Measurement error caused by self-heating in NTC and PTC thermistors

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Introduction

A thermistor is a solid-state temperature-sensing device whose electrical properties change at different ambient temperatures. The word "thermistor" is a combination of the words thermally-sensitive resistor. The device is basically fabricated as a two-terminal solid-state transducer, where its resistivity is a direct function of temperature.

Thermistors can be made from different metal oxides or semiconductors (for example, arsenic diffusion into silicon), with metallized connecting leads onto a ceramic base (disc or bead).[1-3] These thermally-sensitive materials are known to exhibit a large, precise and predictable decrease or increase in their resistivity over the operating temperature range.

Moreover, being solid-state devices that are comprised of P-type or N-type semiconductor materials, thermistors respond differently to temperature changes. Any increase or decrease in the device's junction temperature will affect the atomic band structure and its electrical mobility. As temperature increases, there are more electrons/holes that contribute to conduction, thus producing a negative temperature coefficient (NTC). Contrarily, if free carrier mobility decreases as temperature rises, resistivity will increase, hence producing a positive temperature coefficient (PTC).

This article provides an analysis of the temperature dependency of thermistors and how the self-heating effect can cause erroneous readings in sensor measurements.

The fundamentals of thermistor conductivity

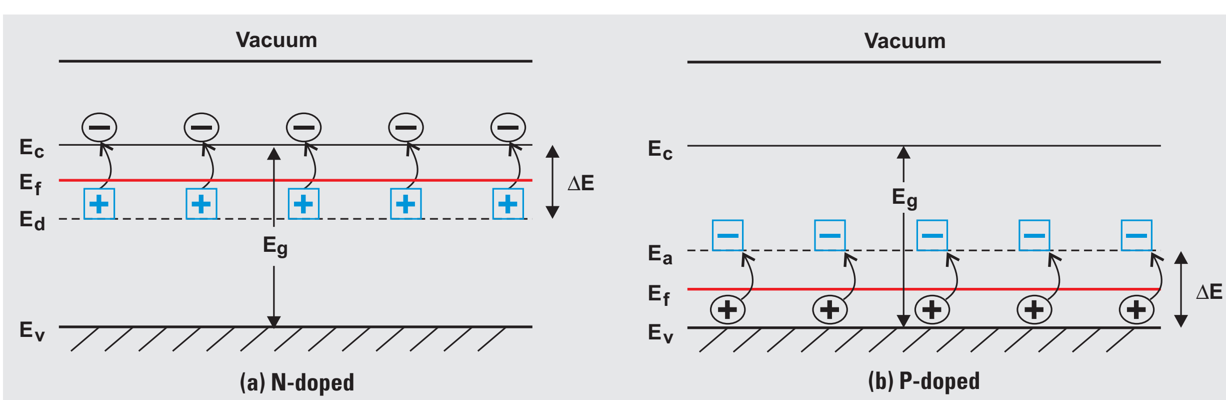
Electrical conductivity is one of the key properties of a semiconductor material and can be tuned in different ways. One common approach is to modify the electron (or hole) mobility by controlling the level of doping concentration diffused into the semiconductor substrate (to create an N-type or P-type doped semiconductor). Tailoring the energy-band structure of the doped semiconductor material (such as silicon) changes the electrical mobility.

Figure 1 shows the energy-band diagram of an N- and P-type semiconductor. The activation energy (ΔE) represents the amount of energy (thermal or other form of energy) required to raise electrons from the donor levels to the conduction band (N-type), or to accept electrons from the acceptor in the valence band (P-type). Therefore, the activation energy corresponds to the energy differences ($E_c - E_d$) and ($E_a - E_v$), respectively, for N- and P-type semiconductors, as illustrated in Figure 1. For an intrinsic semiconductor, activation energy is defined as the amount of energy required to raise electrons from the Fermi level to the conduction band, which is equivalent to half the band-gap energy ($\Delta E = E_c - E_f = 0.5 \times E_g$). References 4 and 5 express the variation of conductivity (δ) or resistivity (ρ) with respect to temperature. See Equation 1.

