Chapter 2
Fundamentals of Thermal Sensors

Thu Huynh

Thermal sensors are found in many items, from commonplace items inside any home to more sophisticated applications. You can find sensors in household electronics like thermostats or thermometers. You will also find sensors in things as sophisticated as your personal computer or in a microprocessor. It is vital for processors to stay within the temperature range specification to perform reliably and for the processor to run at its expected speed performance.

In this chapter, we review the fundamental principles of heat transfer and describe heat transfer in a typical microprocessor package. We also touch on the principles of thermal sensors, including the various sensor materials, operation and applications in a typical semiconductor industry environment.

2.1 What Is a Thermal Sensor?

Sensors are devices that measure a physical or chemical reaction, such as volume flow or heat flux, through changes in electric resistance or signal (Kenny 2004). There are many types of sensors—flow, force, pressure, humidity and motion sensors are just a few. We are focused on one type of sensor in this book: thermal sensors.

2.1.1 Overview of Thermal Sensors

Temperature is the measure of the average kinetic energy of the molecules of a gas, liquid, or solid. A thermal sensor is a device that is specifically used to measure

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temperature. In this way, thermal sensors are able to give us a quantifiable way to describe the substance, whether it is an object, the environment in which an object is placed or the environment in which an object is distributed. More about how these sensors are applied to microprocessors are discussed in later chapters.

2.1.2 Types of Thermal Sensors

One well-known thermal sensor is a mercury or alcohol thermometer. It uses the volume of mercury or dyed ethanol, which expands when temperature increases, to measure temperature in a tube with a temperature scale. Though very well known, mercury and alcohol thermometers are not well suited to measure temperature in a personal computing device or microprocessor because they tend to be too large for those applications. Other kinds of thermal sensors that can be suited for personal electronics and microprocessors include thermocouples, resistance thermometers, silicon sensors and radiation thermometers.

2.1.2.1 Thermocouples

Thermocouples are sensors composed of two different metals at their sensing end. A voltage is created when there is a temperature gradient between the hot sensor element and the cold reference junction. The change in voltage can be reported as a temperature through the Seebeck effect (Love 2007). The Seebeck effect says that the change in voltage is linearly proportional to the change in temperature and the two variables are related to each other through a coefficient that is determined by the materials used in the thermocouple (Janata 2009). Figure 2.1 depicts the construction of a thermocouple.

2.1.2.2 Resistance Thermometers

Resistance thermometers are also known as resistance temperature detectors, or RTDs. They are typically made of a single pure metal (Dames 2008). Each metal has a material property of electrical resistance that is a function of temperature. The most accurate resistance thermometers are ones that use metals that have a very linear relationship with temperature, such as platinum. By using the relationship curves between electrical resistance and temperature, when the resistance of the metal is measured, a temperature can be calculated (Dames 2008). Figure 2.2 depicts the construction of one type of resistance thermometer.

2.1.2.3 Thermistors

A thermistor is a specific type of resistance thermometer. Thermistors are made of metal wires connected to a ceramic base made of several sintered, oxide semiconductors (Janata 2009). Like other resistance thermometers, the change in

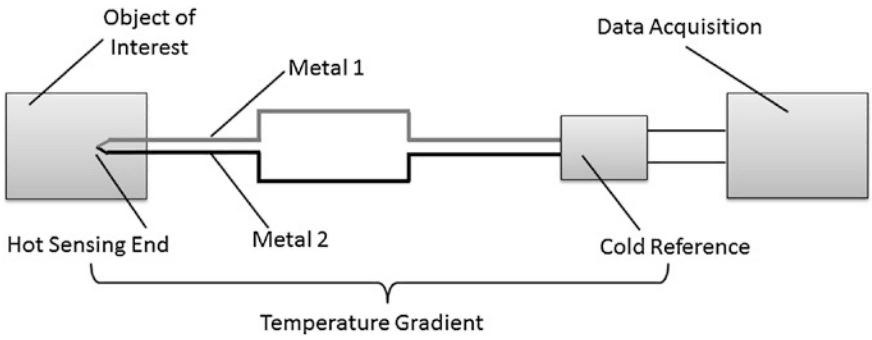


Fig. 2.1 Thermocouple construction. Adapted from Love (2007)

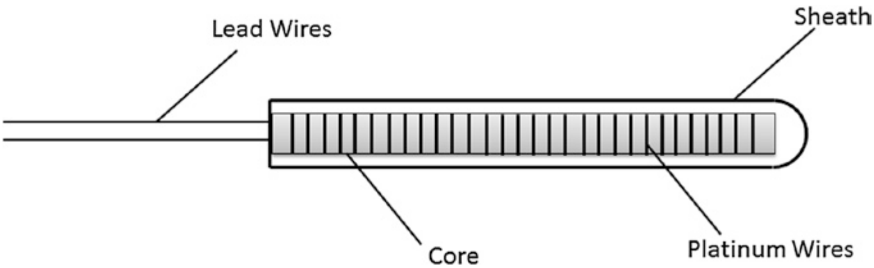


Fig. 2.2 An Example of resistance thermometer construction. Adapted from Desmarais and Breuer (2001)

temperature can be calculated from the change in resistance. But unlike traditional resistance thermometers, the relationship is not very linear. Thus, the temperature range in which thermistors can be used is small compared to traditional resistance thermometers. But thermistors have the advantages of being small in size, inexpensive to buy and very sensitive to temperature changes, so they can be ideal to use in many electronics applications (Janata 2009).

2.1.2.4 Silicon Sensors

These sensors are made of silicon, a semiconductor that is used as the base material for most electronic microprocessors. The process of manufacturing these electronic devices is a carefully controlled, high-volume manufacturing process that includes deposition, doping, and careful layering of metals, oxides, and insulators (Peterson 1983). By utilizing this manufacturing process, integrated circuit (IC) sensors can be created as their own sensor device (Desmarais and Breuer 2001). They can also be embedded inside microprocessors as diodes (Rotem et al. 2006). These types of sensors can have their own memory, can have direct output to meters and can convert signals to temperature readings without extra equipment (Desmarais and Breuer 2001).

2.1.2.5 Radiation Thermometers

All substances and objects emit thermal radiation when it is at a temperature higher than absolute zero (0 K or −273.15 °C). There is a relationship between temperature and radiation energy emitted that can be used to calculate the temperature of the object surface. Unlike other sensors discussed above, radiation thermometers are primarily used at a distance from the object of interest and can be used for hard-to-reach objects. An example of a radiation thermometer is an infrared camera, which measures infrared wavelengths that emit from an object.

2.2 Heat Transfer and Microprocessors

Power is an important design feature of microprocessors. It is linked to the expected silicon performance and also generates the heat that must be cooled from the part. The goal of microprocessor thermal management is to cool the processor efficiently within a specified temperature to ensure reliable performance over the lifetime of the part. Thus, it is important to understand the heat transfer mechanisms in the microprocessor that cool the processor in order to understand the importance of thermal sensors in microprocessors.

2.2.1 Fundamentals of Heat Transfer

Thermodynamics describes the fundamental behavior of heat and temperature and includes the three laws of thermodynamics. Heat transfer goes further and describes the mechanisms of heat exchange and the rate at which heat flows, giving us a way to calculate heat flow within, to and from objects or the environment. There are three modes of heat transfer: conduction, convection and radiation.

2.2.1.1 Conduction

Conduction is the first mode of heat transfer that we will discuss. It is a prominent mode of heat transfer in electronics cooling. Undergraduate transfer textbooks typically devote a large portion of the text to this topic and those books will be able to give a more comprehensive and in-depth discussion on this mode of heat transfer.

Definition of Conduction: Conduction is the heat transfer through solids. It can also occur with stagnant fluids. The one-dimensional rate of conductive heat transfer is determined by Eq. 2.1:

$$Q_{conduction} = \frac{kA(T_{hot} - T_{cold})}{L} \quad (2.1)$$

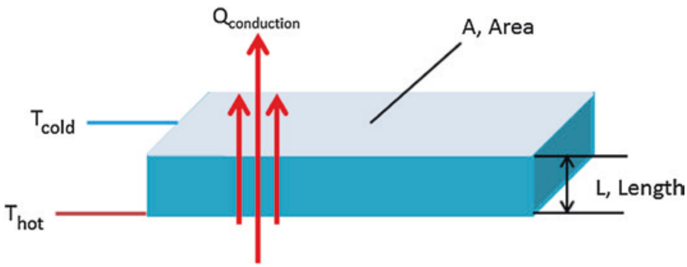


Fig. 2.3 Heat transfer through an object by conduction

where $Q_{conduction}$ is heat flow, k is the thermal conductivity of the material, A is the cross-sectional area of heat flow, T_{hot} is the temperature of the hot surface, T_{cold} is the temperature of the cold surface and L is the length of the material through which heat is conducting. Figure 2.3 depicts the heat transfer through a solid material by conduction. The different variables of the conduction heat transfer Eq. 2.1 are shown.

The conduction resistance is defined by Eq. 2.2:

$$R_{conduction} = \frac{L}{kA} \tag{2.2}$$

As shown in Eq. 2.2, in order to minimize the conduction resistance, conductivity of the material and cross-sectional area of material is maximized while the through-path (length) of the material is minimized.

Three-Dimensional Conduction: Conduction can also occur in three dimensions if the heat source size is smaller than the conducting material. If the heat source is smaller than the conducting material, the heat is concentrated in one spot, causing a hot spot. In Fig. 2.4, heat is being conducting in the x and y direction as well as the z direction. The conduction resistance in the x and y direction is also known as the spreading resistance, which can be solved in idealized boundary conditions by first order equations or more often through computational software. Figure 2.4 depicts one-dimensional and three-dimensional conduction through a solid, as well as the transition between the two types of conduction.

Contact Resistance: Another thing to consider in conduction is contact resistance between two different solid materials. When two materials join to form a conduction path, there is resistance at the point where the two materials join. This occurs because the two surfaces are rarely completely flat and voids of air are present at the junction of two surfaces. This must be taken into account when thermal solutions are applied to electrical packages or when an external thermal sensor like a thermocouple is attached to the package. Minimizing contact resistance is a key factor to consider in electronics packaging and their cooling.

