How To Minimize Thermal Overstress Failures (Part 1)

Careful thermal design is necessary to ensure that today's highly miniaturized components operate properly.

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Miniaturization of electronic systems has led to the packaging of high-speed, high-voltage, high-current, and high-frequency systems in small enclosures. But high-speed systems operating in a small volume invariably generate a lot of heat due to the high power densities involved.

Keeping device temperatures within limits to prevent damage and failures is an important design consideration that shouldn't be ignored. The reliability of a device depends on the temperature that it reaches during operation. Because the flow of electric current through a component produces heat, a device's temperature will continue to rise as the current continues to flow. To prevent the build-up of heat, a method should exist to transfer heat from the device as it's generated to the ambient surroundings. This is usually accomplished by heatsinks, cooling fans, blowers, and other means.

The three fundamental mechanisms of heat transfer—conduction, convection, and radiation—are all equally important. Each one is at a different layer in the thermal management hierarchy and requires consideration during the thermal design of any electronic system.

Semiconductor devices form the key elements in any electronic circuit. A typical device is the bipolar junction transistor. For a good design, remember the safe-operating-area characteristics of the transistor and ensure that operating parameters never fall outside of these limits.

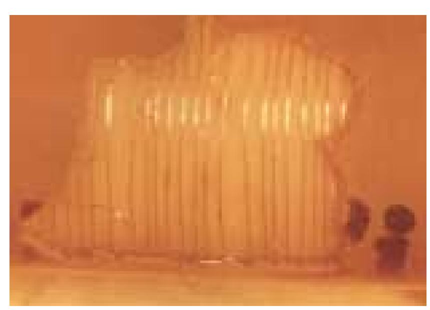
In places where the ambient temperatures could be much higher than 25°C, for which device specifications are listed in data books, the situation becomes far more critical, and the maximum power dissipation of the device should be derated appropriately. Depending on the circuit and device requirements, heatsinks should be provided to keep the devices cool in some cases.

All components are guaranteed to withstand thermal shocks encountered during normal assembly and production operations. These include hand or wave soldering for a short duration. Only the sustained application of thermal stresses beyond the specifications of the component will cause the device to malfunction or fail due to thermal mechanisms. The ability to withstand thermal stresses varies from one component to another.

Power dissipation in semiconductor devices manifests itself in the form of heat. The following mechanisms contribute to power dissipation:

Switching losses in power devices. During turn ON and turn OFF, a certain amount of power gets dissipated. This loss increases at higher frequencies. The dynamic switching of currents to charge and discharge the load capacitances contributes to power dissipation.

Forward conduction loss in the device when it's ON, occurring in diodes, transistors, MOSFETs, thyristors, etc. The power dissipation is equal to the



1. In a wire-wound resistor, overheating can cause the resistance wire to snap off, resulting in an open circuit.

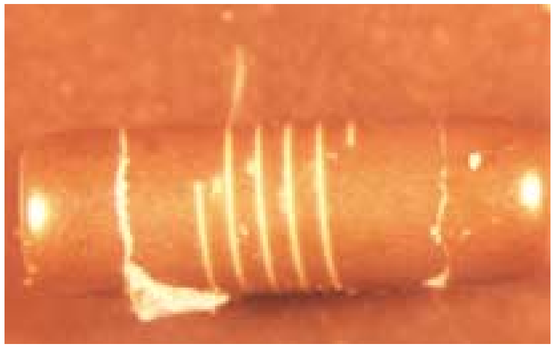
product of the voltage drop across the device and the current flowing through the device**.**

Reverse blocking loss takes place when a device is blocking voltage, like if it's reverse-biased and not conducting. This loss results from leakage current in the device in the reverse-bias condition. This power loss is less than the forward conduction loss.

Short-circuit current loss due to simultaneous conduction of complementary devices in MOSFETs, and in circuits like power supplies (complementary-symmetry, push-pull drives), from signal transition delays.

The above losses accumulate during continuous operation and lead to heat dissipation in the device. This results in a temperature rise that has to be kept within safe limits. If a device is required to operate at a higher than normal ambient temperature, the problem will become aggravated, unless efficient heat disposal mechanisms are employed.

