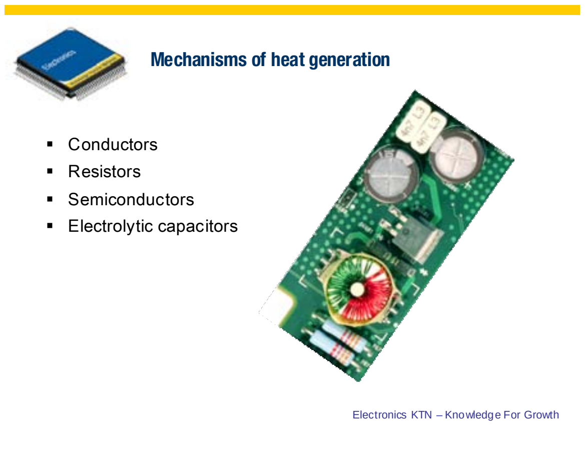
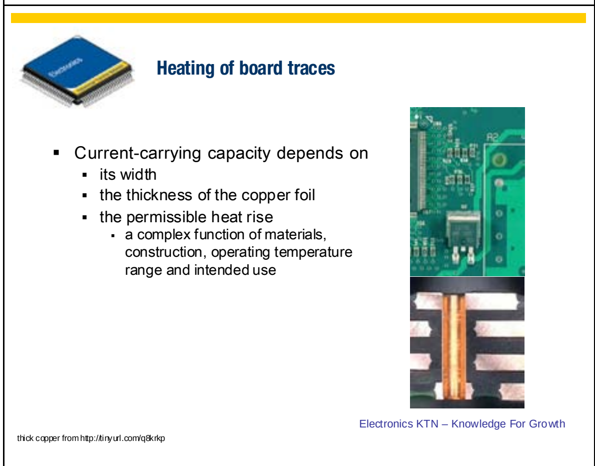
Mechanisms of heat generation



In this first section, we are reviewing how heat is generated within conductors, resistors, semiconductors and electrolytic capacitors, not because these are the only sources of heat within an electronics circuit, which they aren't, but because they are the main contributors, and the principles here can be applied to components of other types.

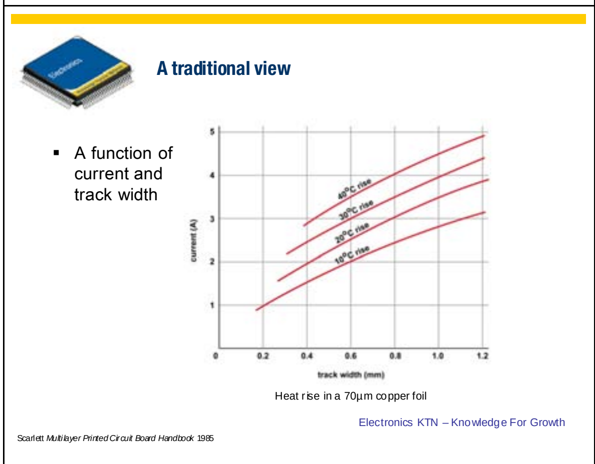
Looking first at conductors, there is of course no such thing as the perfect conductor, because there will always be ohmic heating as a result of current flow, all the way from the metallisation of the integrated circuit chip, through the connections from chip to outside, through the printed circuit board traces, through the connectors from board to system, and through the system wiring. All elements in the chain have some resistance, and all will heat up.

The extent to which this heat is significant will depend on the dimensions of the connections, the current flowing, and the quality of the connection. So we might find that a poorly-made connection gives us thermal as well as electrical problems.



The areas where we will generally have most of the problem are the board traces, and their current-carrying capacity depends on their cross-section, which is the product of the width and the thickness of the copper foil.

The limitation for current flow in any trace is the maximum permissible heat rise, which is a complex function of the materials used in the board structure and the construction of the board, and is influenced by the operating conditions of the system and its intended use – high-reliability applications will generally be more conservative in terms of the temperature increase that is allowed.



The traditional view 20 years back was that a very significant temperature rise on the trace was allowable. In this case, a 3A current through a 0.4mm track in 2oz copper is experiencing a 40°C temperature rise, so you can see it is really getting quite hot.