Example 2.1 A rectangular block has an area of 400 mm^2. An engineer would like to use it to cool his heat source that is producing a total of 50 W with a specification of 90 °C. The heat source is placed in a chamber with an air temperature of

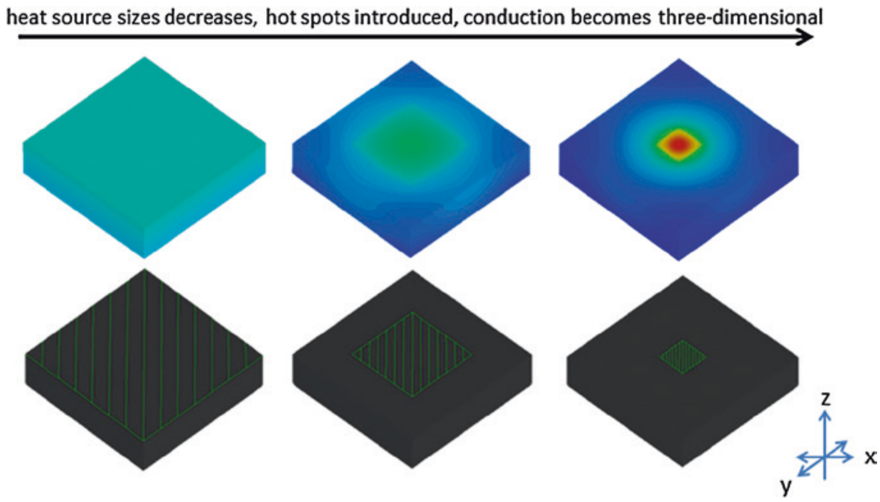
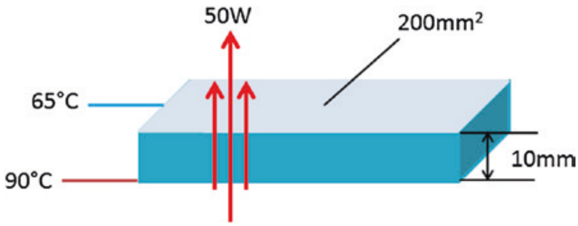


Fig. 2.4 Transitions between one-dimensional and three-dimensional conduction

65 °C. If the through-length is 10 mm, what is the minimum conductivity of the material in order to cool the heat source to specification using the block alone?

Solution
In this example, the mode of heat transfer is conduction through the block. The given information is annotated in the illustration below to help us solve this problem.



We will start with Eq. 2.1 and replace with the given variables. We want to solve for conductivity k in units of W m^{-1} K^{-1}.

$$Q_{conduction} = \frac{kA(T_{hot} - T_{cold})}{L}$$

In order to solve the equation with the correct units, the area and length units must be changed to meters, m. The known values are plugged into the conduction equation to give:

$$50\,\mathrm{W} = \frac{k(0.0004\,\mathrm{m}^2)(90\,^\circ\mathrm{C} - 65\,^\circ\mathrm{C})}{0.01\,\mathrm{m}}$$

Rearranging to solve for conductivity k:

$$k = \frac{(50\,\mathrm{W})(0.01\,\mathrm{m})}{\left(0.0004\,\mathrm{m}^2\right)(90\,^\circ\mathrm{C} - 65\,^\circ\mathrm{C})}$$

$$k = 50\frac{\mathrm{W}}{\mathrm{mK}}$$

By re-ordering Eq. 2.1, we solve for k and find it to be 50 W m^{-1} K^{-1}.

2.2.1.2 Convection

Convection is the second mode of heat transfer we will discuss. Along with conduction, it is typically a large part of electronics cooling in active, fan-cooled systems. An undergraduate textbook can be consulted for in-depth information.

Definition of Convection: Convection is the heat transfer from a surface to a fluid. Some common fluids include air and water. Other fluids such as alcohol and oil can also be mentioned in cooling electronics. The rate of convection heat transfer is determined by Eq. 2.3 below:

$$Q_{convection} = h_c A\left(T_{ambient} - T_{surface}\right) \tag{2.3}$$

where $Q_{convection}$ is heat flow, h_c is the convection heat transfer coefficient, A is the surface area, $T_{ambient}$ is the ambient temperature of the fluid, and $T_{surface}$ is the temperature of the surface of the material. Figure 2.5 depicts the airflow profile and temperature profile you would expect through convection from the surface of the rectangular object. $T_{surface}$ is warmer than $T_{ambient}$, which corresponds to the lower airflow velocity at the surface.

The convection resistance is described by Eq. 2.4:

$$R_{convection} = \frac{1}{h_c A} \tag{2.4}$$

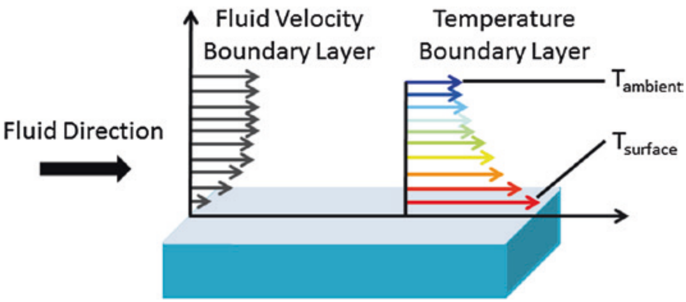


Fig. 2.5 Convection and its airflow and temperature boundary layers

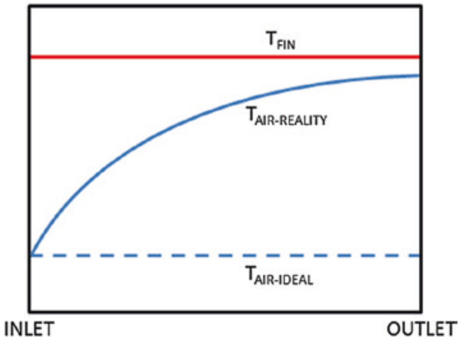


Fig. 2.6 Air heating: ideal versus real air temperature versus fin temperature

As shown in Eq. 2.4, to minimize convection resistance, the convection coefficient and surface area should be maximized.

Surface Area and Fins: To increase surface area and the effectiveness of convection heat transfer, fins are often added to the base of electronic cooling solutions. The fins are often made of a thermally conductive material such as aluminum or copper. Fins can be formed by extrusion from a large block or they can be formed and stacked on top of the base with solder.

Air Heating and Pressure Drop: Another consideration is the air heating along the length of the fin. In an idealized condition, the temperature difference between the air and the fin along the length of the fin would be constant. However, in reality, the temperature of the air increases along the length of the fin and the fin's ability to remove heat is diminished as the length of the fin is increased. It is not effective to simply make the fins infinitely long. Figure 2.6 shows the ideal versus real case for air heating. Additionally, longer fins will have a higher pressure drop across the fins compared to a heat sink with shorter fins. For heat sinks with longer fins, the total airflow will be reduced and thus cooling will be reduced for a given fan curve.

Optimizing Fin Performance: The fin stacks themselves have a fin resistance, which is a function of convection coefficient, fin efficiency and fin surface area. The balance among all three will determine the optimal fin geometry for a given set of boundary conditions, including cost considerations and manufacturing abilities.

2.2.1.3 Radiation

The last mode of heat transfer to discuss is radiation. Typically, this mode of heat transfer can be more complex than either conduction or convection. Graduate level classes cover this mode in more detail. In cooling microprocessors, radiation can play a large part when the primary mode of cooling is natural convection, with no active fan.

Definition of Radiation: Radiation is the heat transfer between surfaces via electromagnetic waves. All matter at a nonzero temperature emits electromagnetic waves, including gases and liquids. However, in many undergraduate heat transfer textbooks, the focus is only on solids. The rate of heat transfer is described by Eq. 2.5:

$$Q_{radiation} = h_r A(T_{source} - T_{surrounding}) \tag{2.5}$$

where $Q_{radiation}$ is the heat flow, h_r is the radiation heat transfer coefficient, T_{source} is the temperature of the source and $T_{surrounding}$ is the temperature of the surroundings (Bergman et al. 2011). The radiation heat transfer coefficient can also be described by Eq. 2.6:

$$h_r = \varepsilon\sigma(T_{source} - T_{surrounding})(T_{source}^2 + T_{surrounding}^2) \tag{2.6}$$

where ε is the emissivity of the source and σ (5.67×10^{-8} W m^{-2} K^{-4}) is the Stefan-Boltzmann constant (Bergman et al. 2011). The radiation heat transfer coefficient is similar to the convection heat transfer coefficient, but the radiation heat transfer coefficient is much more dependent on temperature as shown by raising the temperature terms in Eq. 2.6 to the third power (Bergman et al. 2011). The net radiation heat transfer is well known by Eq. 2.7, where h_r in Eq. 2.5 is replaced by Eq. 2.6:

$$Q_{radiation} = \varepsilon\sigma A(T_{source}^4 - T_{surrounding}^4) \tag{2.7}$$

Figure 2.7 depicts the heat transfer of an object through radiation. The variables in Eq. 2.7 are highlighted in the figure.

Components of Radiation Heat Transfer: An ideal radiative surface is called a blackbody with an emissivity of 1, but in reality, no surfaces are ideal. Radiative heat transfer is highly dependent on all the bodies surrounding the surface in

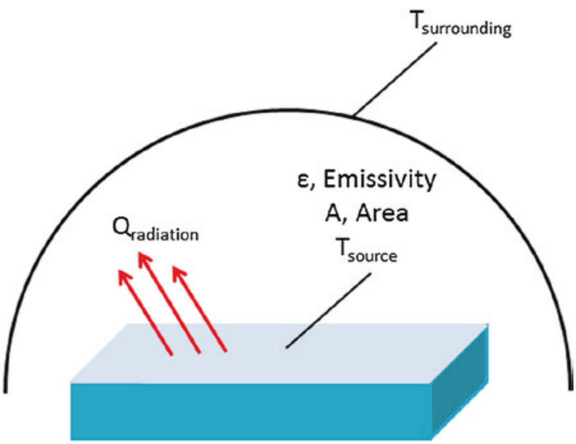


Fig. 2.7 Heat transfer through radiation from an object to its surroundings

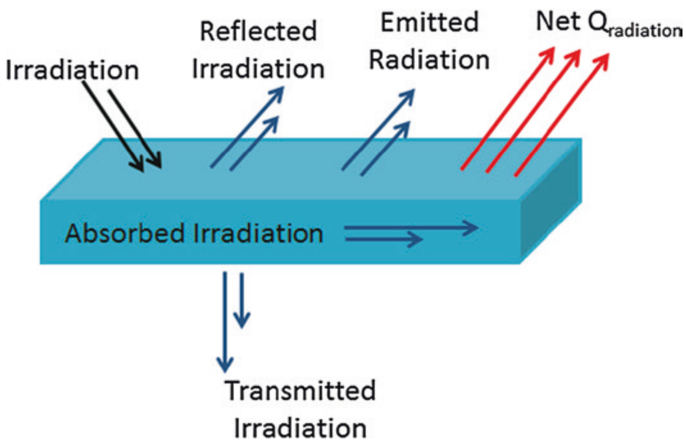


Fig. 2.8 Components of radiation heat transfer

question and the temperature and finish of the surfaces. A solid surface can emit, absorb, reflect, and transmit radiation depending on the material in question. For example, an opaque material can reflect radiation, whereas in a semitransparent material, radiation can be transmitted through the material. Unlike absorption and emission, reflection and transmission do not affect the total thermal energy of the material (Bergman et al. 2011). Figure 2.8 depicts the various components of heat transfer of an opaque solid through radiation.

