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Dynamic Thermal Response and Voltage Feedback in Junction Transistors

The transient thermal response of transistor junctions has been described by Mortenson[1] and Strickland[2] using mathematical and physical models characterized by a number of thermal time constants. Sparkes[3] pointed out the dependence of the electrical voltage feedback upon the thermal resistance of transistors, giving a relationship between thermal and electrical parameters of the devices. In a more recent paper Mueller[4] has developed the relationships describing the effect of thermal feedback on the electrical parameters of four poles in general.

This note develops parameters for characterizing the thermal response of transistor junctions starting from the fundamental thermal feedback relationship of Sparkes and Mueller. Junction response prediction is accomplished with more manageable models and measurements than previously. The thermal-electrical relationships are identified in more detail through the frequency range for voltage feedback in transistors.

Thermal impedance θ

The rate of change of the junction region temperature to power is the thermal impedance of the transistor:

$$\theta = \left.\frac{\partial T}{\partial p}\right|_{T_{\mathrm{ref}}}. \tag{1}$$

The quantity T is the junction region temperature, p is the junction power dissipation, and T_{ref} indicates the constancy of the temperature at some point along the path of heat dissipation from the junction.

An experimentally determined frequency response function of θ provides the basis for a generally useful characterization of the dynamic thermal properties of a device. The thermal impedance θ can be shown to be directly related to observed values of familiar small-signal device parameters. Employing exact or approximate transform techniques, it forms a convenient basis for predicting the time-transient behavior of the devices. An approximation is shown later that allows the prediction of the maximum junction temperature response to a power pulse of duration δ when the sinusoidal temperature response to power is known only at a frequency $1/2\delta$.

The dynamic thermal response of devices may be measured by controlled observation of the frequency or time-transient response of several temperature-sensitive electrical parameters. In either case it will be necessary to analyze the other low- and high-frequency contributions to change of the sampled parameter in order to accurately isolate the thermal effect, particularly as to its high-frequency limit. The writer has found the measurements to be most clearly controlled and interpreted when the low-frequency response of the reverse voltage feedback h_{rb} is employed as the device parameter sensitive to temperature.

Relation to feedback effect

The thermal impedance θ may be shown in transistors to be directly related to the observed small-signal, common base, reverse voltage feedback h_{rb}. Sparkes[3] showed that for low frequencies in most transistors thermal effects dominated the observed h_{rb}. He identified the relative importance of the "Early" base-widening effect[5] and the thermal contribution, writing the latter

$$h_{rb}(\mathrm{thermal}) = \left.\frac{\partial v_{eb}}{\partial T}\cdot\frac{\partial T}{\partial p}\cdot\frac{\partial p}{\partial v_{cb}}\right|_{I_E}. \tag{2}$$

The thermal coefficient $\partial v_{eb}/\partial T$ is independent of collector voltage within the linear range of operation and is termed K_v. Sparkes showed that $\partial p/\partial v \cong I_C$ and that in thermal equilibrium $\partial T/\partial p$ was the thermal resistance (termed θ by Sparkes) here labeled R_T.

However, $\partial T/\partial p$ may be more generally regarded as the frequency-dependent thermal impedance θ. The frequency dependence of $\partial v_{eb}/\partial T$ will be of the order of minority carrier generation and transport times, considerably shorter than thermal transition times. Thus, the thermal part of h_{rb} may be written throughout the frequency variation of θ:

$$h_{rb}(\mathrm{thermal}) = K_v I_C \theta. \tag{3}$$

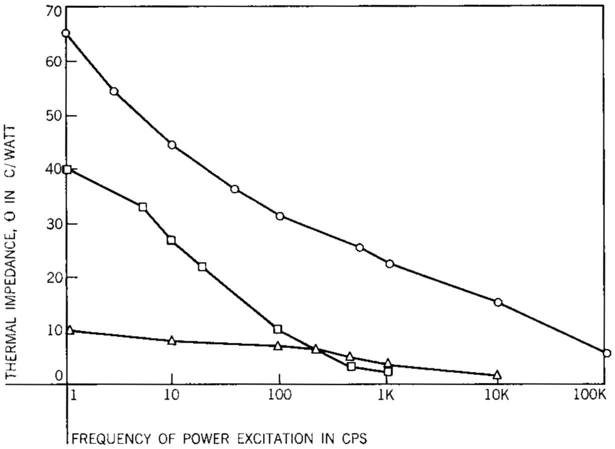

Figure 1 Thermal impedance vs. frequency.
○ Silicon planar logic transistor 20 mil square chip on T0-18 header, $I_E = 50$ mA.
□ Silicon medium power diffused transistor 30 mil. square chip on insulating substrate. $I_E = 500$ mA.
△ Germanium medium power alloy diffused transistor on copper header. $I_E = 500$ mA.

