RCA
Solid State
Division

Power Transistors Application Note

AN-4612

Thermal-Cycling Rating System for Silicon Power Transistors

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Thermal fatigue is a wear-out type of failure that may occur in silicon power transistors as a result of the thermal cycling produced by changes in power dissipation or in the ambient temperature. When a transistor is alternately heated and allowed to cool, cyclic mechanical stresses are produced within the device because of differences in the thermal expansion of the silicon pellet and the metallic materials to which the pellet is attached. In the past, the effect of such stresses has been almost completely ignored in the design of power-transistor circuits. The circuit designer should realize, however, that, just as a wire that is continuously flexed at one point will eventually break because of metal fatigue, cyclic thermal stresses can similarly lead to fatigue failures in power transistors.

This Note briefly analyzes the basic causes of thermal fatigue in silicon power transistors and describes a rating chart that makes it possible for a circuit designer to avoid such failures during the operating life of his equipment. Examples are provided on the use of this chart to determine the transistor operating conditions required to assure a desired thermal-cycling capability and to determine whether the thermal-cycling capability of a transistor is adequate for the requirements of a given application.

Analysis of Thermal Fatigue in Silicon Power Transistors

Power transistors are subjected to some thermal stresses in all practical circuits in which they may be employed. In many common applications, these stresses are very severe, as indicated by the examples of the thermal-cycling requirements of several typical applications listed in Table I. The cyclic stresses may eventually result in physical damage to the semiconductor pellet or the mounting interface.

In most silicon power transistors, the small silicon pellet is bonded to a copper header. The coefficient of thermal expansion for silicon (3×10^{-6}) is much less than that of copper (17.5×10^{-6}). Temperature variations within the transistor, therefore, result in cyclic stresses at the mounting interface of the silicon pellet and the copper header because of the difference in the thermal expansions of these parts. If a hard solder, such as silicon gold, is used to bond the pellet to the header, these stresses are transmitted to the silicon pellet. Silicon is relatively weak in tensile strength and is highly "notch sensitive." Such stresses therefore, often result in pellet fractures. In general, however, lead solder is used to bond the silicon pellet to the copper header. The cyclic thermal stresses then are absorbed by non-elastic deformation of the soft lead solder, and very little stress is transmitted to the pellet.

The continuous flexing that results from cyclic temperature changes in the transistor may eventually cause fatigue failures in the lead solder. Such failures are a function of the amount of change in temperature at the mounting interface, the difference in the thermal-expansion coefficients of the silicon pellet and the material to which the pellet is attached, and the maximum dimensions of the mounting interface.[1] Fatigue failures occur whenever the cyclic stresses damage the solder to the point at which the transfer of heat between the pellet and the surface to which it is mounted becomes impaired. This condition may exist in only a small portion of the pellet. This portion, however, overheats, and transistor failure results because of conditions that very closely approximate those encountered during second breakdown.[2]

Thermal-fatigue failures in power transistors are accelerated because of dislocation "pile-ups" that result from impurities in the lead solder.[3] RCA has developed a process that substantially reduces the amount of impurities introduced into the solder. Use of this proprietary "controlled solder process" (CSP) makes it possible to avoid the microcracks that propagate to cause fatigue failure in power transistors and, therefore, greatly increases the thermal-cycling capability of these devices.[4]

Thermal-Cycling Rating Chart

The mathematical relationship among the factors that affect fatigue failure in silicon power transistors can be expressed, in terms of the number of thermal cycles to failure N, as follows:[1]

$$N = Ae^{\psi_o / [\Delta T(a_A - a_B) L]}$$

Table I - Thermal-Cycling Requirements for Typical Applications of Power Transistors

Application	Circuit	P_T (W)	ΔT_C (°C)	Minimum Equipment Life Required (years)	Typical Thermal-Cycling Rating Required (cycles)
Auto radio audio output	Class A	8	75	5	5,000
	Class AB	2	45	5	5,000
Power supply	Series regulator	50	65	5	5,000
	Switching regulator	15	65	5	5,000
Hi-Fi audio amplifier	Class AB	35	50	5	5,000
Computer power supply	Series regulator	50	65	10	10,000
Computer peripheral equip.	Solenoid driver	5	5	10	1.3×10^8
Television	Vertical output	10	75	5	5,000
	Audio output	8	75	5	5,000
Sonar modulator	Linear amplifier	100	55	10	144×10^3

where A is a constant determined by the mounting system, ΔT is the change in temperature at the mounting interface, a_A and a_B are the thermal-expansion coefficients of the silicon and the metal under the solder joint, ψ_o is a material constant proportional to the change in temperature ΔT and the difference in the thermal-expansion coefficients a_A and a_B, and L is the maximum length of the solder joint under the pellet.

For a given transistor, the only variable in the thermal-cycling equation that can be controlled by the circuit designer is the change in temperature at the interface of the silicon pellet and the material to which the pellet is mounted. This change in temperature ΔT is, of course, less than the change in transistor junction temperature ΔT_J, but is greater than the change in case temperature ΔT_C.

RCA has devised a rating chart that relates the thermal-cycling capability of a silicon power transistor to total device dissipation and the change in case temperature. This chart is presented in the form of a log-log presentation in which power dissipation is shown on the vertical axis and the number of thermal cycles is shown on the horizontal axis. Rating curves are shown for various magnitudes of case-temperature swings. Fig. 1 shows an example of a typical rating chart of this type.

