THERMAL
DESIGN
PART 9

Thermal characteristics of ICs gain in importance

Consideration of several factors offers ways to enhance reliability; one testing method is preferred when high accuracy is uppermost concern

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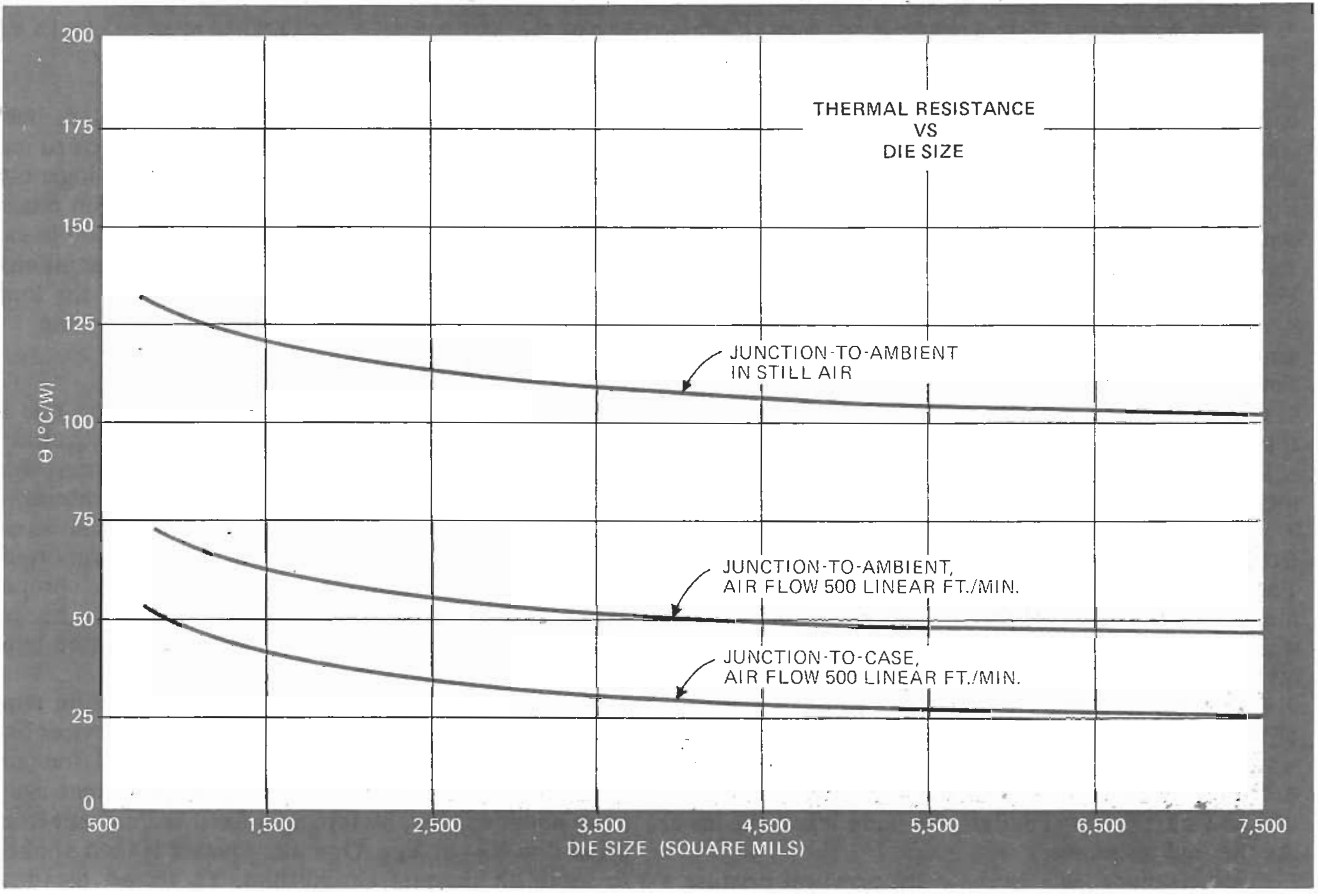
☐ All-out thermal analysis of an electronic design is usually reserved for the most sophisticated, expensive systems, and for systems that must operate in unusual environments. These days, however, as electronic packaging becomes more dense, as greater numbers of heat-producing active elements are placed on a single chip, as more ICs are mounted on a single board, designers must be increasingly concerned with the thermal aspects of systems.