$$\delta = \delta_o e^{\left(-\frac{\Delta E}{2KT}\right)} \text{ or } \rho = \rho_o e^{\left(-\frac{\Delta E}{2KT}\right)} \tag{1}$$

where δ and ρ are the base conductivity and resistivity of the semiconductor material, respectively. For example, in Figure 1, the activation energy (ΔE) is required to raise electrons from donor to conduction level for N-type, and from valence band to the acceptor level in a P-type material.[6]

Figure 1. Energy-band structures of semiconductors



For intrinsic N- and P-type semiconductor materials, References 4 and 5 give these parameters as Equations 2, 3 and 4:

For intrinsic semiconductors,

$$\delta_o = 2e(\mu_e \times \mu_h) \times (m_e \times m_h)^{\frac{3}{4}} \times \left(\frac{2\pi KT}{h^2}\right)^{\frac{3}{2}} \quad \text{and} \quad \Delta E = E_a - E_v \tag{2}$$

For N-type semiconductors,

$$\delta_o = 2e\mu_e \left(\frac{2\pi m_e KT}{h^2}\right)^{\frac{3}{2}} \text{and} \quad \Delta E = E_c - E_d \tag{3}$$

For P-type semiconductors,

$$\delta_o = 2e\mu_h \left(\frac{2\pi m_h KT}{h^2}\right)^{\frac{3}{2}} \text{and} \quad \Delta E = E_a - E_v \tag{4}$$

where $\mu_{e/h}$ is the electron/hole mobility constant, $m_{e/h}$ is the electron/hole effective mass, e is the single electron charge, K is the Boltzmann's constant, T is the absolute temperature and h is the Plank's constant. Also, ΔE represents the activation energy previously discussed.

Note that in the real world, it is impossible to obtain intrinsic semiconductors around room temperature. Even with advancements in silicon technology, it would be very difficult to get to an impurity level below 1E13, as compared to an intrinsic level of around 1E10 for an ideal situation. Intrinsic behavior in silicon is possible if it is operated at high enough temperature (~250˚C and above). This would also put a limit on the silicon PTC maximum operating temperature (150°C used in this study).

Neglecting dimension changes during temperature variations, Equation 5 expresses the actual resistance of the semiconductor device as a function of the temperature (T) and semiconductor activation energy (controlled by doping):

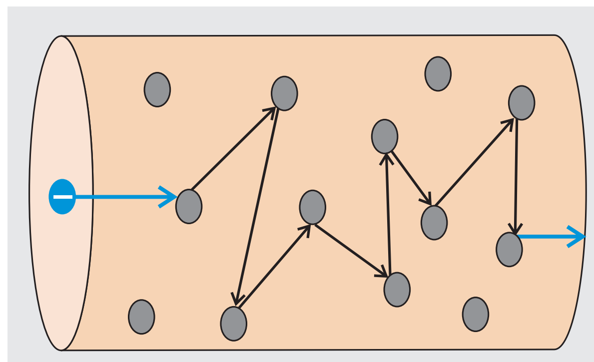
$$R = R_o e^{\left(+\frac{\Delta E}{2KT}\right)} \tag{5}$$

Equation 5 shows that if the temperatures increases, the resistance decreases. In other words, rising temperatures produce more charge carriers and contribute to the electrical conduction; hence, the resistivity drops.

On the other hand, the charge carrier mobility of a semiconductor is also affected by scattering events. In a solid-state temperature-sensing device, the mean free path reduces due to increased atomic vibrations and lattice scattering of carriers, so electrons/holes get less time to accelerate between collisions. This tends to increase resistivity opposed to the phenomena given by Equation 5. In the case of low-doped semiconductors, the first effect is predominant, so they are NTC thermistors. It is worth mentioning that with ceramic NTC, the situation is different than silicon. Generally, in non-crystalline semiconductors, the conduction mechanism is involved with carrier hopping from localized states, which is more complex.