2.2.2 Heat Transfer in a Microprocessor

As discussed in the previous section, the three modes of heat transfer can play important roles in the cooling and temperature sensing of microprocessors. Typically, in active, forced air-cooled systems, conduction and convection play the largest role. In natural convection systems or in systems where there is no room to attach a fan, radiation can play an important role.

2.2.2.1 Active Cooling

In active cooling systems, fans are attached in the system; they provide airflow over the microprocessors and can be used to help cool them. In these cases, the thermal engineer can conduct heat from the package out to a heat sink made of a thermally conductive material such as copper or aluminum. In cases where more cooling is needed, fins can be added to the cooling solution. Though actively cooled, it is also important to consider the conductive path from the package to the motherboard or any other substrate the microprocessor is attached to. Figure 2.9 depicts a few examples of heat sinks that can be used to cool microprocessors.

Fig. 2.9 Various heat sink configurations

2.2.2.2 Natural Convection Based-Cooling

In natural convection cooling solutions, no air movers are present or very little air is available due to airflow blockages. In these cases, radiation is an important cooling mechanism as well as conduction into the motherboard and natural convection. Analysis would have to include all the parts in the system in order to accurately predict thermal performance of the microprocessor or object in question. This analysis is one of the most complex heat transfer modes to model because all the surfaces, materials, and properties associated with the object must be specified accurately.

2.2.3 Package Thermals

Heat is spreading through conduction within the die and out of the package via active or natural convection cooling. The package is composed of the die, which is attached to a substrate made of FR-4 material with embedded copper layers. The package designer may decide not to cover the die; this is typically called a bare-die package. Alternatively, a package can include over-molding made of an epoxy or plastic to protect the die. It can also be covered with a copper integrated heat spreader (IHS) to help reduce spreading resistance and increase conduction to the heat sink. If the die is covered with a spreader, another material is needed between the die and spreader to fill in small air voids and gaps with conductive material. This interface material is typically called the thermal interface material. In Fig. 2.10, three package options (bare die, over-molded, integrated heat spreader) are shown.

Example 2.3 A heat sink is placed over a package with an integrated heat spreader. The package itself is attached to a substrate. The heat sink has metal fins and a metal base. Draw the resistance stack that should be accounted for in order to accurately find the die temperature (junction). Make sure to take into account any interfaces that would be present in a real assembly.

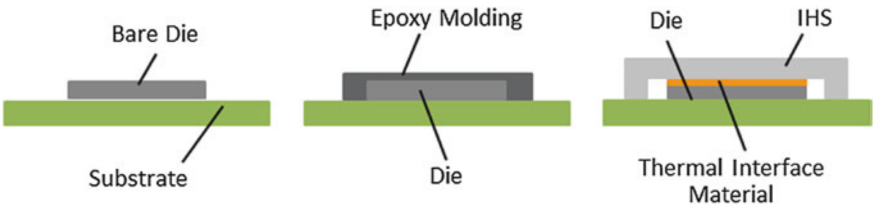
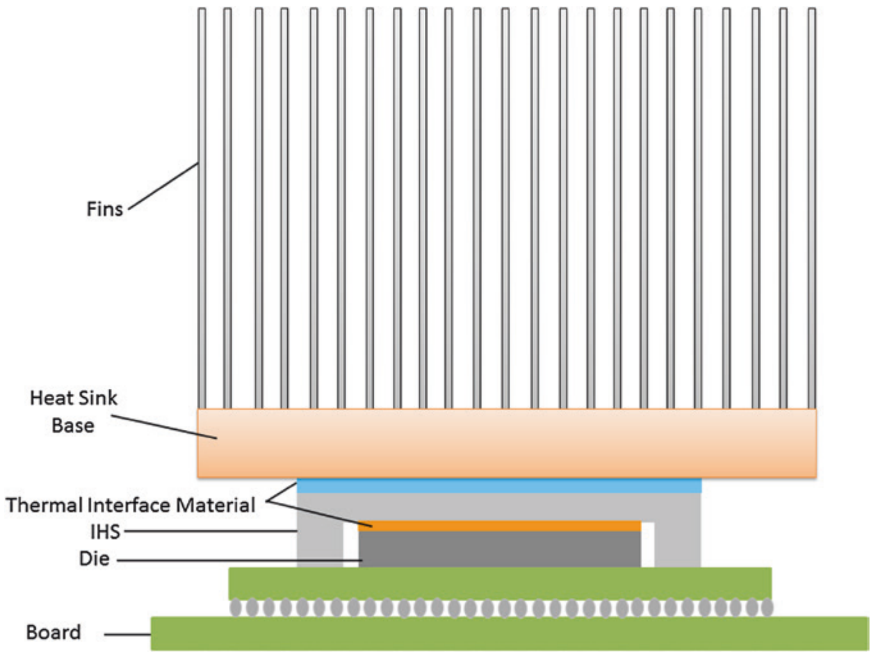


Fig. 2.10 Various package configurations with and without lid protection

Solution

To understand the different interfaces that should be accounted for, a schematic would be the first place to start. The problem statement gives the description for what the thermal solution looks like. The illustration below depicts the description given in this example of a heat sink with fins placed on top of a package with an integrated heat spreader.

The heat sink can be a radial heat sink or one of another shape, but for simplicity, we chose a simple rectangular base with straight fins. In this problem, it does not matter how tall or long the fins are. The base area and thickness are also not important. In this problem, the package is a ball-grid array (BGA) package, attached to the motherboard using solder balls. Alternatively, the package can be attached to the motherboard using a land-grid array (LGA) socket.



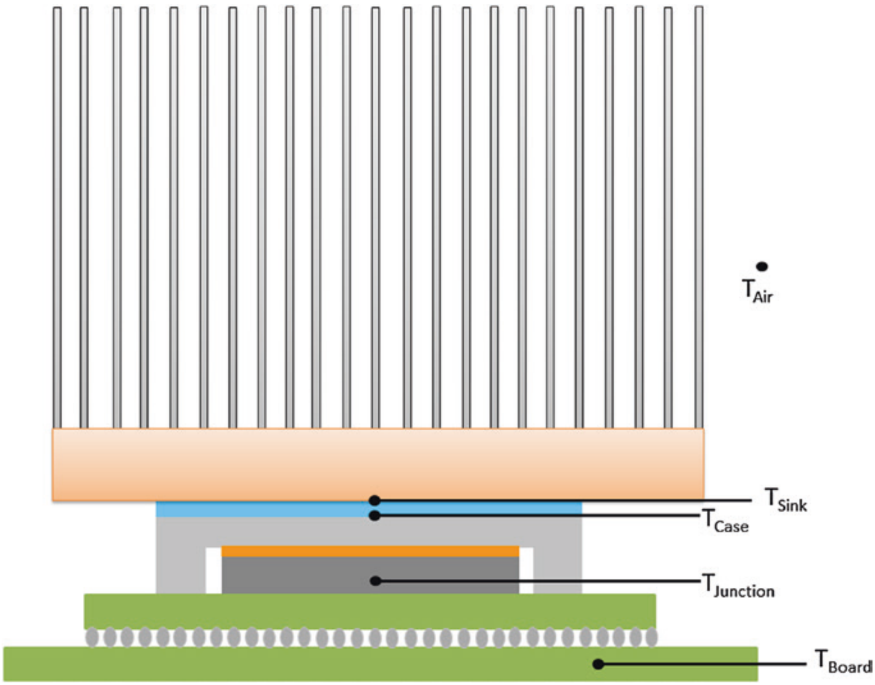
There are two places where thermal interface material would be placed in this configuration: within the package between the die and integrated heat spreader (Thermal Interface Material 1) and between the integrated heat spreader and the heat sink base (Thermal Interface Material 2).

Not only can power go up from the die into the heat sink, power may also go down through the substrate. It is also important to know that if power is dissipated into the substrate, the power will eventually be cooled by $T_{air.}$

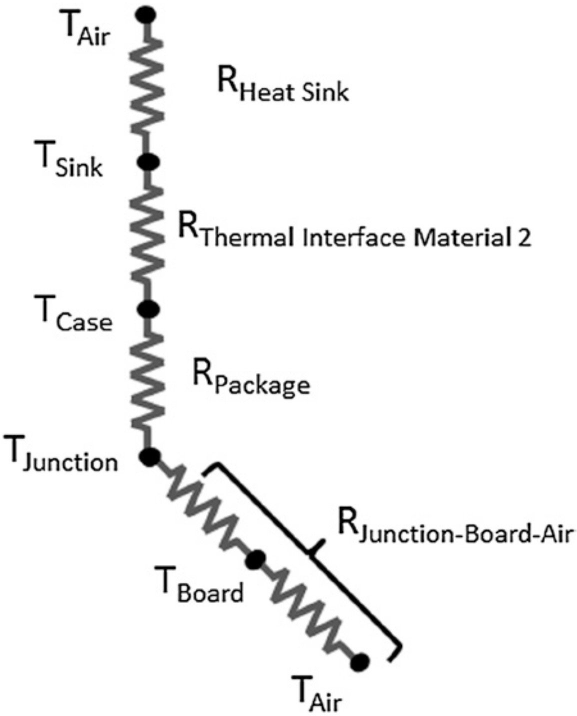
The resistance stack can be created by choosing temperature points along the path through which heat will be dissipated, as shown in the next schematic.