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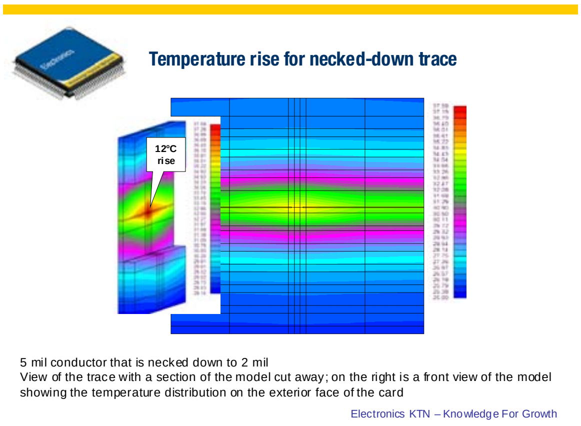
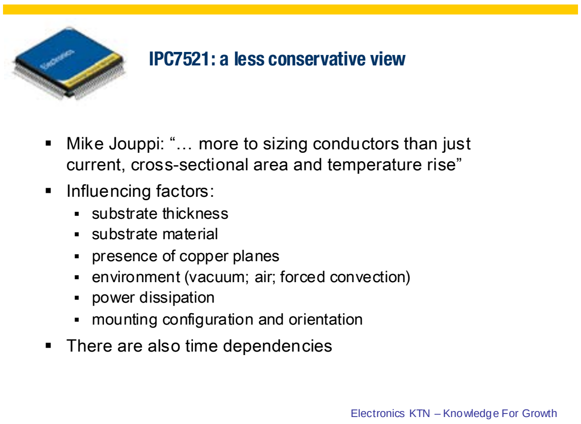


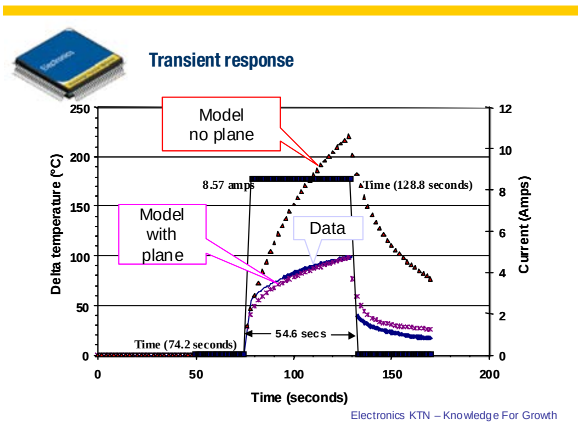
But whether tracks actually get that hot is a moot point, because there will be significant conduction away from the trace as well as some convection loss. And the results will depend on the structure of the board, and whether there are any singularities in the trace. This view is a computer simulation, which shows a general temperature rise of around 8°C, but significantly higher in the narrowed section.



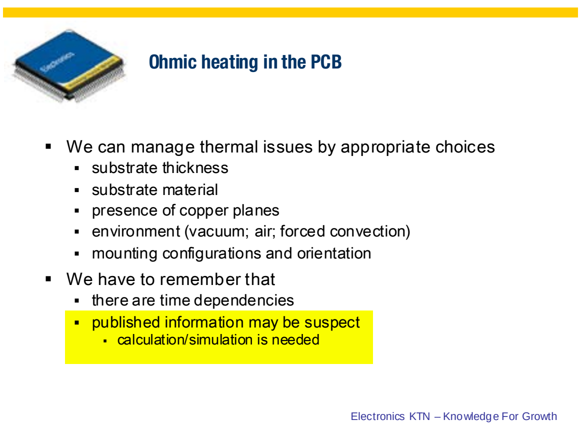
There have been moves to try and get away from the traditional view, which has its origins in some 1950s experimental work. Whilst the work on IPC7521 seems to have stalled, Mike Jouppi's comment that "there is more to sizing conductors than just current, cross-sectional area and temperature rise" is still apt.

Influencing factors are the thickness of the board and the material from which it is made, the presence of copper planes within the board, and the environment, as well as the power being dissipated. And the temperature rise will also depend on the mounting configuration, and the orientation of the track.

Finally, of course, the temperature will also depend on time, as we see in our next slide.