Contrarily, heavily-doped semiconductors are already ionized at room temperature, so the second effect is predominant, resulting in a PTC thermistor. Note that the ionization energy of typical donors or accepters in common compound semiconductors is on the same order of thermal energy (KT) around room temperature. Therefore, the resistivity of most semiconductor devices is relatively constant around room temperature, rather than any exponential dependence. Charge particles, including electrons and holes, suffer from collisions with atoms such that their path through space between atoms is short, resulting in mobility degradation and increases in material resistivity. Figure 2 schematically shows the small scattering event of the charge particle caused by random collisions.

Figure 2. Scattering event of a charge particle

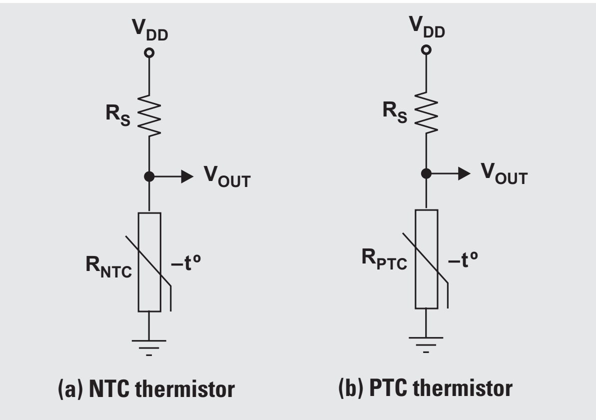


Unlike an NTC thermistor, in which the device's resistance changes exponentially against temperature (Equation 1), a PTC thermistor behaves linearly because the resistivity versus temperature is controlled by the mean free path. By using the concept discussed in this section, it's possible to design and fabricate different types of thermistors with NTCs and PTCs. These devices can then produce analog output signals in proportion to small changes in their temperature.

The self-heating effect in thermistors

To help understand the concept of self-heating, first consider one common approach when utilizing a thermistor device to measure temperature. As mentioned in the previous sections, a thermistor is a resistive device and therefore follows Ohm's law. According to Ohm's law, current passing through a resistive component will produce a voltage drop across that component. This voltage is proportional to the magnitude of the component resistance and the flowing current. Since a thermistor is a passive type of sensor, it requires an excitation signal (biasing signal) for its operation. Therefore, any changes in its resistance as a result of changes in temperature can be converted into a voltage signal and detected. One simple and common way to do this is to use the thermistor as part of a voltage divider circuit, as shown in Figure 3.

Figure 3. The voltage-divider circuit configuration to bias a thermistor



As shown in Figure 3, a constant voltage source is applied across the thermistor in series with a current-limiting resistor, and the output voltage is measured across the thermistor. The magnitude of the output signal V_{OUT} is proportionally related to the ratio of the resistive divider R_S and $R_{NTC/PTC}$. Thus, the potential divider circuit of Figure 3 is an example of a simple resistance-to-voltage converter, where the resistance of the thermistor is controlled by temperature and the output voltage produced is proportional to that temperature. Although this seems to be an easy method of using a thermistor, this method can suffer from self-heating and potential measurement errors. The self-heating effect is a phenomenon that takes place whenever there is current flowing through the thermistor.

Since a thermistor is basically a resistor, it dissipates power in the form of heat when current flows through it. This heat is generated in the thermistor core and affects measurement precision. The extent to which this happens depends on:

- The amount of current flowing through the sensor, which is proportional to the amount of power dissipated by the thermistor.
- The environmental conditions and thermal conduction (whether the sensor is surrounded by a liquid or a gas, and whether there is any flow over the sensor).
- The temperature coefficient of the thermistor.
- The thermistor's physical size/footprint.
- The electrical board layout on which the thermistor is mounted.

Under different ambient temperatures, the resistance value of the thermistor changes, which leads to a different power-dissipation and self-heating profile. NTC-type thermistors are known to have very nonlinear behavior, attributed to their exponential nature. At low temperatures, they normally have very large resistances. As the temperature increases, they substantially lose their resistance value. More importantly, the resistance-versus-temperature slope (sensitivity) of an NTC also becomes very small for higher temperatures.