The die temperature is also referred to as the junction temperature in many specification sheets and is shown as the junction temperature in this example.

It is important to note that the package resistance is in reality made of many parts: spreader resistance, thermal interface material 1 resistance, and so forth. However, many specification sheets simply give an overall resistance target from junction to case, which should be defined in the specification sheet, rather than describe all the details.



For this example, the resistance network is shown in the following illustration. This network reflects the simplification within the package by combining the spreader and thermal interface material 1 resistances into one resistance and reflects that the power through the package will be cooled by air.



2.2.4 *Need for Temperature Measurement in a Microprocessor*

Each microprocessor needs a mechanism to give feedback to the user and system on how hot it is getting when it is powered. Without temperature measurement, the system may not provide enough airflow to cool the part or the engineer may not know if the thermal solution is adequate to keep the microprocessor within specification.

2.2.4.1 Hot Spots in the Microprocessor

In an ideal thermal situation, the microprocessor would be uniformly heated when it is powered. However, in reality, the microprocessor is made up of many different subsections that are designed to do different tasks. Thus, it is often the case that certain parts of the microprocessor are hotter than others and hot spots develop on the die where the microprocessor is more heavily utilized. Where the hot spots are located is dependent on the application and the layout of the die. The non-uniformity of heating and its dependence on workload application adds more complexity to understanding the processor temperature and it is not easily modeled accurately. Sensors are needed to understand where the hottest temperature is in real-use conditions.

2.2.4.2 Microprocessor Performance

There are many inputs into determining microprocessor performance, including voltage, leakage power, and thermal design power (TDP). The inputs are dependent on temperature and subsequently, the performance of the part, its frequency, is also dependent on temperature. Higher TDP, higher voltage, and lower leakage power increases frequency. This is the ideal case when performance is the most important variable in the design. However, if both temperature increases and reliability metrics are fixed, the voltage decreases and leakage power increases, leaving less power devoted to TDP. This is the opposite trend of what is needed for optimal performance. It is vital to measure the temperature of the microprocessor accurately to properly set frequency.

2.2.4.3 Microprocessor Reliability

The silicon microprocessor has an upper temperature limit specification that is set to prevent immediate microprocessor damage. In addition, microprocessors have an allowable failure rate and are specified to work for a certain period of time, usually in the number of years. If reliability is relaxed and the part can tolerate more failures or a shorter lifetime, voltage may not need to decrease when temperature increases, which allows for better performance. To ensure that there is minimal immediate damage and that the part failure rate is acceptable in its lifetime, the microprocessor temperature must be accurately understood.

2.3 Sensor Materials

There are many materials that are used for sensors. Metals are typically used for RTDs and thermocouples. The semiconductor silicon is used to make microprocessors and this is where many thermal sensors are built into the die. The following is a quick, but by no means an exhaustive, overview of the materials.

2.3.1 Platinum Sensors

Platinum is the choice material to use for RTDs. The typical temperature usage range for platinum RTDs is −250 to 600 °C, but some platinum RTDs can be used up to 850 °C (Love 2007). Its electrical resistivity has a very linear relationship

Table 2.1 Physical and thermal properties of platinum

Physical property	Platinum (Pt)
[a]Thermal conductivity (W m^{-1} K^{-1}) at 25 °C	71.6
[b]Melting point (K)	2042
[c]Temperature coefficient of resistance	3.92×10^{-3}
[d]Electrical resistivity Ω cm at 0 °C	9.6×10^{-6}
[b]Coefficient of linear thermal expansion (K^{-1})	8.8×10^{-6}
[e]Specific heat capacity (J g^{-1} K^{-1})	0.133
[b]Density (g cm^{-3})	21.45

Sources [a]Ho et al. (1972)
[b]Touloukian et al. (1975)
[c]Serway (1990)
[d]Hall (1968)
[e]Wagman et al. (1982)

with temperature over a large range of temperature (Dames 2008) and has a higher resistivity compared to other metals such as copper and nickel, which make it ideal for RTDs (The RTD 2014). The temperature coefficient of resistance (TCR) is 0.0039 K^{-1} at room temperature, where the TCR is the change in resistance per unit change in temperature. A higher TCR represents a more sensitive RTD to temperature and a high TCR is ideal. As a material, it is chemically inert and stable in different kinds of environments and is not likely to corrode or reduce, making it useful to measure temperature in many different environments (Dames 2008). Table 2.1 shows a few common thermal and electrical properties for platinum.

2.3.2 Thermocouple Materials

Many metals and alloys other than platinum are used in sensors, especially thermocouples. Though RTDs are mostly made of platinum, copper and nickel RTDs can also be found. In thermocouples, alloys are common materials (ANSI and IEC Color Codes 2014). Because of the wide range of materials, the temperature range of thermocouples is much wider than RTDs: temperatures can range as low as −270 °C and as high as 2300 °C. Common non-alloy thermocouple metals are summarized in Table 2.2.

In Table 2.3, a few common thermocouple alloys are summarized. The alloys in the table are made of copper, nickel, and chromium and they are found in J, K, T, and E thermocouple types.

Care must be taken in choosing thermo-electric materials for the environment they are used in: for example, thermocouples containing iron can be more susceptible to oxidization at high temperatures and is recommended for lower temperatures (ANSI and IEC Color Codes 2014). Chromium-based thermocouples can also see oxidation or "green rot" at higher temperatures when exposed to low levels of oxygen (Nicholas and White 2001). Table 2.4 summarizes the recommended and limiting conditions of a handful of thermocouple types.

Table 2.2 Physical and thermal properties of copper, nickel and iron

Physical property	Cu	Ni	Fe
[a]Thermal conductivity (W m^{-1} K^{-1}) at 25 °C	401	90.9	80.4
[b]Melting point (K)	1357.6	1728	1811
Temperature coefficient of resistance (Ω/Ω °C)	[c]3.9×10^{-3}	[d]5.9×10^{-3}	[c]5.0×10^{-3}
[e]Electrical resistivity Ω cm at 0 °C	1.545×10^{-6}	6.23×10^{-6}	8.7×10^{-6}
[b]Coefficient of linear thermal expansion (K^{-1})	16.5×10^{-6}	13.4×10^{-6}	11.8×10^{-6}
[f]Specific heat capacity (J g^{-1} K^{-1})	0.385	0.444	0.449
[b]Density (g cm^{-3})	8.933	8.90	7.87

Sources [a]Ho et al. (1972)
[b]Touloukian et al. (1975)
[c]Serway (1990)
[d]Electrical Conductivity (2014)
[e]Hall (1968)
[f]Wagman et al. (1982)

Table 2.3 Physical and thermal properties of copper-nickel and nickel-chromium alloys[a]

Physical property	Cu-Ni	Ni-Cr
Thermal conductivity (W m^{-1} K^{-1}) (typical)	20	19.2
Melting point (°C)	1260	1427
Temperature coefficient of resistance (Ω/Ω °C)	-0.01×10^{-3}	0.4×10^{-3}
Electrical resistivity Ω m (typical)	49×10^{-8}	70.6×10^{-8}
Coefficient of linear thermal expansion (K^{-1})	18.8×10^{-6}	13.1×10^{-6}
Density (g cm^{-3})	8.9	8.73

Source [a]Physical Properties of Thermoelement Material (2014)

Table 2.4 Recommended environmental conditions and thermocouple type[a]

Thermocouple type	Recommended and limiting conditions
E	Recommended for inert and oxidizing environmental conditions. Not recommended for use in reducing or vacuum environmental conditions
J	Recommended for inert, reducing and vacuum environmental conditions. Not recommended for use in high temperature, oxidizing environmental conditions
K	Recommended for inert and oxidizing environmental conditions. Not recommended for use in a reduced or vacuum environmental conditions
R	Recommended for inert or oxidizing environmental conditions without metal sheath protection
T	Recommended for inert, moist, oxidizing and vacuum environmental conditions

Source [a]ANSI and IEC Color Codes (2014)

Table 2.5 Physical and thermal properties of silicon

Physical property	Silicon (Si)
[a]Thermal conductivity (W m^{-1} K^{-1}) at 25 °C	149
[b]Melting point (K)	1687
[c]Specific heat capacity (J g^{-1} K^{-1}) at 300 K	0.712
[b]Density (g cm^{-3})	2.42

Sources [a]Ho et al. (1972)
[b]Touloukian et al. (1975)
[c]Hall (1968)

2.3.3 *Silicon Sensors*

Silicon is a semiconductor, which at a very basic level is a material that has an electrical resistance between an insulator and conductor (Yacobi 2002). Silicon has a diamond lattice structure and its neutral valence electron configuration allows silicon to equally share its valence electrons with other elements (Yacobi 2002). Because of this, silicon can be doped with other elements near it on a periodic table, such as boron or phosphorous, to fill its lattice structure with electrons that carry electrical current, thereby increasing the electric properties of silicon by orders of magnitude (Berger 2013). Thermally, silicon's thermal conductivity increases as temperature increases, the opposite of what occurs with most metals (Yacobi 2002). Most importantly, electronics are often made of silicon for several key reasons:

- Silica can be purified and turned in single-crystal silicon in a very pure form by vapor deposition (Habashi 2013).
- It is an inexpensive material (Peterson 1983).
- Its melting point is sufficiently high enough for silicon to be stable during high volume manufacturing, specifically for high temperature oxidation, diffusion, and annealing (Yacobi 2002).
- Silicon electronics can be manufactured in batches very precisely (Peterson 1983).

However, one important disadvantage of silicon sensors is the narrow range of temperature use compared to thermocouples and resistance thermometers: silicon sensors are generally only good from −50 to 150 °C (Bakker 2002). Table 2.5 is a summary of some of the electrical and thermal properties of silicon.

2.4 Principles of Thermal Sensors

There are many considerations to take into account in choosing a sensor to use. Some questions that frequently come up during that process are:

- What is being measured?
- What cost is acceptable?
- What is the accuracy required for the measurement?

In this section, we will have a quick overview of some factors that play a part in selecting a sensor for use in the industry, including temperature range for measurement, how the measurement will be made and the accuracy required.