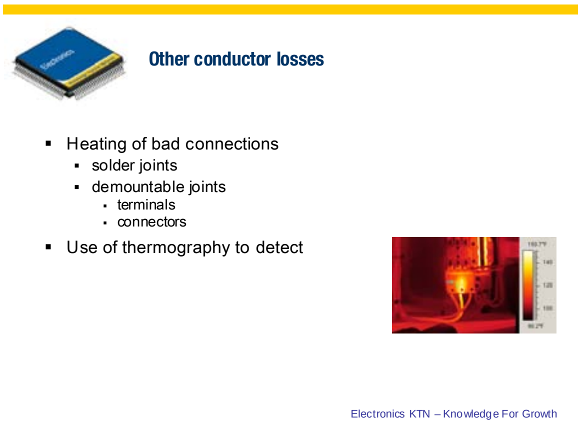


In this case, the trace was subjected to a considerable pulse of current lasting almost a minute. The diagram shows the current pulse, and the corresponding peak temperature in the model. With no copper present, the model predicts a very high temperature peak, whereas the result is much more reasonable with typical copper around. It's important to bear in mind that the traces are not random connections in thermal isolation, they are connected to other places, particularly thermally.



So we can manage thermal issues by making appropriate choices of the influencing factors we saw earlier, and we can take into account time dependencies. But we also have to remember that quite a lot of the published information on this topic goes right back to the 1950s, although the pictures have been redrawn, so calculation or simulation may well be required.

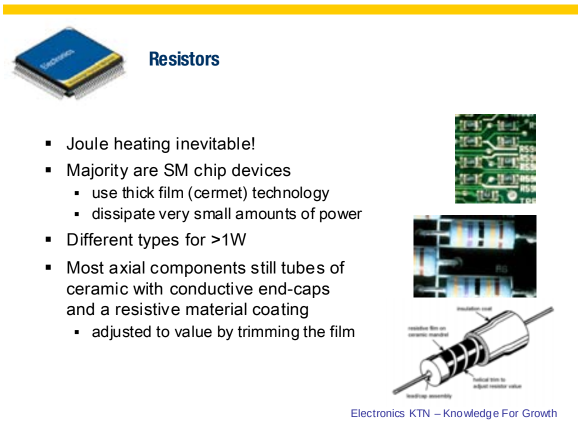
Mechanisms of heat generation



Conductor problems aren't confined to board traces – we can also find unwanted I^2R heating in other parts of the circuit where we might have anticipated low resistance values. Bad connections are a particular source of problems, both with solder joints and with the type of demountable joint found in connectors.

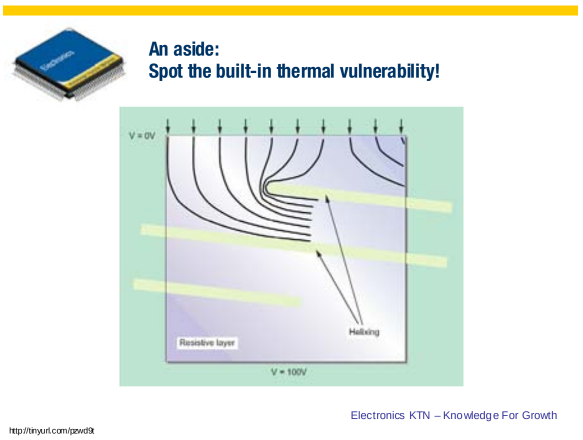
Anything that can be plugged in and out can go high resistance, and this is a type of problem which gets worse with time, both because frequently-used connections wear and lose their plating, and because over-temperature from heating can do damage. If a connector gets hot, the shroud may even become plastic, reducing the pressure on the connection, increasing the contact resistance and therefore the problem is a vicious spiral.

Whilst this is not a problem that is present by design, we have to be aware of the potential for problems, particularly with high currents, and take avoiding action by specifying appropriate components. There is also the option of using thermography to detect unwanted hot spots in equipment.

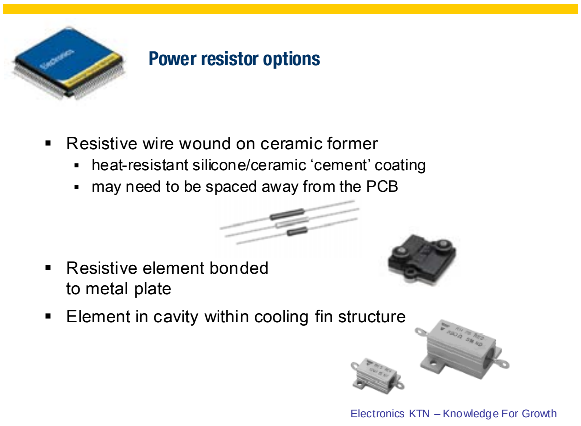


It is only under fault or high-current conditions that conductors generate significant heat, but with resistors Joule heating comes with the territory. Fortunately, in most circuits the majority of resistors are surface-mount chip devices which use a cermet technology and dissipate small amounts of power.