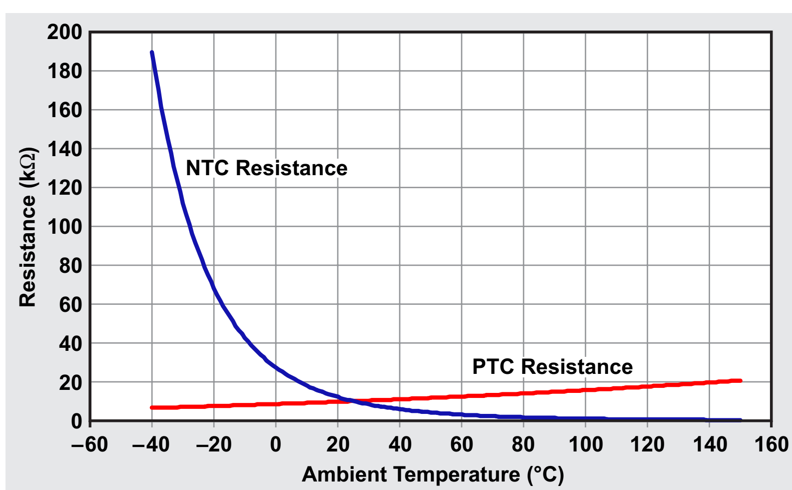
Conversely, silicon-based PTC devices have somewhat linear behavior with roughly constant sensitivity. As a result, the self-heating behaviors in NTC and PTC sensors can be significantly different using the method shown in Figure 3.

Figure 4 compares the NTC and PTC thermistors used for this study in a temperature range from –40°C to 150°C. The NTC thermistor has large resistance and sensitivity gain at lower temperatures, while the PTC thermistor has relatively linear behavior with roughly constant sensitivity gains.

Due to the substantially different behavior between NTC and PTC thermistors, proper selection of R_S (Figure 3) is of prime importance. Using a larger R_S will lower the biasing current through the thermistor. Lower current through the sensor essentially means lower power dissipation of the thermistor device. However, as the biasing current gets smaller, the sensitivity gain of the sensor will also become smaller, which causes noisy measurements and other potential issues.

This becomes more of a problem for NTC thermistors. Since the thermistor's resistance value and sensitivity are small at higher temperatures (Figure 4), R_S must be sufficiently small to maintain a reasonable sensor sensitivity gain. On the other hand, a PTC thermistor has larger resistance and sensitivity gain at higher temperatures.

Figure 4. Thermistor resistance versus ambient temperature



Therefore, the R_S component value can be sufficiently large to limit the biasing current and minimize the dissipated power at the PTC device junction.

Using R_S = 2 kΩ for the NTC thermistor and R_S = 10 kΩ for the PTC thermistor keeps a reasonable balance between the sensitivity gain and the biasing current. Then, under different supply voltages, the dissipated powers across the NTC and PTC thermistors can be calculated. Equation 6 expresses the self-heating power across the NTC and PTC thermistors employed in the circuit of Figure 3.

$$P_d(NTC) = R_{NTC} \times \left(\frac{V_{DD}}{R_{NTC} + R_S}\right)^2 \tag{6}$$

and

$$P_d(PTC) = R_{PTC} \times \left(\frac{V_{DD}}{R_{PTC} + R_S}\right)^2$$

Figure 5 compares the dissipated power across NTC and PTC thermistors under different biasing voltages (V_{DD}). The magnified view for V_{DD} = 1.8 V and 3.3 V is also shown in the same figure. The simulation data shown in Figure 5 is obtained by using the thermistor resistance values (R_{NTC} and R_{PTC}) versus the ambient temperature shown in Figure 4. Note that the power consumption of the NTC thermistor is substantially larger than shown by data collected for the PTC thermistor under the exact same biasing voltage. Also note that the NTC has a nonlinear power consumption profile, whereas dissipated power across the PTC thermistor is almost constant.