2.4.1 Objective of Measurement

There can be several reasons why temperature is being measured for a given process, test, or object. The temperature may have a big effect on the chemical process that is being monitored. For example, in silicon high volume manufacturing, the temperature has to be set precisely to control layer growth and depth. In other cases, the temperature can be the main output of the test. An example of this case is during the performance test of a thermal heat sink. Temperature can also be measured to ensure reliability over time. Silicon dies usually have temperature monitors to ensure they remain under the maximum temperature limit and reliably work over a set number of years. Whatever the situation, care must be taken to pick a sensor that can get the job done accurately within the required conditions without being too costly.

2.4.1.1 Temperature Range of Measurement

It has been briefly mentioned in the section on sensor materials that each type of sensor has a certain temperature range of use. For thermocouples, the general range of use is between −270 and 1300 °C, but it can be as high as 2300 °C. For resistance thermometers, the temperature range of use is between −250 and 600 °C. For silicon sensors, the useful temperature range is between −50 and 150 °C. Of the three main sensor types, silicon has the most restrictive range, while thermocouples can be applicable in a wide variety of temperature cases.

Within the thermocouple group, different thermocouple types are rated for different temperature ranges. For example, Type J thermocouples, made with iron and nickel-copper materials, are useful to as high as 1200 °C. However, Type T thermocouples, made with copper and nickel-copper materials, are only useful to 400 °C (ANSI and IEC Color Codes 2014).

Resistance thermometers also have different temperature ranges depending on the material used. Platinum is the preferred choice of material for RTDs and its usable temperature range is widest, roughly between −200 and 650 °C. Nickel and copper alloys have the smallest usable temperature ranges, roughly between 0 and 205 °C, while nickel and copper have narrower usable temperature ranges between platinum and nickel/copper alloys (Desmarais and Breuer 2001). Thermistors, which use semiconductor oxides, have an even narrower range of use, between −100 and 300 °C (Desmarais and Breuer 2001).

If the conditions in which the thermometers are used reach or exceed the extremes of the usable temperature ranges, uncertainty can increase and temperature can deviate from the specifications. Determining the temperature ranges of the environments in which the sensors are being used during testing, processing and over their lifetimes will prevent these inaccuracies in measurement.

2.4.1.2 Environmental Conditions for the Thermal Sensors

Each type of sensor can also have limitations in certain environments. Material type will play a large part in this consideration. For example, iron and nickel-iron alloys can oxidize above 535 °C and corrode (Desmarais and Breuer 2001). These materials should be avoided under these conditions. Platinum is a very inert material and can be used in high temperatures and moist environments without any problem (Dames 2008). Each sensor with limiting materials can also be protected with special sheaths and materials under extreme environments, but this may change the size and cost of the sensor. In addition, some sensors, like thermocouples, would withstand higher shock and vibration conditions than thermistors or other resistance thermometers (Desmarais and Breuer 2001). In general, all environmental conditions—temperature, humidity, exposure to moisture, exposure to shock and vibration—must all be taken into consideration in choosing a sensor.

2.4.1.3 Cost

Cost can be an important factor in choosing a sensor. Platinum is an expensive material and because of the resistance of the material, it typically will result in a long sensor element (The RTD 2014). Copper, nickel, and lead are very low cost materials that can make them more appealing despite their material limitations, such as a narrower use-temperature range. Because silicon sensors can be produced in batches, their cost can also be quite low compared to resistance thermometers, but their temperature range is much narrower in comparison. In addition, the cost of the sensor can increase as the accuracy required increases. To approximately estimate the cost of a thermometer, including the costs of the material, manufacturing, calibration and metrology equipment needed, the following calculation can be used (Nicholas and White 2001):

$$Cost = \frac{\text{USD } 100}{Accuracy\ Required\ in\ {}^{\circ}\text{C}} \tag{2.8}$$

Using Eq. 2.8, a thermometer requiring an accuracy of 0.01 °C will be 500 times more expensive than a thermometer requiring an accuracy of 5 °C, with the former costing an estimated USD 10,000. Thus, it is very important to not only pick the correct material, but the correct level of accuracy required to limit the cost of the thermometer.

2.4.1.4 Accuracy

Accuracy is the ability of the thermometer to exactly hit a specified temperature. This can be considered a qualitative description. In contrast, uncertainty is the range of expected error between the actual and ideal temperatures (Kenny 2004). Thermometer A can have an uncertainty of ±0.55 °C and thermometer B can have an uncertainty of ±1.3 °C quantitatively, while thermometer A can be described qualitatively as being more accurate than thermometer B.

Resistance Thermometers and Accuracy: Resistance thermometers can be accurate to 0.15 °C. Most platinum RTDs follow the International Electrotechnical Commission (IEC) standard 60751, which has equivalent standards published by the Deutsches Institut für Normung (DIN) and American Society for Testing and Materials (ASTM) (Dames 2008). The IEC accuracy standard is divided between Class A and Class B accuracy, where Class A is stricter and covers a smaller temperature range between −200 and 650 °C versus Class B, which has a range up to 850 °C. The formulations for temperature uncertainty are shown in Eqs. 2.9 and 2.10 (Dames 2008):

$$\text{Class A: } Uncertainty = \pm(0.15 + 0.002|T|)\ ^\circ\text{C} \tag{2.9}$$

$$\text{Class B: } Uncertainty = \pm(0.3 + 0.005|T|)\ ^\circ\text{C} \tag{2.10}$$

Table 2.6 shows the expected uncertainties calculated over a range of temperatures using Eqs. 2.9 and 2.10. Class B RTDs are easily found and bought and they will be less expensive than Class A RTDs. When buying RTDs, the class and required uncertainties should be specified.

Thermocouples and Accuracy: Thermocouples are generally less accurate than platinum RTDs. Thermocouples are classified according to type (J, K, and so on), where each type is distinguished based on the different metal combinations used to make the thermocouple. Manufacturers may follow the ASTM E230 specification listed in Table 2.7 for several thermocouple types. Some suppliers also have thermocouples that follow tolerances based on the IEC standard, which may have different tolerances from the ASTM E230 standard.

Even though manufacturers sell thermocouples of various types, it is always best to check them for accuracy in the environment they will be used in. Thermocouples do not always arrive within specification. Also note that care must be taken to specify which standard, type and temperature range is needed when ordering from suppliers.

Silicon Sensors and Accuracy: Silicon sensor accuracy is dependent on the process tolerances in manufacturing the silicon sensor. Uncertainties are also introduced during the conversion from analog to digital temperature as well as using power supplies with their own uncertainties (Sharifi et al. 2008). Typically,

Table 2.6 IEC accuracy standard—uncertainties of Class A and Class B

Uncertainty at temperature (°C)	Class A (°C)	Class B (°C)
−200	±0.55	±1.3
0	±0.15	±0.3
200	±0.55	±1.3
400	±0.95	±2.3
600	±1.35	±3.3
800	N/A	±4.3

Table 2.7 ASTM E230 standard: standard limits[a]

Type	Temperature range (°C)	Tolerance, whichever is greater
E	0–900	1.7 °C or 0.5 %
J	0–750	2.2 °C or 0.75 %
K	0–1250	2.2 °C or 0.75 %
R, S	0–750	1.5 °C or 0.25 %
T	0–350	1.0 °C or 0.75 %

Source [a]ANSI and IEC Color Codes (2014)

the accuracy of silicon sensors is between 0.5 and 3 °C (Bakker 2002), though higher sensor errors have occurred in experience.

2.4.1.5 Response Time

In addition to cost, accuracy, and useful temperature range, the rate for the measured object or substance to change temperature should also be taken in account. For example, if the rate of temperature change for the substance in question is very fast, then the thermometer choice should also have a quick response. If the thermometer response is too slow, then it may inaccurately report the temperature at a given time and may allow the temperature to exceed a specified limit.

To get an accurate temperature reading, the thermometer should be in equilibrium with the system being measured. After heat is added, it will have to move by conduction or convection from the source closer to the thermometer and then be conducted into the thermometer—process steps that will all take time. Equation 2.11 shows the time it will take the thermometer to respond with system temperature change as a time constant, when the mode of heat transfer is conduction (Nicholas and White 2001):

$$\tau = C/\left(\frac{kA}{L}\right) \tag{2.11}$$

where C is the heat capacity of the fluid or object in J K^{-1} and the denominator is the inverse of the conduction resistance in Eq. 2.2. The time constant can also be written in terms of convection rather than conduction by using the inverse of the convection resistance in Eq. 2.4. Equation 2.12 would result (Tomsen 1998):

$$\tau = C/(h_c A) \tag{2.12}$$

The heat capacity is a material property that describes the amount of heat required to change the temperature of the object by one degree. It is found in units of J K^{-1}, which shows the relationship between heat, power and temperature. A larger heat capacity means that it will take more heat to change the temperature of a substance. Thus, generally, the higher the heat capacity of the object, the longer it will take for the temperature to change. Error between the thermometer and system will decrease exponentially with the time constant (Nicholas and White 2001).

Heat capacity is also function of mass. Oftentimes, the heat capacity is described in terms of a constant mass and the resulting specific heat capacity would be in units of J kg^{-1} K^{-1}. If the thermometer is large, the thermometer will have a longer response time. The thermometer will require more energy to change by a degree. Bigger thermometers like platinum resistance thermometers can have problems if quick response times are needed. However, small sensors like thermocouples will have quicker response times (Desmarais and Breuer 2001).

2.4.1.6 Calibration

The sensor's accuracy can be increased from the production or supplier specifications through calibration before test. Calibration can be done in the laboratory before test, or it can be completed by the manufacturer, usually at a cost. There are two basic ways that sensors can be calibrated, using fixed points or through bath calibration.

Calibration Using Fixed Points: In this context, fixed points refer to temperature points that are associated with thermodynamic properties of a pure substance, such as the triple point or melting point of a substance (Nicholas and White 2001). These points consistently occur at the same temperature and are highly reproducible, making them one of the most accurate ways to calibrate a thermometer. The International Temperature Scale of 1990 (ITS-90) is the adopted standard temperature scale that defines temperature in relation to fixed points. On the ITS-90 scale, the fixed points range from −270 to 1084 °C in the original scale (Preston-Thomas 1990), with secondary points added for temperatures up to 3414 °C (Bedford et al. 1996). One of the most important points widely used is the triple point of water, which occurs at 0.01 °C.