The "Early" base widening effect also depends upon mechanisms of considerably faster response than thermal effects and will be constant throughout the frequency variation of θ. This component of the h_{rb} may be written in terms of small-signal equivalent circuit parameters for the base resistance r_b and collector conductance g_c: $h_{rbE} = r_b g_c$.

Another feedback effect due to collector capacitance C_c becomes important at frequencies where

$$\omega C_c \cong g_c.$$

$$h_{rb}(\text{capacitive}) = \omega C_c r_b, \qquad \omega C_c \ll 1/r_b.$$

This capacitive feedback contributes an h_{rb} component of phase $+\pi/2$ increasing in magnitude linearly with frequency in the range shown.

The three effects combine in complex addition such that the observed h_{rb} behaves as θ at low frequencies, exhibits a minimum at medium frequencies, and increases linearly at moderately high frequencies. The phase lags at low frequencies and approaches $+\pi/2$ at higher frequencies. Roughly, the minimum magnitude of the observed h_{rb} is equal to the "Early" component.

The frequency at which the capacitive h_{rb} component becomes significant is greater than the cutoff of the thermal impedance for most transistors. Thus, it is usually possible to find a medium range of frequencies for which the observed h_{rb} is minimum or constant and equal to the "Early" effect. Zero phase in the minimum insures this. Nonzero phase requires measurement of the magnitude of h_{rb} in the capacitive frequency range such that its effect may be extrapolated back to the minimum region to isolate the "Early" component.

Once the "Early" component is known, its value may be subtracted from the total h_{rb} in the low-frequency range isolating h_{rb} (thermal). This approach is the only way the writer believes that any conclusions may be made concerning the speed limit of junction thermal response. Similarly, this type of analysis is necessary to accurately isolate the true "Early" effect or the truly electrical value of any temperature-sensitive transistor parameter.

All small-signal h parameter measurements should be made at the frequency at which h_{rb} is minimum when seeking true low-frequency electrical values.

Experimental characteristics

Figure 1 presents the experimental characteristic of θ for several types of transistors. At sufficiently low frequencies θ approaches, as a low-frequency limit, the equilibrium dc thermal resistance of the device. At sufficiently high frequencies θ vanishes because of the ability of the thermal capacitance of the junction region to store the relatively small energy of a high-frequency pulse with negligible temperature rise. With increasing frequencies, the temperature response lags the power excitation. Hence, θ is a complex quantity characterized by magnitude and phase, even at low audio frequencies. An empirical characteristic is preferable over attempts to determine analytic frequency functions because of the thermal complexity and variability of most device geometries.

The significant thermal response of small diffused collector devices extends from a fraction of one cycle to hundreds of kilocycles, while that of large power transistors extends only to several hundred cycles.

Method for predicting device junction temperature

For purposes of applying the thermal response information contained in the frequency response of θ to prediction of device junction temperature in power switching applications, exact or approximate transform techniques can be used.

In general the junction temperature time response to a power excitation having spectral distribution $P(\omega)$ by the inverse Fourier transform

$$T(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} T(\omega)e^{-i\omega t}\,d\omega, \text{ where } T(\omega) = P(\omega)\theta(\omega).$$

However, for rectangular waves and pulses a useful approximation has been found from the Fourier series expansion of the time response of the junction temperature to a rectangular power excitation.[6] The thermal impedance θ varies slowly with frequency in many transistor structures. The harmonic series expression of periodic waves typical of transistor power excitation converges in a band of frequencies over which assumption of bounds on θ will not make a large error.