The results in Figure 5 confirm that PTC thermistors not only have superior performance with lower self-heating, but also predictable behavior over a wide range of measurement temperatures. Having a constant and predicable power-consumption profile makes it much easier for sensor calibration and self-heating autocorrection. This could be interpreted as one of the key advantages of PTC thermistors.

As mentioned previously, the extent to which self-heating in thermistors affects sensor-reading precision depends on several factors, including the sensor's thermal conduction (thermal conduction between the sensor and surrounding environment), the thermistor's physical size, and the electrical board layout on which the thermistor is mounted. Using a 0.5°C/mW temperature-drift coefficient for both NTC and PTC thermistors estimates the temperature drift caused by self-heating. Equation 7 calculates the self-heating temperature errors caused by dissipated power across both NTC and PTC thermistors.

$$\Delta T_{NTC} = \theta_{JA} \times P_d(NTC) \text{ and } \Delta T_{PTC} = \theta_{JA} \times P_d(PTC) \tag{7}$$

where θ_{JA} = 0.5°C/mW and ΔT denotes the temperature errors caused by self-heating.

Figure 5. The dissipated power across NTC and PTC thermistors

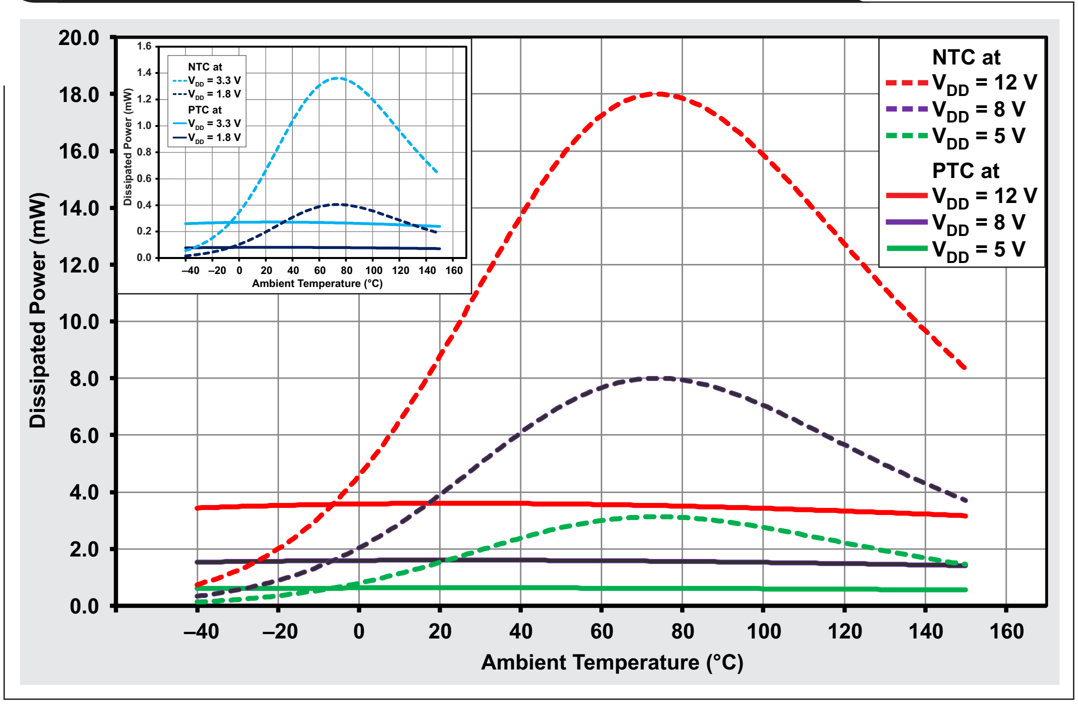
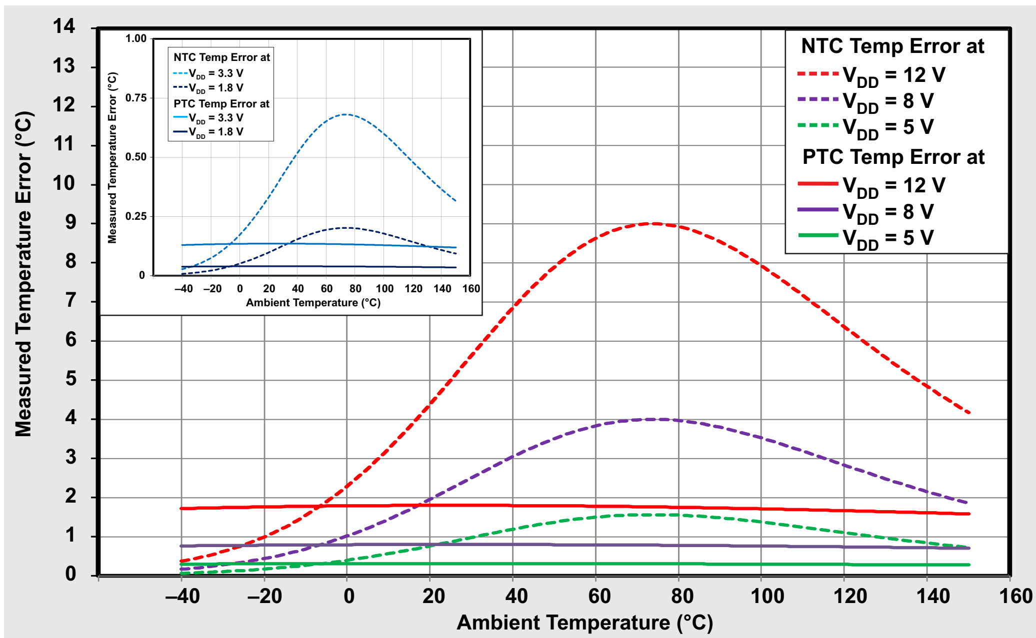