To minimize thermal stress-induced failures, we must first understand the mechanisms involved *(see the table)*. Conversely, we can use these mechanisms as a guide to design the tests for



2. When a metal film resistor has thermal overstress damage, the resistive coating can peel off the substrate, causing the resistor to fail as an open circuit.

different types of components. The failure mechanisms of commonly used components due to thermal stresses are explained below.

Thermal fatigue: By subjecting a semiconductor device to a recurring heating and cooling cycle, like switching the device ON and OFF, stresses develop in the device, encapsulating plastic, and the metal interconnections. Over time, this cyclical differential thermal expansion and contraction between the materials used can cause cracking and fracture. Subjecting a semiconductor device to thermal shocks results in sudden temperature changes and can lead to thermal-fatigue induced failures.

Thermal runaway: A transistor is generally specified to operate up to a certain power limit at a specified temperature. At higher temperatures, the maximum power dissipation of the transistor should be derated by a certain factor multiplied by the difference between the temperature at which the device specifications are given (typically 25°C) and the actual ambient temperature under operating conditions.

In thermal runaway, the junction temperature of a transistor rises as a result of the device's intrinsic heating due to power dissipation and ambient temperature. The collector-base junction gets heated from power dissipation. This causes an increase in carrier mobility and, in turn, an increase in collector current. This leads to a further increase in the power dissipated by the device, another increase in collector current, and so forth. This multiplier effect, brought on by a positive feedback mechanism, results in a chain reaction known as thermal runaway. It will ultimately destroy the device.

Thermal overstress: The term includes factors responsible for device failure

Arrhenius Semiconductor Failure Model

According to the Arrhenius model, the failure rate of a semiconductor device is given by:

$$R = Ae^{(-E_a/kT)}$$

where,
R = failure rate,
A = empirical constant,
E_a = activation energy for the failure mechanism in eV,
k = Boltzmann's constant (8.6×10^{-5} eV/°K),
T = junction temperature of the semiconductor device in °K

Taking the logarithm of the above equation, we get

$$\ln R = [\ln A + (-E_a/k)(1/T)]$$

and differentiating the above equation with respect to T,

$$d(\ln R)/dT = (E_a/kT^2)$$

Considering small changes in temperature and failure rate, we obtain

$$\text{in } \Delta R = (E_a/kT^2)\,\Delta T$$

$$\text{or in } (R_2 - R_1) = (E_a/kT_2T_1)(T_2 - T_1)$$

where R_1 and R_2 are the failure rates at temperatures T_1 and T_2, respectively. Failure mechanisms in semiconductor devices have a typical activation energy of about 0.45 eV. Substituting $T_1 = (273 + 135)$°K and $T_2 = (273 + 160)$°K, and the value of k, we have

$$\ln(R_2/R_1) = (E_a/kT_1T_2)(T_2 - T_1)$$

$$= \{0.45/[8.6 \times 10^{-5}(273 + 135)(273 + 160)]\}[(273 + 160) - (273 + 135)]$$

i.e., $\log(R_2/R_1) = (1/2.303)\{(0.45)(25)/(8.6 \times 10^{-5})(433)(408)\}$

$= 0.3215$

i.e., $(R_2/R_1) \approx$ antilog 0.3215
$= 2.09 \approx 2$

In other words, the ratio of the failure rates is about 2. That is, the failure rate at 160°C is double that at 135°C, which confirms the Arrhenius model for temperature dependence of failure rates for semiconductor devices. Therefore, you have to keep the devices on your board cool, so that junction temperatures are within limits and failure rate can be reduced.

caused by excessive heat dissipation beyond safe operation. This may result from internal or external factors. For example, an external failure can happen if there's a flow of high current in the device from an electrical fault. The high current could produce excessive heat and damage the internal device structure, causing the failure.

Another cause of external thermal overstress is electrostatic discharge (ESD). In this scenario, electrostatic charge builds up and discharges into the device, rupturing the thin oxide layer. This dielectric breakdown leads to a burst of current that results in thermal overstress and failure.