Thermal resistance, therefore, is one parameter becoming more important in specifying packaging products. It is a measure of how effectively heat is dissipated from sensitive areas; the lower the figure the better. In emitter-coupled logic devices, for example, reference bias supply voltages are set internally by a diode-resistor network that is affected to a great degree by heating. If device power dissipation and package thermal resistance at operating conditions are known, the final junction temperature on the chip can be determined, making possible the correct design of the bias network.

A half-dozen factors can be considered in arriving at the thermal resistance of an IC:

- Die size. The larger the die size the more heat sinking



1. Chip size counts. The thermal resistance of an integrated circuit drops as die size increases. Data plotted here is for a 16-pin ceramic dual in-line package with gold die attach and Alloy 42 frame, at 25°C ambient or bath temperature.

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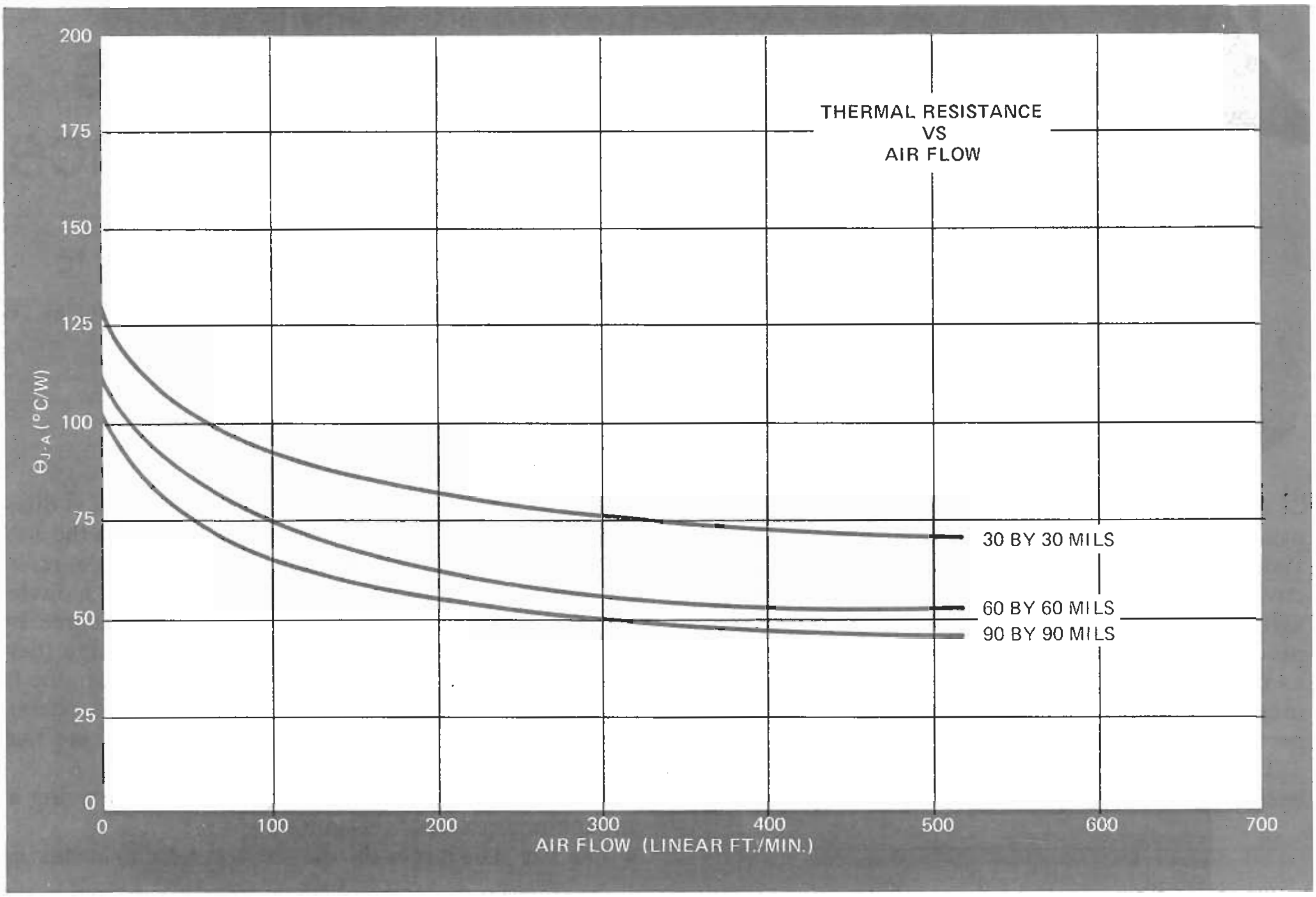