Figure 6 is a temperature-error comparison between NTC and PTC thermistors used in the network of Figure 3. Obtaining these results enables an investigation of the temperature-error dependency on the supply voltage for the two thermistors under study. The magnified view for V_{DD} = 1.8 V and 3.3 V is also shown in the same figure.

In PTC thermistors, the dissipated power over the entire temperature range is roughly constant, which results in a well-behaved and predictable temperature error, whereas in NTC thermistors, the consumed power profile is very nonlinear.

Similar to the results shown in Figure 5, the temperature error has a strong dependency on the supply biasing voltage. The temperature drift caused by self-heating in the PTC thermistor is much less than that obtained for the NTC thermistor. Also, as expected, the temperature drift in the PTC thermistor is almost constant over the entire temperature range. Again, this is a great advantage of linear PTC over NTC thermistors, since it's more convenient to calibrate the sensor and reject self-heating errors. These great advantages make silicon PTC thermistors more attractive, especially for applications where larger DC biasing voltages are available.

Figure 6. Temperature drift due to the self-heating effect in NTC and PTC thermistors



Conclusion

PTC thermistors increase their resistance as the temperature increases, while NTC thermistors reduce their resistance value as the temperature goes higher. NTC devices suffer from nonlinearity compared to silicon-based PTC devices. The NTC's nonlinearity degrades device performance and makes sensor biasing very challenging compared to silicon-based PTC thermistors.

Adding a series resistor (R_S) as part of a simple potential divider circuit provides current limiting such that changes to the thermistor's resistance caused by changes in temperature produce a temperature-related output voltage. However, the operating current of the thermistor must be kept as low as possible to reduce any self-heating effects. Test results demonstrated that due to the nonlinear nature of NTC thermistors, proper selection of R_S to limit the biasing current while achieving acceptable gain (especially at higher temperatures) is extremely difficult.

Sensitivity gain and self-heating are two competing parameters in NTC thermistors. For silicon PTC devices, however, self-heating errors are minimized compared to NTC thermistors. Not only are self-heating errors smaller in PTC thermistors, but the resulted drift is almost constant over the entire temperature range, and is easily correctable using cost-effective calibration methods.

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