has been shown to be a good isothermal approximation and is being increasingly adopted by manufacturers of power semiconductors for inclusion in their datasheets. A word of warning here, not all manufacturers quote the formula with the coefficients in the same order, for instance GE, Dynex, Powerex and Westcode all use  $V_{TM} = A + B \cdot \ln(I) + C \cdot I + D \cdot \sqrt{I}$  whilst ABB use  $A + B \cdot I + C \cdot \sqrt{I} + D \cdot \ln(I+1)$  and Infineon uses  $A + B \cdot I + C \cdot \ln(I+1) + D \cdot \sqrt{I}$  so great care must be used if using a spread-sheet to compare the forward voltage characteristics of devices from different manufacturers.

For the user the one problem with the equation

$$V_{TM} = A + B \cdot \ln(I) + C \cdot I + D \cdot \sqrt{I} \quad [2]$$

is that, when multiplied by the equation for current, it is not easy to integrate to give the power loss. However the equation is easily solvable by numerical integration. The following equation for **half sine waves** used the ABCD coefficients used in equation 2, their values depending upon the device being considered.

$$P = [A \cdot (I/E) + B \cdot (I/E) \cdot \ln(I/E) \cdot F + B \cdot (I/E) \cdot G + C \cdot (I/E)^2 \cdot H + D \cdot (I/E)^{3/2} \cdot J] \quad [4]$$

Where **I is the peak value of the half sine wave of current** . The values E,F,G,H, and J depend on the conduction angle and are given in table 1.

For Rectangular waves,  $P = [ A + B \cdot \ln(I \cdot 360 / \alpha) + C \cdot (I \cdot 360 / \alpha) + D \cdot \sqrt{I \cdot 360 / \alpha}] \cdot I$  [5]

Where **I is the average current** (not the peak current) and  $\alpha$  is the conduction angle in degrees.

Dynex Semiconductor has calculated the values of A,B,C & D and these are given in the datasheets for High Voltage Phase Control Thyristors and Rectifier Diodes.

Conduction Angle (degrees)	E	F	G	H	J
180	1	0.31830986	- 0.0976260	0.25	0.27820862
120	1	0.23752350	- 0.0522407	0.02000795	0.21579720
90	0.75	0.15776190	- 0.0488128	0.12361100	0.13771530
60	0.45	0.08077821	- 0.0453849	0.04992036	0.06241130
30	0.25	0.02062772	- 0.0245605	0.00686488	0.01166912
15	0.067	0.00506346	- 0.0095093	0.00084797	0.00203133

Table 1

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