2. Air flow dependence. Thermal resistance also drops off with increasing air flow. Most noticeable when airflow is small, the effect is less pronounced when air flow becomes larger. Θ_{J-A} is plotted for three die sizes with power dissipation of 215 mW and an ambient of 25°C.

is provided for the junctions and the larger the area of contact for heat transfer. A number of thermal resistance measurements may be made on a package; in Fig. 1, these are junction-to-ambient without air flow, junction-to-ambient with air flow, and junction-to-case. As the graph shows, the increase in thermal resistance becomes more pronounced as the die gets smaller.

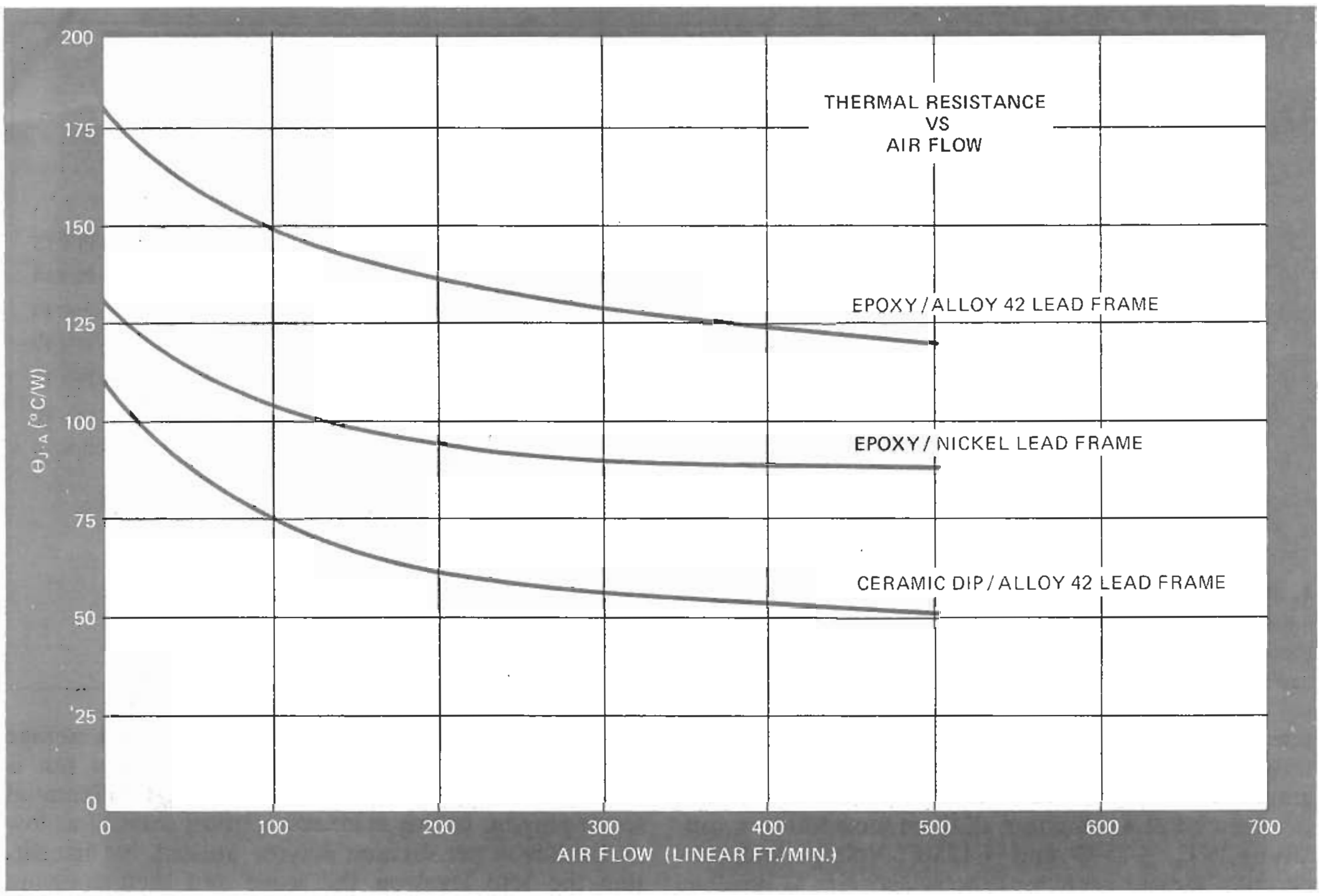
- Air flow. Even slight air flow can cause thermal resistance to fall off sharply (Fig. 2). Falloff continues as air flow increases, but not as sharply.
- Die attach method. Gold is a better conductor of heat than glass, so the gold eutectic die attach method yields a lower thermal resistance than does the glass attach method.
- Package material. In order of thermal resistance, from lowest to highest, are ceramic, epoxy and plastic. The superiority of ceramic over epoxy, moreover, is much greater than the superiority of epoxy over plastic.
- Lead frame material. As an example, nickel affords lower thermal resistance than alloy 42. As shown in Fig. 3, a nickel lead frame decreases the thermal resistance of the epoxy package from 120°C per watt to 88°C per watt when the air flow is 500 linear feet per minute.
- Number of leads bonded to frame. Since each lead acts as a heat sinking conduit, the more leads, the lower the thermal resistance.

Considerations such as these are practical because a device designer must see to it that maximum junction temperatures will not be exceeded at anticipated ambient temperatures. Testing becomes a problem here because limits on junction temperature are specified under "soak" conditions; in an emitter-coupled logic circuit, for example, thermal equilibrium has been established and transverse airflow of greater than 500 linear feet per minute is maintained. Under these conditions, production testing is not practical because of the long time it takes the device to reach thermal equilibrium.

More practical method

A more practical method on the production line is called "rapid" testing. Devices are checked quickly, without bringing them up to thermal equilibrium. But to prevent failures at untested higher temperatures, a correlation between soak and rapid testing must be established. Thermal time constants become important because the manufacturer can provide the proper guardbands if he knows, first, the changes to be expected in parameter values per degree of junction temperature, and, second, the equipment test time.

The device manufacturer can monitor junction temperatures by using actual on-chip functional devices like isolation diodes or clamp diodes. The initial forward voltage of the diode must be measured, *without operating power applied*, by forcing a fixed test current from ground to V_{CC} or V_{EE}. Operating power is then applied to establish thermal equilibrium. To record the final value of the diode voltage, operating power must then be removed and the fixed current applied once more.