For a square wave of power of peak P_{pk} and period 2δ,

$$p(t) = P_{av} + \frac{4}{\pi} P_{pk} \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{2n-1} \cos \frac{2\pi(2n-1)t}{2\delta}.$$

The corresponding junction temperature response is

$$T(t) = P_{av} R_T + \frac{4}{\pi} P_{pk} \sum_{n=1}^{\infty} |\theta(\omega_n)| \frac{(-1)^{n+1}}{2n-1} \times \cos\left[2\pi \frac{(2n-1)t}{2} + \phi(\omega_n)\right], \qquad (4)$$

$$\theta(\omega) = |\theta(\omega)| \angle \phi(\omega).$$

The peak of the junction temperature response will be at the end of the power peak $t = \delta/2$.

It has been found[6] that the transient part of $T(\delta/2)$ converges to a value bounded by

$$P_{pk}\theta(\omega_1)[(\pi/3) \cos \phi(\omega_1) - \sin \phi(\omega_1)]$$

$$P_{pk}\theta(\omega_1)[\cos \phi(\omega_1) - \sin \phi(\omega_1)],$$

a 5% band, if θ is bounded by $\theta(\omega_1)$ and

$$\theta(\omega) \geqq \theta(\omega_1) \frac{2(\omega/\omega_1) - 1}{(\omega/\omega_1)^2}, \quad \text{where} \quad \omega_1 = \pi/\delta.$$

Thus the peak temperature response to a square wave of power of ON time δ may be approximated to within 5% in terms of the thermal impedance $\theta(\omega_1)$ only at the frequency ω_1.

$$T_{max} = T(\delta/2) = P_{av} R_T + P_{pk}\theta(\omega_1)[(\pi/3) \cos \phi(\omega_1) - \sin \phi(\omega_1)]. \qquad (5)$$

For the bounds on θ discussed, Eq. (5) has been found to be valid to within 10% for rectangular power excitation of power ON time δ and duty between zero and 50%. This degree of approximation is useful considering the simplification and resulting increase of accuracy of testing it allows.

The response may be expressed in terms of the useful parameter transient thermal resistance r_T as defined by Gutzwiller and Sylvan:[7]

$$r_T(\delta) = \frac{T_{pk}(\delta)}{P_{pk}} = \theta(\omega_1)[(\pi/3) \cos \phi(\omega_1) - \sin \phi(\omega_1)]$$

In terms of the measured quantities previously discussed,

$$r_T(\delta) = \frac{h_{rb}(\omega_1) - h_{rbE}}{K_v I_C} [(\pi/3) \cos \phi(\omega_1) - \sin \phi(\omega_1)]. \qquad (6)$$

An r_T characteristic derived from the results of Fig. 1 is shown in Fig. 2.

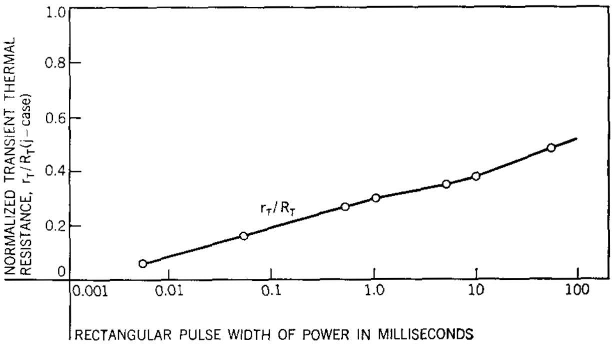

Figure 2 Transient thermal resistance.
Silicon planar logic transistor, T0-18 header. For rectangular power pulse, $0 <$ duty factor $< 50\%$.

The transient parameter may be applied in a conventional manner for prediction of maximum junction temperature

$$T_{j\,max} - T_{amb} = R_T P_{av} + r_T P_{pk}.$$

T_{amb} is the ambient temperature. R_T is the dc thermal resistance from the junction to the ambient. P_{av} is the average junction power.

In addition to junction temperature prediction θ provides a basis for description of the influence of the dynamic thermal response of device junction on the observed values of the electrical parameters as has been discussed by Mueller.[4] For example, at high levels and low frequencies, junction thermal effects can dominate the observed electrical value of h_{rb} and can alter observed values of β and h_{ib} by several percent. The modification of these electrical parameters may be expressed in terms of θ similarly as has been done for h_{rb} in Eq. (3).

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