A circuit designer may use the rating chart to define the limiting value to which the change in case temperature must be restricted to assure that a power transistor is capable of operation at a specified power dissipation over the number of thermal cycles required in a given application. Conversely, if the power dissipation and the change in case temperature are known, the designer may use the rating chart to determine whether the thermal-cycling capability of the transistor is adequate for the application. These uses of the rating chart are illustrated by examples on the chart shown in Fig. 1.

The chart shows the thermal-cycling ratings for an experimental silicon power transistor that has a thermal

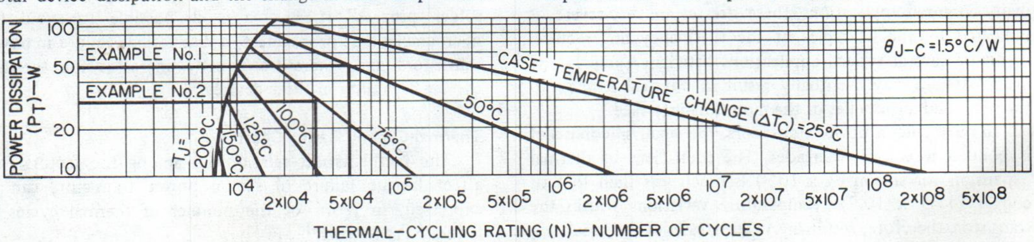

Fig. 1— Thermal cycling rating chart

resistance from junction to case of 1.5°C per watt. If a designer wishes to determine the maximum allowable change in the case temperature of this transistor for the thermal-cycling requirements of a given application, he simply plots the point of intersection of a horizontal projection of the total device dissipation with a vertical projection of the total number of thermal cycles required in the application. If this point lies exactly on one of the power-dissipation curves, the maximum allowable change in case temperature can be read directly from the chart; if not, the allowable temperature change can be approximated by linear interpolation. This use of the rating chart is illustrated by example No. 1 in Fig. 1.

For this example, it is assumed that the transistor is to be operated intermittently at a power dissipation level of 50 watts and that a thermal-cycling capability of 5.0×10^4 cycles is required to assure that the life of the transistor exceeds that of the equipment in which it is to be used. The point of intersection of line projections of the power dissipation and the required number of thermal cycles indicates that the change in case temperature must be restricted to a maximum value of 50°C per thermal cycle. This value determines the requirements of the transistor heat sink. If the thermal cycles are long in comparison to the thermal time constant of the heat sink, the total thermal resistance from case to ambient should not exceed 1°C per watt. If the thermal cycles are short relative to the thermal time constant, a higher thermal resistance is permissible provided that the thermal capacitance of the heat sink is sufficient to assure that the change in case temperature does not exceed 50°C during the thermal cycle.

Example No. 2 in Fig. 1 illustrates the use of the rating chart to determine whether the thermal-cycling capability of a transistor is adequate for a given application. In this example, a transistor dissipation of 30 watts and a case-temperature swing (measured) of 75°C are assumed. A vertical projection of the 30-watt point on the $\Delta T_C = 75°C$ power-dissipation curve indicates that, for these operating conditions, the transistor has a thermal-cycling rating of 3.2×10^4 cycles. If this rating is not adequate for the intended application, either the power dissipation must be reduced or a larger heat sink must be used so that a smaller change in case temperature will result during a thermal cycle.

In many applications, a power transistor may be subjected to thermal cycles that differ in both duration and magnitude. In such instances, the fractional amount of the thermal-cycling life of the transistor used by the total number of thermal cycles of each type during the required life of the equipment must be separately determined and then added together to ascertain whether the thermal-cycling rating of the transistor will be exceeded in the application. The ratio of the total number of cycles of each type to which the transistor will be subjected during the life of the equipment to the total number of cycles of the same type that the transistor is rated to withstand before fatigue failure is obtained for all the dissimilar thermal cycles. If the sum of these ratios is less than unity, the transistor is obviously operated within ratings in the application. If the sum is greater than unity, the thermal-cycling rating of the transistor is exceeded in the application, and device failure may occur during the operating life of the equipment.

The technique used to determine whether the thermal-cycling ratings of a transistor are exceeded in a specific application in which the transistor is subjected to different types of thermal cycles can be illustrated by use of the examples of different operating conditions shown in Fig. 1. If the transistor is assumed to be subjected to the conditions specified for examplele No. 1 for 2.5×10^4 thermal cycles and to the conditions specified for example No. 2 for 1.6×10^4 thermal cycles, the following summation is made to determine whether the transistor will be operated within its thermal-cycling ratings:

$$\frac{2.5 \times 10^4}{5.0 \times 10^4} + \frac{1.6 \times 10^4}{3.2 \times 10^4} = 1$$

This summation indicates that, for the conditions assumed, the transistor is operated exactly to the limit of its thermal-cycling rating.

The RCA thermal-cycling ratings allow a circuit designer to use silicon power transistors with assurance that no fatigue failures of these devices will occur during the operating life of his equipment. These ratings provide valid indications of the thermal-cycling capability of silicon power transistors for all types of operating conditions and, therefore, enable the circuit designer to "design out" the possibility of transistor thermal-fatigue failures.

Obviously, all power transistors cannot be tested to determine their thermal-cycling capability because such tests are expensive, time consuming, and destructive. The validity of the thermal-cycling ratings results from the application of stringent process controls at each step in the manufacture of the transistors and from the testings of a statistically significant number of samples. Thermal-cycling ratings for silicon power transistors provide the same type of assurance that a device will not fail when operated within ratings as that provided by the more familiar voltage, current, and second-breakdown ratings.

Bibliography

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