But others do dissipate heat, and can actually get quite hot, and we will focus on some of these. Many power resistors will be axial components, and these are typically still tubes of ceramic with conductive end caps and a coating of a resistive material which is trimmed to adjust the resistor value, using a helical cut.

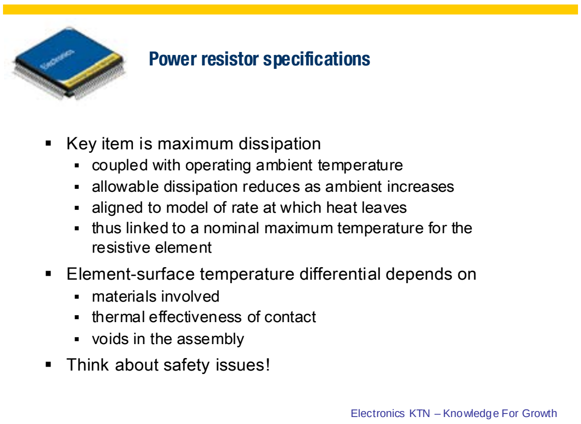


The form of cut means that there may be current crowding, and if you have current crowding then you also have hot spots. Every time you lay out a resistive material, even a low resistivity material such as copper, you have to think: Where is the current going to go? The answer, of course, is that it will take the easiest path, and this may lead to current crowding, to hot spots, and to thermal vulnerability.



Power resistors use a variety of structures, including resistive wire wound on a ceramic former and coated either with a heat-resistant silicone or ceramic cement. These components are intended to run at high temperature, so may need to be spaced away from the board.

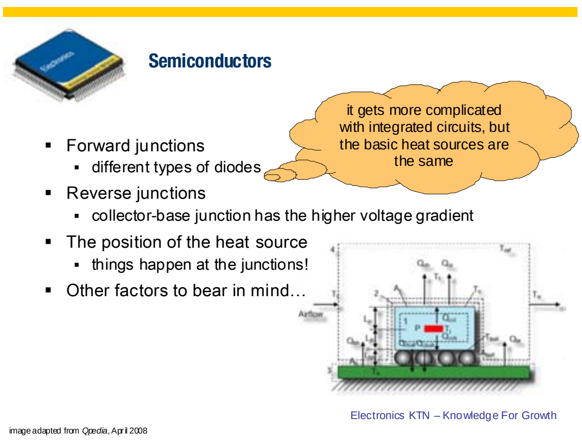
In other high-power applications, the resistive element is bonded to a metal plate, or uses a resistive element in a cavity within a cooling fin structure.



With most of these components, the limit on dissipation will be the operating ambient temperature and the maximum temperature of the resistor structure, so the allowable dissipation reduces as the ambient temperature increases. A typical specification sheet will show a de-rating linked to that maximum temperature for the resistive element, and aligned in some way to a model of the rate at which heat leaves the device.

The temperature differential between element and surface will depend on a number of factors, including the materials involved, the thermal effectiveness of the contact, and whether there are any voids in the assembly. As with other power components, unintended voids can lead to internal hotspots and to unreliability. Admittedly this is a reliability issue, rather than directly associated with thermal management, but it is worth keeping in mind.

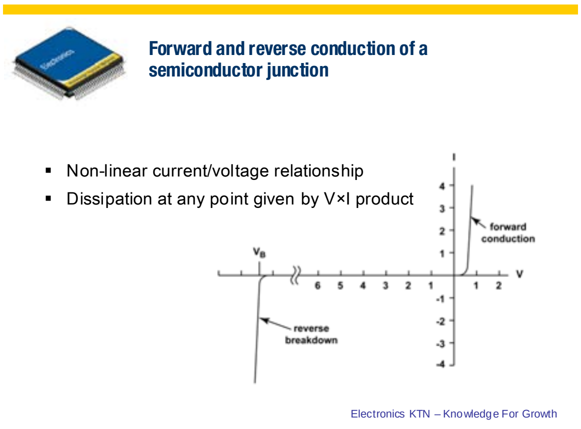
As is the fact that, in many cases, the maximum outer case temperature is well over 250°C, so you need to consider safety aspects and not just thermal issues!