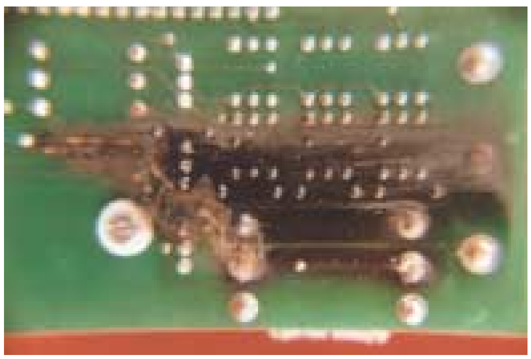
An internally caused thermal overstress failure can happen if there's a defect in the crystal structure, thereby building up an excessive amount of heat in the device. In the case of an integrated circuit, thermal overstress manifests itself as charring of the device, melting of bond wires, and in some cases, melting and carbonation of the plastic encapsulating material, which will be found stuck to the die.

Hot spots: These can be caused by defects or an improper provision for conducting the heat away from a semiconductor. Failures related to hot spots can occur not only in semiconductor devices, but also in other components, such as transformers and coils, capacitors (like tantalum), and resistors.

Semiconductor failure versus temperature: The lifetime and reliability of semiconductor devices will be better if their junction temperatures, under worst-case conditions, is kept sufficiently low. Semiconductor manufacturers generally specify the range for junction temperature during continuous operation as 125°C to 150°C. But to achieve high reliability of operation, the junction temperature should be reduced further to 100°C. Experience tells us that for every 10°C rise in junction temperature beyond 100°C, the life span of the device gets cut in half. This is based on the application of the Arrhenius model for the predicted failure of semiconductor devices. Based on this model, a reduction of junction temperature from 160°C to 135°C will reduce the failure rate by half *(see "Arrhenius Semiconductor Failure Model," p. 26)*.

Resistors: Any type of resistor—metal film, wire-wound, carbon composition, metal-oxide film, cermet, thin film, thick film—whether fixed or variable, can fail if the current flow through the resistor exceeds the rated current capacity, which causes more heat dissipation than the resistor is designed to withstand. Therefore, resistors must be carefully selected to meet the appropriate current and power ratings.

The way that power resistors are mounted on the pc board also contributes to thermal considerations. For example, designers want to be sure that there's an adequate provision for the free flow of air around such resistors.



3. Shown is the resulting discoloration of a power-supply board caused by improperly mounting rectifier diodes on the board.

This will permit a better transfer of heat away from hot resistors and while avoiding thermal failures.

The heat dissipated in a power resistor, even during normal operation, could be a cause for concern. With today's crowded pc boards, it's important to mount such resistors away from heat-sensitive components, like capacitors, inductors, and semiconductor devices, such as diodes, transistors, and integrated circuits. Also, if the ambient temperature is high, as in tropical countries, heat generation in the resistor will increase the overall temperature. This will result in a heat transfer to other components through convection, radiation, and conduction, through the resistor leads to the pc-board tracks, and then to other components through their pins or leads soldered to the pc-board traces. It then could lead to thermal mode failures in those components.

Overheated resistors can also be a fire hazard. This should be taken into account during the design stage by proper resistor selection and placement on the pc board. Wire-wound resistors generally dissipate a lot of heat because of their usage in high-power applications. Care must be taken in their board placement and cooling requirements, such as air circulation.

In the wire-wound resistor, excessive heat causes the resistance wire to melt *(Fig. 1)*. In the case of the metal film resistor, the resistive coating blisters and peels off *(Fig. 2)*.

Coils and transformers: When designing coils and transformers, the thermal calculations for the operating conditions should be taken into account. At high currents, considerable I^2R loss will occur in the coil or transformer winding, and the generated heat can affect the material properties. For instance, copper becomes brittle at high temperatures. Repeated and sustained application of hot and cold conditions will lead to fractures of the copper winding. The winding and manufacturing technique for the coil must allow for these factors and provide adequate derating for the current-carrying capacity of the winding wire.