Bath Calibration: In bath calibration, the thermometer in question is calibrated against a standard or reference thermometer. Both are placed in the same environment, such as a bake chamber, a bath, or vacuum chamber (Dames 2008). Like in calibration using fixed points, it is important for both the thermometer to be calibrated and reference thermometer to be correctly attached or immersed in the chamber or bath. In addition, the reference thermometer must also be very accurate. In this type of calibration, many temperature points can be tested quickly and calibration can be completed for a batch of thermometers for a range of test temperature (Nicholas and White 2001). This kind of calibration can be completed for resistance thermometers, thermocouples, or silicon sensors.

2.4.2 Direct Versus Indirect Measurement

When a measurement is needed, another consideration to take into account is where the sensor is located. If the object is very far away, attaching a sensor directly on or in the object may be impossible. However, not attaching a sensor on an object of interest can introduce measurement errors. We briefly discuss direct and indirect measurements below, with a few examples of each.

2.4.2.1 Direct Measurement

In direct measurement, the sensor has direct contact with the object or substance that is being measured. Some examples of direct measurement include:

- Attaching a thermocouple to the center of an integrated heat spreader of a microprocessor to measure the case temperature of the package.
- Using a sheathed, platinum resistance thermometer to measure the bath temperature of water.
- Incorporating an on-die silicon diode onto a microprocessor to measure the temperature of the active area of the silicon.
- Placing thermocouples upstream and downstream of test setup, in the flow stream of the test, in order to measure the inlet and outlet air temperature of the test.

Direct measurement is often the most accurate way to take a temperature of an object. Even in direct measurement, making sure the correct location and correct number of sensors used is still important. For example, if the bath of water is taking up the volume of an Olympic-size pool, using one resistance thermometer may not capture temperature variation of different points in the pool of water.

2.4.2.2 Indirect Measurement

In indirect measurement, contact is not made with the object or substance of measurement. Radiation thermometers make almost exclusively indirect measurements with no contact with the object. However, thermocouple and resistance thermometers can also be making an indirect measurement if they are not placed exactly at the location of interest. Some examples of indirection measurement include:

- Using a radiation thermometer to measure the temperature of an object at a far distance.
- Placing an on-die diode that is on the die but not directly at the hot spot of the processor during workloads.
- Using an infrared camera to measure the temperature contours of a powered-on processor.

2.4.3 Temperature Scales

Temperature scales that are linked to heat sensitivity were not always in existence and it has taken many years to standardize the scales (Biró 2011). The first thermometers, where scales were included next to a measuring tube, are associated with several people, including Galileo and Ferdinand II of Tuscany (Biró 2011). For most scientists and engineers today, the most well-known scales are the Celsius, Fahrenheit, and Kelvin scale. In this section, we discuss these relevant scales. We also briefly discuss the more recent International Temperature Scale of 1990.

2.4.3.1 Fahrenheit

The Fahrenheit scale was named after Daniel Fahrenheit, who created this scale in 1724 (Biró 2011). This scale, like other scales of the time, is based on using fixed points to determine extremes of the scales and divided by an easy to remember number of steps (Nicholas and White 2001). Fahrenheit's scale is sometimes called the 96-based system, because he divided his scale by 96 parts. At the high extreme, he used the human body temperature of 96 °F as one of his fixed points and at the low extreme, he used the melting point of salty ice to be 0 °F (Biró 2011). This scale is often related to the Celsius scale, by the Eq. 2.13 below:

$$^{\circ}\mathrm{F} = 32 + \left[\frac{9}{5}\right] {}^{\circ}\mathrm{C} \tag{2.13}$$

This equation is not always convenient. But most remember the relation by knowing that 32 °F is associated with the freezing point of water at 0 °C and that 212 °F is associated with the boiling point of water at 100 °C.

2.4.3.2 Celsius

The Celsius scale is also a well-known and widely used temperature scale. It is named after Anders Celsius, who created the scale in 1742 (Biró 2011). Like the Fahrenheit scale, it is based on using fixed points at the ends of the scale but instead of dividing by 96 parts, Celsius divided by 100 parts. For fixed points, he used the boiling temperature of water at the high end of the scale and the freezing temperature of water at the other end of his scale. Equation 2.11 can be rewritten to obtain degrees Celsius from degrees Fahrenheit by Eq. 2.14:

$$^{\circ}\mathrm{C} = \left[\frac{5}{9}\right] \times \left({}^{\circ}\mathrm{F} - 32\right) \tag{2.14}$$

2.4.3.3 Kelvin

The Kelvin scale was created to describe the absolute zero temperature point. Absolute zero is described as the point where there is no thermodynamic motion and where the thermal energy is zero (Biró 2011). Through experiments, absolute zero was determined to be −273.15 °C. Like the Celsius and Fahrenheit scales, the Kelvin scale is fixed at two points: 0 K is set to absolute zero and 273.15 K is set to the triple point of water. Because of how absolute zero and 0 K are defined, degrees Celsius and kelvin are often related by Eq. 2.15:

$$K = {}^{\circ}C + 273.15 \tag{2.15}$$

Unlike degrees Celsius and degrees Fahrenheit, kelvin is not reported as degrees Kelvin. Instead, it is just report as *K*, a unit of temperature (Nicholas and White 2001).

2.4.3.4 ITS Scale

As mentioned earlier under calibration with fixed points, the International Temperature Scale of 1990 (ITS-90) is an adopted standard temperature scale that defines temperature in relation to fixed points. On the ITS-90 scale, the fixed points are from −270 to 1084 °C in the original scale (Preston-Thomas 1990). An addition with quality secondary points was added for temperatures up to 3414 °C (Bedford et al. 1996). The fixed points, which occur consistently at the same temperature and are highly reproducible, are chosen from thermodynamic points—boiling point, melting point, or triple point, to name a few—of substances such as water, hydrogen, copper, and more. On the original scale, the lowest fixed point was the vapor pressure point of helium at −270.15 to −268.15 °C and the highest point was the melting point of copper at 1084.62 °C. With the secondary reference points, the lowest fixed point is now zinc at −272.3 °C and the highest point is the melting point of tungsten at 3414 °C. The ITS scale is often used to provide a reference calibration point.

2.5 Sensing Noise

Sensors are manufactured with specified accuracy ranges, which can further be calibrated by the manufacturer or user to gain even more accuracy. Despite the knowledge and experience on obtaining accurate sensors, readings can still have inaccuracies due to noise. Noise can be caused by process, metrology, or it can be intrinsic to the sensor. This section briefly discusses those three sources of noise.

2.5.1 Process Noise

Many manufacturing processes are now very controlled and products from the manufacturing line are consistent and are mass copies of one another. Despite this control, it is impossible to hit the same values, such as thickness or diameter, every single time for every single product off the line. Manufacturing processes can have some standard deviation from the mean or set point, which the end user can see as ranges of accuracy in sensors or as sensors that are not made to an exact specified length or diameter.

A good example of process noise occurs in silicon manufacturing. This variation will be present in diodes that are embedded in the microprocessor or in stand-alone silicon sensors. To make silicon sensors and microprocessors, the manufacturing process involves growing and laying down several layers of silicon, oxides, and metals, each with its own thickness set point. If the layer is supposed to be 10 microns thick, it likely can vary between 10, 10.1, or 9.9 μ, depending on the tolerances allowed.

Sensors can be rated to be accurate to ±5 °C, but a specific sensor could be accurate to 1 °C or perhaps 4 °C. When sensors are delivered from the manufacturing plant, process noise will be present. Calibration or tests versus temperature references (that is, a well-stirred water bath) can be used to understand how process noise may affect the performance of the sensors and to reduce any errors.

2.5.2 Metrology Noise

In addition to process noise, metrology noise is introduced through calibration and measurement equipment, such as chambers, power supplies and data acquisition machines, to name a few sources.

During Calibration: In order to calibrate sensors, the user or manufacturer must use reference points by calibrating to fixed points or reference thermometers. If the reference thermometer is not exactly accurate itself or if it has drifted over time, then the sensor being calibrated to it can see this error in accuracy. When baths or chambers are being used, the temperature distribution within the bath and chamber can introduce errors to the sensors being calibrated in them. If the temperature at the edge of the chamber is 0.2 °C warmer or cooler than the center, sensors near the edge would not be calibrated to the same temperature as those located in the center and a 0.2 °C error is introduced. It is best to make sure the bath and chamber is well-stirred and that the temperature distribution is as even as possible during calibration. It is also advisable for the reference sensors to be calibrated on a periodic basis.

During Measurement: During measurement, power supplies, data acquisition machines, temperature readers, voltmeters, multi-meters and similar equipment can be used in providing power, in recording data and in reading out data. These electronics will have specific tolerance ranges and accuracy limits separate from those of the sensors. Calibration may also be required for the electronics used in gathering measurements from the sensors. If, for example, the power supply is deviating slightly from the specification and is providing more voltage than is being reported, the sensor can read a higher temperature than it would at the correct voltage. It is advisable to use calibrated electronics with the sensors and to compensate for any errors introduced if needed.

2.5.3 Sensor Intrinsic Noise: Material and Thermal Effects

In all thermal sensors, there is noise that is associated with how the sensors work, with the types and quantity of materials used, and with the long periods of heat exposure. This kind of noise can be unavoidable, but can be reduced to minimize its effects. Ignoring or being unaware of these noise factors may introduce large errors in measurement.

Self-Heating: Self-heating errors occur when the temperature reading in the sensing element is increased due to heat caused by the sensing element itself. For resistance thermometers, the current flowing through the wires causes self-heating. The increase in temperature is described by Eq. 2.16,

$$\Delta Temperature_{self-heat} = \frac{R \times I^2}{D} \tag{2.16}$$

where R is the resistance of the element, I is the current flowing through the element, and D is a constant that describes the dissipation between the element and the fluid or solid being measured (Nicholas and White 2001). The relationship between the self-heat error and current tells us that even a small current can produce a large error because current is raised to the second power. To reduce self-heating effects, the current should be as small as possible while balancing the required accuracy of the temperature reading (Dames 2008). Self-heating effects can also be decreased by maximizing the constant D as much as possible—in order to do this, the contact between the sensor element and fluid or solid should be very good, with no gaps and no weak attachment methods. Despite the efforts to decrease self-heating errors, in some cases it will be impossible to avoid them—for example, in cases where the sensor is measuring the temperature of very stagnant air (Nicholas and White 2001). Stagnant air would not provide very effective cooling and it is likely that the whole sensor setup would self-heat in this environment.