The majority of circuits don't have high currents to contend with, nor do they contain power resistors. But almost every product contains semiconductors! Often these are power-hungry devices like microprocessors, but the problems start back at basics: because a semiconductor junction is not perfect, there will be losses, particularly in the forward direction, which become significant with power devices. Reverse junctions also lead to heat dissipation, the amount of heat depending both on the current and the voltage gradient.

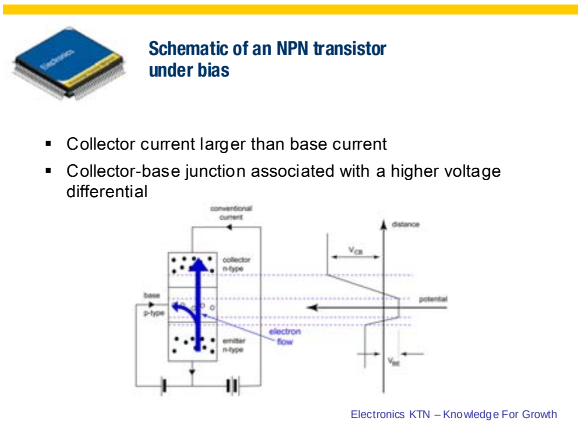
Things get more complicated with integrated circuits, but their basic heat sources are the same I^2R or Joule heating, and the position of the heat source is the same, with the heat generation happening at the junctions, from where the heat generated has to be conducted away through the silicon. Fortunately, a thin semiconductor die presents little thermal impedance. And, as we will see, there are other factors to bear in mind.

Mechanisms of heat generation

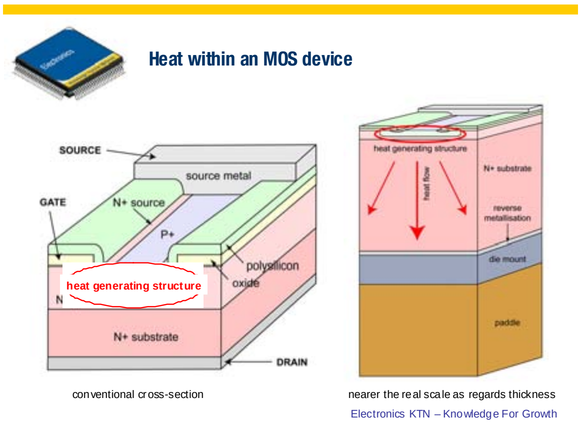


The simplest device is a semiconductor junction, which has a non-linear current-voltage relationship, and whose dissipation at any point is given by the product of current and voltage. So, for most diodes, the most significant dissipation is during forward conduction.

Similarly, if we look at an MOS device, the resistance of the channel will depend on the bias applied, and effectively we have a dynamic resistance modulated by the gate voltage. If you pass current through the channel, I^2R heating will cause the junction to heat up.



Transistors have a more complex structure than a diode, but if we look at the graph of voltage against position, we will see both voltage drop and current passing, and in consequence power generated at the junction. In this case it is the interface between p-type and n-type material.



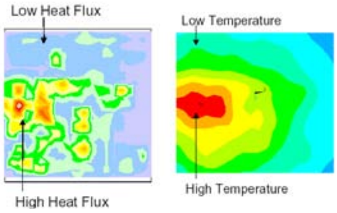
If we look at an MOS device, then the position of our heat-generating structure will be different, but the same rule applies, that the heat that is generated has to flow through the structure to the outer environment. The conventional cross-section on the left, of course does not represent reality – the sketch on the right is nearer the real scale as regards thickness. The heat flows through the highly-doped substrate through any reverse metallization to the die mount material, and then to the paddle.

We will see in Part 3 something of the general structure of semiconductor packages, but it is worth pointing out even at this stage that we have mostly good conductors here, except the die mount material, which is typically a silver-loaded epoxy, and which is kept as thin as possible in order to optimise its thermal conductance.

Mechanisms of heat generation

Heat flux/temperature distribution in an integrated circuit

- Concentrations of power-dissipating elements
- Some lateral conduction of heat
- May be thermal gradient within the die that is not apparent from the surface



Of course, real integrated circuits have tens of thousands of small structures, all dissipating heat, and not all devices will dissipate equally. The situation is complicated by the fact that some of the heat will move laterally, rather than straight through the die, and the consequence is that there may be a thermal gradient within the die that is not apparent from the surface.

This illustration shows areas of high and low heat flux, together with a plot of the resulting temperature distribution. Often when we are looking at the maximum junction temperature of the device, what we really want to control is the temperature of any hotspots.