3. Package effects. Thermal designers must consider that different packages and lead frames have different thermal resistances even for the same die. Data here applies to a 60-by-60-mil chip dissipating 215 milliwatts. Ambient temperature is 25°C.

Calculation of thermal resistance (Θ), with this method is as follows:

$$T_J\ rise = V_{FF} - V_{FI} / slope$$
$$\Theta = T_J\ rise / PD$$

Where V_{FI} is the initial forward diode voltage at zero power, V_{FF} is the final forward diode voltage after thermal equilibrium (in volts), T_J is the junction temperature, PD is the power dissipation (in watts), and slope is the change in voltage due to change in temperature (in millivolts per °C).

Time span critical

The time span between the point when the power is turned off and the point when a final diode voltage is measured is critical. Switching from power on to power off and making a final measurement cannot be done fast enough to measure the true thermal equilibrium voltage. By measuring a lower value, the thermal resistance always appears smaller than it actually is.

The same problem is encountered with the clamp diode method and with techniques involving measurement of output voltage. In addition, clamp diodes and outputs may be so situated that they won't respond to the actual rise in junction temperature because of temperature gradients across the chip.

The most accurate method for measuring thermal resistance involves a set of test dies, an example of which is shown schematically in Fig. 4. Here, four series-parallel diodes are placed strategically around three 300-ohm resistors on a monolithic chip. The diodes and resistors are isolated from each other by individual back-biased diodes not shown in the schematic. The design permits a fixed diode current to flow continuously even though power is being applied to the resistors. This method eliminates the need to switch off power and switch on diode current, allowing an accurate measurment of V_{FF} at thermal equilibrium.

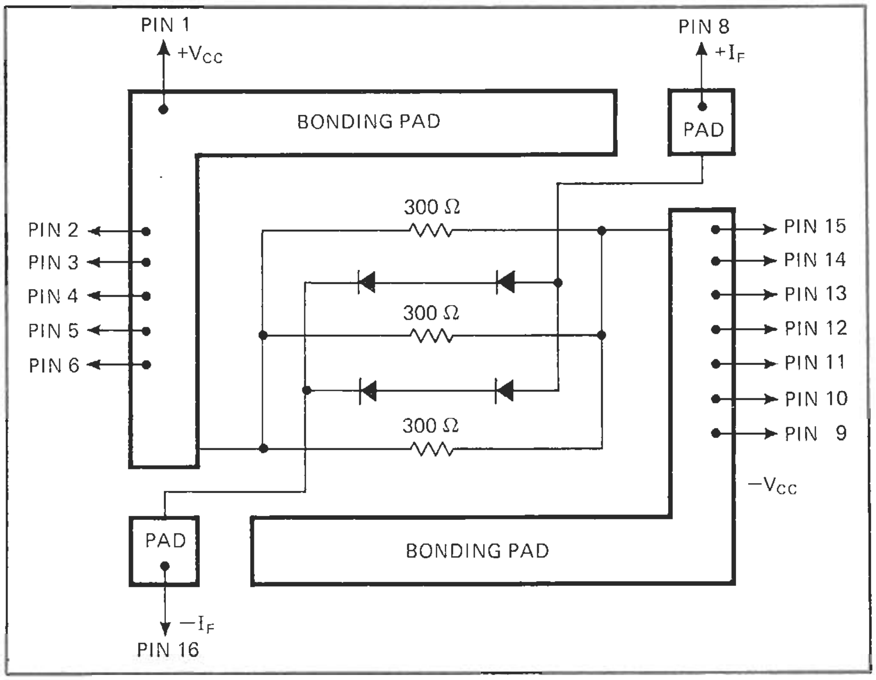
Fixed die sizes are used, starting with 30 by 30 mils and increasing by 30-mil increments up to the largest die size, 180 by 180 mils. Reverse breakdown voltages of the back-biased diodes allow up to 10 volts to be applied, which gives a maximum power of one watt.