Thermoelectric Effects: Thermoelectric errors occur when more than one type of metal is used in the construction of the sensing element and associated body and wiring (Dames 2008). Other areas where different metal wires can be introduced include metrology electronics, such as data acquisition machines, and power supplies. When more than one metal is used, the different metals can produce a Seebeck voltage that would lead to a temperature gradient along the sensing element and associated wires (Dames 2008). For resistance thermometers, this would lead to different voltage readings along the wire and introduce error to the temperature reading of the sensing element. The Seebeck effect is vital in order for thermocouples to work properly, but introductions of different metal types in the construction of thermocouple extension wiring can produce temperature gradients in the wires in a similar manner to what occurs in resistance thermometers (Nicholas and White 2001). In both sensor types, the degree of error is dependent on the Seebeck coefficient of the metals involved. The temperature gradient in the wiring can be as much as 10 °C and consequently, this temperature gradient can lead to inaccurate readings of 1 °C or more for resistance thermometers and thermocouples (Dames 2008); Nicholas and White 2001).

Other Thermal Effects: The long-term exposure to heat has the effect of elastically deforming the wires or leads of the sensor. With deformation, the metal can stretch and contract through several cycles, introducing errors as a result of different rates of expansion and contraction and the subsequent change in the resistance of the wire (Nicholas and White 2001). In addition, other causes of thermal gradients than the two previously discussed (self-heating and thermoelectric effects) will produce noise. For example, thermal effects that lead to larger thermal gradients can be introduced from inadequate connection between sensing wires and leads or extension wires (Nicholas and White 2001).

2.5.4 Sensor Intrinsic Noise: Lead Wire Resistance

For thermocouples, if the correct instrumentation is used with little current through the circuit, there should be negligible resistance in the wires (Nicholas and White 2001). Lead wire resistances have a larger effect on resistance thermometers, because current needs to flow through the sensors for RTDS to work. Resistance thermometers have several wire configurations with different numbers of wires: two-wire, three-wire, or four-wire. The circuit they are based on is commonly called the Wheatstone bridge (Love 2007). One of the resistors in the circuit is the resistance thermometer of interest. The other resistors are defined to complete the circuit in equilibrium at a reference temperature (Love 2007).

Two-Wire Resistance Thermometers: A two-wire configuration is a common and inexpensive configuration for resistance thermometers. However, it is also the configuration that is most susceptible to error. Figure 2.11 depicts the configuration of a simple two-wire bridge.

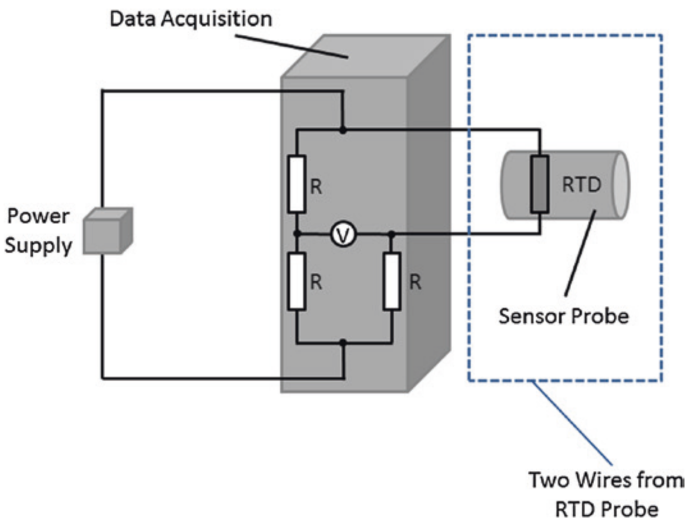


Fig. 2.11 RTD—simple two-wire resistance network. Adapted from Love (2007)

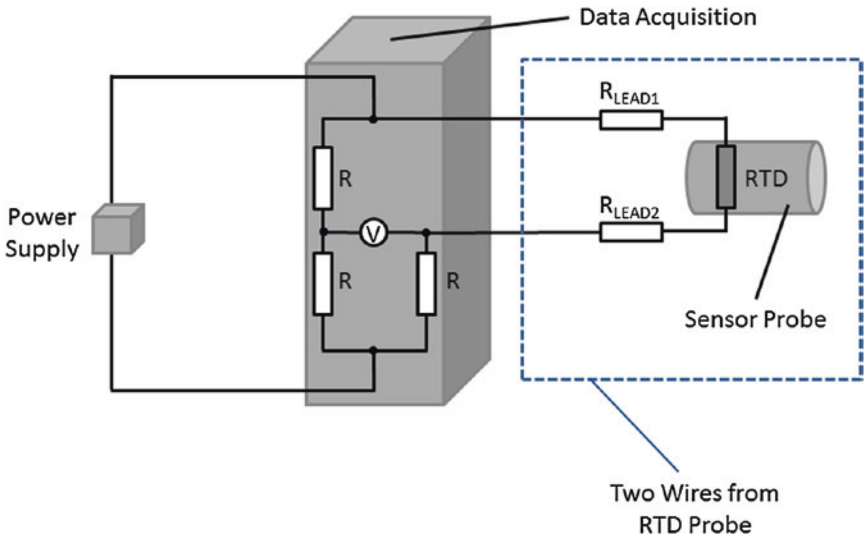


Fig. 2.12 RTD—two-wire resistance network with long leads. Adapted from Love (2007)

The bridge works well if the leads to the resistance thermometer are negligible and there is no measurable resistance in those leads. Error is introduced when the leads to the thermometer are very long, so that the lead resistances are not equal or small (Love 2007). Figure 2.12 depicts where the extra resistors would be introduced in series with the resistance thermometer. The extra resistances would cause inaccurate readings for the resistance thermometer.

Three-Wire Resistance Thermometers: A three-wire resistance thermometer features three leads from the resistance thermometer, as depicted in Fig. 2.13. It is more accurate but also more costly than a two-wire circuit. R_{LEAD1} and R_{LEAD3} will cancel out in this configuration when the circuit is in equilibrium (Love 2007). R_{LEAD2} is the resistance between the voltmeter and the lead across the circuit. The network should have very little current through R_{LEAD2} when the circuit is balanced so its resistance should be very small (Love 2007). In real conditions, there could be some error due to the lead resistances because no two resistors are exactly equal, but the error in a three-wire circuit is much less than using a two-wire circuit.

Four-Wire Resistance Thermometers: The most accurate circuit configuration for a resistance thermometer is the four-wire circuit, as depicted in Fig. 2.14. It is the most expensive because it uses more material than a two-wire or three-wire circuit. In this configuration, the lead resistances carry constant current in the outer loop and another inner loop with two other resistors measure the resistance across the thermometer directly (Love 2007).

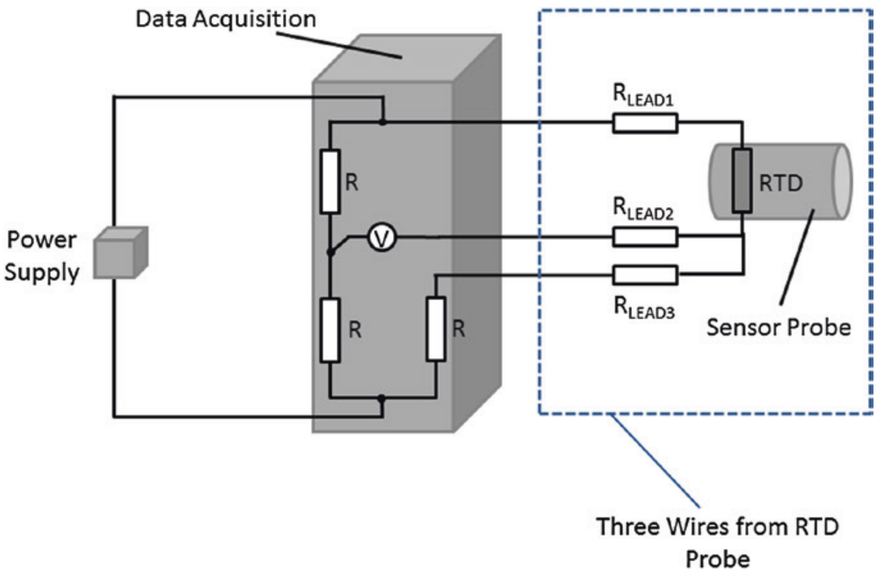


Fig. 2.13 RTD—three-wire resistance network. Adapted from Love (2007)

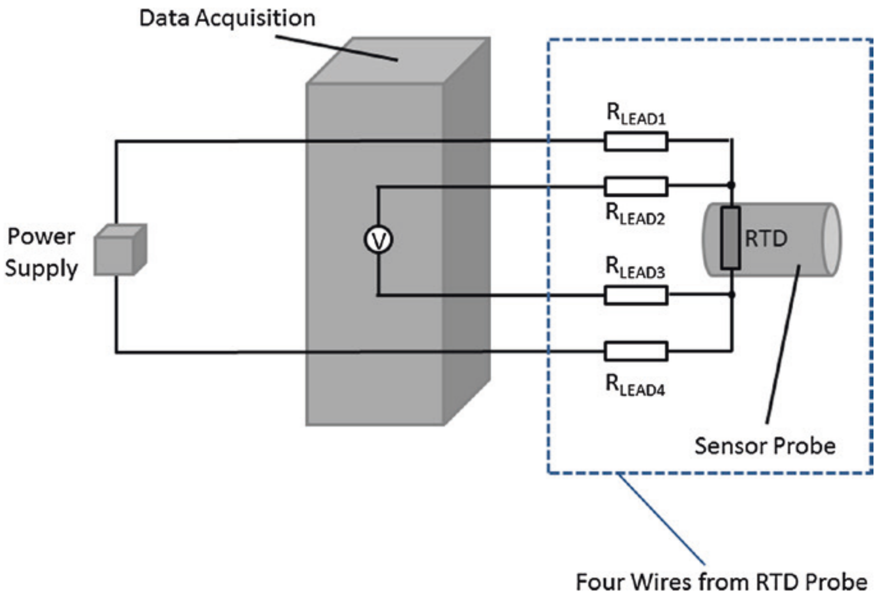


Fig. 2.14 RTD—four-wire resistance network. Adapted from Love (2007)

2.6 Sensor Reliability

Thermal sensors will be exposed to temperature cycling and high temperatures throughout their use. Inevitably, this will cause degradation in sensor accuracy and complete breakdown of the sensor as it reaches the end of its life. In addition, there are other sources that can cause complete sensor error or breakage well before the end of its expected lifetime. There are techniques and sensor configurations that can prevent catastrophic failure and extend its life, but sensors are not meant to last forever. This section discusses a few sources that contribute to unreliable accuracy and causes of sensor failure.