Other factors to bear in mind

- Variation with temperature
  - inherent negative TCR
  - *conductance* increases with temperature
- Current 'hogging'
  - potential for thermal runaway
  - LEDs and power semiconductors
- Many different factors
  - different technologies
  - widely different packages
- Common features
  - one or more heat-generating junctions
  - thermal path through bulk silicon, then to package

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With semiconductors, we have to bear in mind that the basic material is unusual, in that it has a negative temperature coefficient of resistance. Most conductors, such as metals, increase in resistance as they get hotter; by contrast, it is the conductance of silicon that increases with temperature. This can be important if current is being shared between a number of different devices: the one that happens to be of lowest resistance takes more current, and so gets hotter. After all, this is I squared R heating. In an extreme case this leads to thermal runaway, which can become significant with LEDs and power semiconductors.

With semiconductors the key thing to bear in mind is that many factors come into play, as there are different technologies, and in particular widely different packages. However, whatever the device, there will be one or more junctions within the semiconductor chip that generate the heat, and a thermal path first through the bulk of the silicon and then through to the package.

Capacitors — 1

- All capacitors have some losses
  - impedance is not pure reactance
  - has a resistive (that is 'lossy') component
  - normally modelled as Effective Series Resistance

Dielectric	Dissipation factor	ESR (1μF capacitor)
aluminium electrolytic (50V)	10% at 120Hz	132Ω
tantalum electrolytic (50V)	4% at 120Hz	53Ω
polyester	1% at 1kHz	1.6Ω
polypropylene	0.1% at 1kHz	0.16Ω

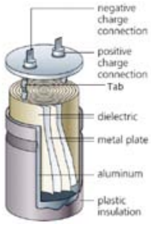
- ESR
  - not just limited to electrolytic types
  - important factor at high frequencies, though not a thermal issue

Electronics KTN – Knowledge For Growth

All capacitors exhibit some losses, because their impedance is not pure reactance, but includes a "lossy" resistive component that is normally modelled as Effective Series Resistance or ESR. ESR is not just limited to electrolytic types: it is an important factor at high frequencies, but there not a thermal issue.

Capacitors — 2

- Aluminium electrolytic capacitors
  - characteristic not linear
  - ESR increases as electrolyte “dries out”
- Mains smoothing capacitors subjected to high “ripple currents”
  - I^2R heating can be very significant
  - degradation mechanisms exacerbated by ripple current heating
- Good practice
  - consider heat dissipated when modelling
  - place away from major sources of heat
  - model large electrolytic capacitors thermally



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Aluminium electrolytic capacitors have a non-linear characteristic, their value increasing with temperature, and their ESR reducing with both frequency and temperature. They also lose electrolyte through outgassing and chemical changes to the electrolyte and oxide layer, so that the ESR increases over time.

Mains smoothing capacitors are subject to high ripple currents, and ripple current plus significant AC impedance equates to power dissipation. Not only is I squared R heating very significant for a new part, but things get worse with life, especially as the degradation mechanisms are exacerbated by ripple current heating.

Good practice for all styles of capacitor is not only to think about the heat that is being dissipated when modelling, but to try and keep them as cool as possible, and certainly place them away from any major sources of heat. If you have a power supply in your system, and large smoothing capacitors, then these will need to be modelled thermally.

Mechanisms of heat generation

- Heat comes from
  - the board itself
  - many components (not just the ones we’ve described)
- In most cases
  - the source of heat is not uniformly distributed
  - heat has a significant distance to travel from source to outside surfaces
  - there will be a temperature difference between active area and package exterior
  - device reliability depends on the maximum temperature and the temperature excursions of the active area
- We need to keep in mind the idea of thermal paths from source to the surroundings (“ambient”)

Electronics KTN – Knowledge For Growth

So heat comes from the board itself and from many components, and not just the ones we have described. In most cases the source of heat is not uniformly distributed, and the heat dissipated has to travel a significant distance between the source of heat and the outside surfaces of the package, so there will be a temperature difference between the active area and the package exterior.

Typically the device reliability depends on the maximum temperature reached, and on the thermal excursions of the active area – it’s the repeated cycling from cold to hot and back again that generates damaging stress.

Wherever the heat comes from, we need to keep in mind the idea of there being many different thermal paths from the sources of heat to the exterior of the package, to the board, and to the surroundings, often referred to with the term “ambient”.