The characterization of a package normally uses three die sizes, yielding three points on graph showing thermal resistance versus die size (Fig. 1). From this graph, the thermal resistance of any functional device may be found by knowing that device's die size.

Slope measured first

Forced diode current is normally between 3 and 5 milliamperes. A large diode current is used so that diode voltage measurements may be made on the essentially linear portion of the diode forward characteristic. This reduces the effect of increasing forward leakage of the diode due to rising junction temperature, which may affect the calibrated slope.

The slope characteristic is measured first to determine



4. Thermal test die. When making thermal measurements, a special die, like the one shown schematically here, can yield more useful data than a functioning chip.

the $\Delta V/\Delta T$ of the diodes. With two diodes in series the forward voltage drop is approximately 1.5V with an average slope of 3.6 millivolts per °C. The forward voltage is measured at a minimum of three temperatures, usually +25°C, +75°C, and +125°C. Voltage and temperature measurments must be as accurate as possible. A 5-digit voltmeter should be used and the temperature held to ±1°C. A 5% error in slope measurement will be reflected as a 5% error in thermal resistance.

In preparation for making a set of thermal resistance measurements, a device is mounted on a pc board via socket pins which accept the device leads. These pins, and a rectangular hole in the pc board directly beneath the device, allow air or oil to flow freely around the device, a requirement for some of the tests that may be performed later.

To measure thermal resistance from junction to case at zero airflow, the pc board and device under test are mounted in an enclosure with holes drilled along the bottom edges. The enclosure prevents any air from flowing around the device.

Two fans are used

To make measurements with airflow, the device is placed in another enclosure where air can be forced across the device. Junction-to-ambient is measured first with 500 linear ft./min. air flow, then at 250 linear ft./min., then at 100 linear ft./min. Two fans separated by a partition are used, one to provide airflow across the device and the other to blow air at a downward angle, producing a wall of air in front of the device under test that prevents air flow variations across the device due to external disturbances.

To measure thermal resistance from junction-to-case, the device is immersed in an oil bath. Air is bubbled through the oil to maintain a flow of oil around the device under test. This flow holds the case temperature at the oil temperature.

Thermal time constants are measured using a storage scope. The diode voltage of the device under test is zeroed out using an external supply and differential scope plug-in. In this manner a vertical scale of as low as 1 millivolt per division may be utilized. By first setting the zero level on the scope and then applying power for a specified amount of time, the thermal time constant curve is stored. Several V_F readings are recorded after each power application. Power application time is increased each time to record from a full scale reading of 10 milliseconds to 50 seconds. The device under test is allowed to cool to the initial V_F after each power application. A stop watch is used to monitor time intervals over 50 seconds.

For all of the three measurements, a fixed method is used:

- Apply an I_F of 5mA and a V_{CC} of 1.00V; allow ample time for the device to come to thermal equilibrium. Thermal equilibrium is reached when a constant V_F can be measured.
- Record V_F, initial forward voltage.
- Record I_{CC1} at V_{CC1} = 1.00V.
- Apply increased V_{CC2} specified for amount of power required.
- Allow 15 minutes for thermal equilibrium.
- Record V_{FF}, final forward voltage.
- Record I_{CC2} at V_{CC2} specified.
- Using the previously calibrated diode slope, calculate Θ as follows:

$$V_{FF} - V_{FI} / slope = T_J \text{ rise above ambient}$$

$$T_J \text{ rise above ambient} / (V_{CC}) \times I_{CC2}) - (V_{CC1} \times I_{CC1}) = \Theta$$

For the thermal time constant measurement, V_{FF} is recorded as V_F since V_{FI} has been zeroed out.

For junction-to-ambient with air flow, V_{FI} is recorded at 500 linear ft./min. and this V_{FI} used at all lesser air flows. ☐