2.6.1 Shock and Vibration

Two causes of sensor failure and sensor reading drift are shock and vibration during packaging and shipping from the supplier to the calibration laboratory and ultimately to the use location. Sensors can also experience shock and vibration effects during attachment and during use while measuring the fluid or object temperature. Shock and vibration can cause total failure by breaking the sensor wires completely and cause slow deterioration and accuracy drift if the effects are experienced over time, for example, as a sensor that is attached to vibrating machinery would (Nicholas and White 2001). Shock and vibration can also cause the sensor wires to kink, bend or change shape, leading to changes in electrical resistance (Nicholas and White 2001). In addition, any metal strengthening due to plastic deformation caused by shock and vibration can change the electrical resistance of the wire (Nicholas and White 2001). To prevent shock and vibration effects, the sensors should be adequately packaged and carefully handled during shipping. Insulation can also be used to dampen the shock and vibration effects during shipping as well as use.

2.6.2 Hysteresis

Hysteresis is a condition where, in addition to the current sensor environment, the previous sensor environment also affects the current sensor readings (Kenny 2004). Hysteresis becomes apparent for temperature sensors during temperature cycling (Nicholas and White 2001). The metal wires used in sensors will stretch and contract as the temperature cycles between temperatures. The different rates of expansion and contraction will affect the next sensor reading and result in erroneous readings. As an example, let us take a sensor that is used to measure a fluid at a high temperature of 400 °C and is then used to measure fluid temperature as its temperature decreases. The sensor at 375 °C will likely not have had enough time to fully contract and will still see expansion effects from being exposed to 400 °C. The reading at 375 °C will subsequently have errors. As the number of cycles increase, the error also increases. Hysteresis effects can be reduced by allowing the sensor to contract back and reach equilibrium at a specific measurement point (Nicholas and White 2001). However, after many thermal expansions and contractions, the sensor will reach a point where deformation will no longer be elastic and the sensor will deform permanently. At that point, the sensor will be irreversibly damaged and its resistance will be permanently changed.

2.6.3 Chemical Environment

Because many thermal sensors and sensor peripherals are made of metals or alloys, the chemical environment to which the sensors are exposed becomes a very important factor for long-term reliability. Several different of types of thermocouples were described in an earlier section of this chapter, including ones made of iron, nickel, platinum, nickel-iron, copper-nickel, and other alloys. Each metal has a different reaction to moisture, vacuums, oxidizing, and reducing environments. For example, iron-based thermocouples may not be suitable at high-temperature, oxidizing environments because iron is easily oxidized (ANSI and IEC Color Codes 2014). In addition to the wires themselves, thermocouple wire insulators are subject to their own behaviors in different chemical environments. For example, many materials used as insulators for thermocouples break down in reducing environments, leaving the bare wires exposed to high temperatures (Nicholas and White 2001). Chemical environment effects lead to electrical resistive changes and to changes to the Seebeck coefficient of the metal materials (Nicholas and White 2001). This results in lower accuracies and can ultimately break the sensor. To avoid negative environment effects, thermal sensor type must be carefully chosen.

2.6.4 General Thermal Effects

Because thermal sensors are used to measure temperature, sometimes at very high temperature, thermal sensors are naturally going to suffer from thermal effects. The thermal effects are often compounded because of sensor exposure to unfit chemical environments or to vibration at the same time, as was already described earlier in this section. High temperatures will cause the metals to generally change shape, internal electron structure, and even external physical dimensions, which all change the sensor's resistance properties (Nicholas and White 2001). As temperature increases, the metals within one sensor may have different thermal expansion rates, causing work hardening (Dames 2008). High temperatures can also lead to metal migration in the wires, leading to metal contamination and increasing electrical resistance (Nicholas and White 2001). Because of these effects, it is important for the sensors to have proper insulation and for them to be used in the proper temperature environments. If sensors are not chosen carefully for measuring capability, the sensors may fail or result in erroneous measurements. Additionally, sensors should go through reliability tests to ensure that the thermal effects are understood before permanent installation.

2.7 Thermal Sensors in Handheld Devices

Smartphones and tablets have become very popular devices and they are present in many households in replacement of traditional laptops or landline phones. Because of widespread smartphone and tablet use, there has been a push to use the handheld devices to do more than their traditional functions of making phone calls, text messaging, or browsing the Internet. The ability of smartphones and tablets to connect to the Internet or to a wireless communication network also makes them good candidates for use as devices that collect information via sensors and share them with other applications or the Internet for consumption (Fujinami et al. 2013).

In handheld devices today, there are many embedded sensors that are commonly used. Accelerometers are used to detect which direction the handheld device is being held and they are also used in connection with applications that track running speed. There are also sensors that detect sound, which can be used to detect surrounding noise like music for music-recognition applications and light, which is frequently used today to automatically adjust screen brightness to accommodate changing dark or bright ambient lighting. In addition, there are GPS, proximity sensors, gyroscopes, and compasses embedded into smartphones that enhance location-based applications (Lane et al. 2010).

Within the handheld processor and attached to the board of the phone, thermal sensors can be used in traditional roles of monitoring the temperature of the processor and electrical hardware. These sensors are typically built-in silicon diodes or thermistors. However, despite the multi-functionality of smartphones and tablets, there are not as many instances where embedded sensors are being commercially used to monitor environmental readings such as temperature, humidity, or UV-radiation (Fujinami et al. 2013). Studies and development opportunities exist to expand the use of handheld devices to encompass thermal sensors. For example, there is a published proposal by Fujinami et al. to use smartphones as devices that can monitor temperature for heat stroke prevention by using a silicon sensor and Android†-based software (Fujinami et al. 2013). However, because handheld devices can be placed in several different positions, the inaccuracy of the temperature readings to the intended measurements can be large. For example, a handheld device placed in a bag will be more inaccurate when compared with a device hanging from a person's neck in measuring the ambient environment temperature (Fujinami et al. 2013). The complication of inconsistent handheld device placement would also make it difficult to use handheld devices to monitor body or skin temperature for medicinal purposes. Some other considerations for smartphone and tablet temperature monitoring to be effective include development of a robust and standard sensing methodology with handheld devices and agreement on where data is being stored and how it is transmitted (Lane et al. 2010). In addition, if thermal sensors are to be used to monitor health and ambient conditions uninterrupted, CPU bandwidth, memory use, and battery consumption with other applications in the handheld device should be considered and will need be balanced (Lane et al. 2010).

2.8 Thermal Sensors in Remote Applications

As sensor technology becomes more sophisticated, smaller, and cheaper, there have been research and proposals to use sensors wirelessly to measure an object or fluid from afar or to embed them into textiles to provide on-body sensing. In this section, we briefly discuss thermal sensors as wireless sensors and in wearables. Like the previous section on thermal sensors in handheld devices, the discussion is not exhaustive but highlights the emergence and development of how thermal sensors can be used in the future.

2.8.1 Smart Sensors

At the basic level, wireless sensors and sensors for wearables can be considered smart sensors. Traditional sensors are hard-wired, specialized to one task, localized, and require support equipment to transform the electrical input to the intended output like temperature (Mekid et al. 2010). Smart sensors can have the ability to collect various types of sensor data in one unit or die, like temperature, pressure, and humidity (Roozeboom et al. 2013). Smart sensors can also integrate various other functions to one sensor unit, including the ability to transform the input to a consumable output within the wireless unit, compensate for expected errors, and communicate and transmit data (Mekid et al. 2010). For temperature sensors, they can be made “smart” by integrating the analog-to-digital converter (ADC) with the temperature sensor (Bakker 2002). Temperature sensors are also likely to be silicon-based, like doped-Si resistance thermometers or bipolar transistor-based thermal sensors (Roozeboom et al. 2013).

2.8.2 Wireless Sensors

The temperature sensor can be one node in a network of many temperature sensing or other sensing nodes (Mukhopadhyay 2013). For wireless sensors, communication is typically transmitted through radio frequency signals. Currently, three of the more popular signals to use are Wi-Fi†, Bluetooth†, and Zigbee† (Mekid et al. 2010). The radio frequency should be chosen for the application so that there is minimal interference from other radio sources, like microwaves or television, and so that the wireless sensor can operate no matter the location (Mukhopadhyay 2013). Additionally, the cost and power-bandwidth of each type of signal should be considered. For example, Wi-Fi has large range and more data bandwidth capability, but it also consumes large amounts of power compared to using Zigbee signals (Mekid et al. 2010). There is an increasing interest in sensors to wirelessly monitor for applications such as environmental efficiency, transportation, in smart homes and in health care (Mukhopadhyay 2013). It is easy to envision the latter two areas as examples where temperature sensors can easily be applicable. Temperature sensors may be used to coordinate room temperatures within the home for increased energy efficiency or comfort. Temperature sensors can also be useful for health-care monitoring to measure body and skin temperature.

2.8.3 Smart Sensors for Wearables

For health-care monitoring, smart sensors can be embedded in a wearable, which can be defined as anything from traditional clothing or small electronics like wristwatches, wristbands, glasses or chest-bands (Anliker et al. 2004). There have been several attempts to use temperature sensors to monitor body temperature, such as in the advanced care and alert portable telemedical monitor (AMON) project (Anliker et al. 2004), in the Bioharness† monitoring system (Johnstone et al. 2012), and in protective equipment to protect firefighters (Talavera et al. 2012). Even though there is high interest in monitoring temperature for health care, the AMON and Bioharness monitoring systems have shown inaccuracies in using wearable temperature sensors. For the AMON system, the wristwatch approach does not provide an adequate means of predicting body temperature (Anliker et al. 2004). For the Bioharness chest-belt, readings from an infrared camera have low correlation to actual body temperature measurement by a calibrated thermistor attached to the skin (Johnstone et al. 2012). While these studies are not exhaustive, it does showcase some attempts at using temperature sensors in wearables and is also indicative of needed improvements in the future to provide accurate temperature readings for wearables.

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