As with other components, it's important to make provisions for the proper circulation of air to cool the coil during operation. Sometimes this may contradict the requirement for a tight winding technique used to reduce the leakage inductance of the winding. Leakage inductance is a parasitic element that can cause havoc with switching devices used in the design, such as transistors and MOSFETs. Further complicating things is the fact that it may be necessary to provide electromagnetic shielding for the transformer or coil to prevent radiated EMI (leaking magnetic flux) from affecting adjacent sensitive circuits on the board. This might impose constraints that will impact thermal considerations.

A hot transformer or coil also can induce thermal-mode failures in other components on the board, like capacitors, semiconductor devices, and so on. Designers should develop suitable compromises and optimize the design to meet different requirements.

Capacitors: The operating-temperature range of a capacitor depends on the employed dielectric type. Plastic dielectric capacitors are affected by and soften at high temperatures. Similarly, at low temperatures, the dielectric may become brittle and the capacitor might not function at all. Wet-electrolyte capacitors exposed to high temperature during operation can have electrolyte leakage and related failures. Also, heat radiation from wire-wound resistors, heatsinks, and transformers may affect capacitors. Therefore, proper placement of components on the pc board is an important factor during board-design consideration. Furthermore, the temperature range of operation specified by the capacitor manufacturer should be taken into account, and the expected temperature rise of the capacitor during operation under various ambient temperatures should be studied.

Thermal effects on pc boards: Consider a pc board containing various types of components—passive and active devices, ICs, connectors—mounted on it, and think about the heat-transfer mechanisms that could take place. Possible sources of heat generation on the populated pc board might include power transistors, high-power resistors like wire-wound types, transformers, power diodes, and power MOSFETs.

Devices such as power transistors are mounted on heatsinks to carry away the heat and prevent any abnormal rise in temperature. Heat transfer can take place from a hot device to another device on-board by any or all of the three fundamental heat-transfer mechanisms. Conductive heat transfer can occur through the leads of the power device to the pc-board traces where the leads are soldered. Next, the heat gets conducted through interconnecting traces to the leads of other components. If the component that receives this conducted heat happens to be sensitive to a temperature rise, and the temperature rise itself is quite high, then the reliability of the component might drop and the component could fail.

Excess application of heat can cause measling, delamination and discoloration of the board *(Fig. 3)*. The discoloration observed in this power-supply pc board is due to heat transferred from components mounted on the board. **a**

THERMALLY INDUCED FAILURE MECHANISMS

Component type	Failure mechanism	Type of temperature dependence
Semiconductor devices, ICs	Cracking of encapsulation	Thermal shock, high temperature, EOS induced thermal overstress
	Cracking of die	Temperature cycling
	Die-metallization corrosion	Steady-state temperature dependent
	Hillock formation	Temperature cycling
	Electromigration	High temperature and high current
	Stress-corrosion of package	Temperature dependent
	Ionic contamination	Temperature dependent above 200°C
	Delamination at chip-resin interface	Temperature cycling
	Resin cracks	Thermal shock
	Die-bond defect, package seal, wire-bond defect, thermal coefficient mismatch, and substrate defect	Temperature cycling, thermal shock
	Metallization defect, corrosion, and bulk silicon defects	High temperature storage
Resistors	Melting of wire in wire-wound type, discoloration, charring, change of resistance, and open circuit	Temperature cycling, thermal shock, high temperature during use
Inductors, transformers	Open circuit	High temperature during use, thermal shock, and temperature cycling
PC board	Discoloration, warping, delamination, and measling	Exposure to high temperature during soldering/use, thermal shock
Capacitors, common to all types	Change in capacitance, change in dielectric strength, change in insulation resistance, change in electrical characteristics, and surface cracking	Life test at elevated temperature
Electrolytic	Electrolyte vaporization, electrolyte leakage, and damage to hermetic seal	High temperature during storage/operation, thermal shock, prolonged high-temperature soldering
Ceramic	Cracking near leads and body	High soldering temperature
Plastic dielectric	Softening of dielectric	High temperature during soldering/use
Chip capacitors	Cracks in body/attachment joints	Temperature cycling
Porcelain/glass	Cracking of dielectric	Thermal shock
All electrical, electronic, and electromechanical parts (including cables and connectors)	Damage to mechanical joints, loosening of terminations, softening of insulation, opening of solder seals, and change of electrical characteristics	High soldering temperature, thermal shock

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