Semiconductor Sensors:

Ch5: Temperatures Sensors

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انواع حسگرهای دما

۱- حسگرهای دمای مقاومتی

- ✓ مقاومت وابسته به دما RTD
- ✓ ترمیستور

۲- ترموکوپل ها

۳- حسگرهای دمایی مدار مجتمع

۴- حسگرهای دیداری مادون قرمز (اندازه گیری به روش غیر مستقیم)

مقایسه حسگرهای دما

مقایسه محدوده دمایی:

Sensor	Useful Temperature Range
Typical resistance temperature detectors (RTDs)[1]	–196°C to 661°C
Thermistors	–55°C to 100°C
Integrated circuit sensors	–55°C to 150°C
Thermocouples	–270°C to 2320°C

Ref: T. W. Kerlin ,and M. Johnson. *Practical thermocouple thermometry*. Instrument Society of America, 2012.

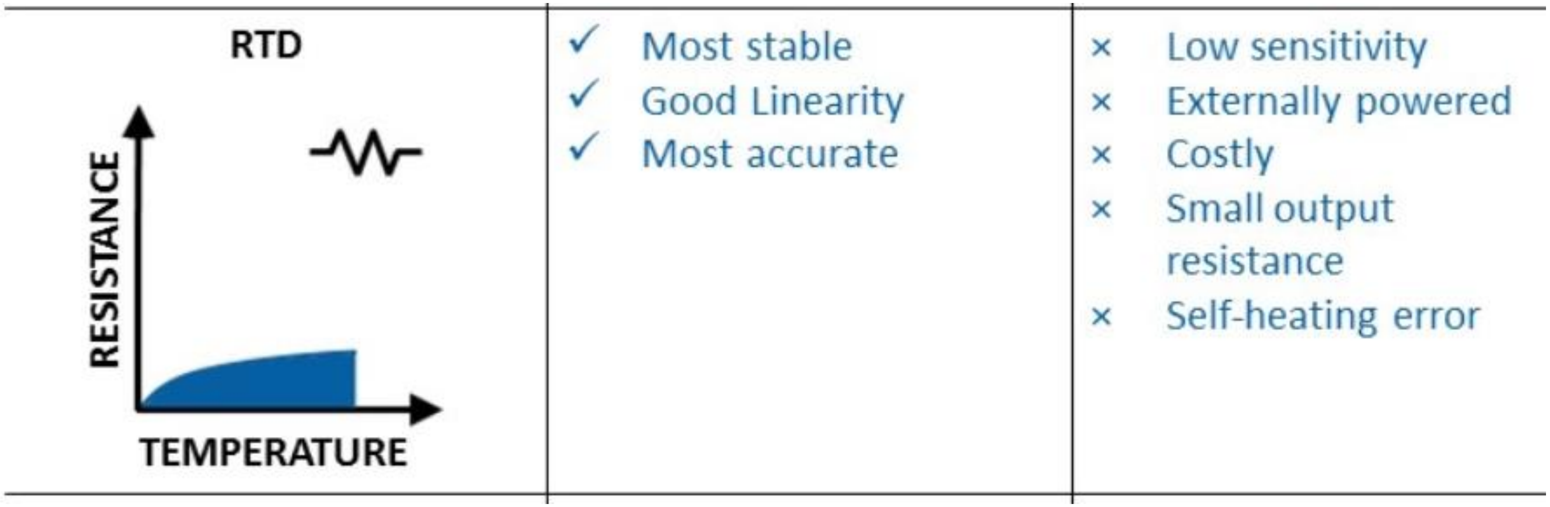
مزایا و معایب ترموکوپل:

	Advantages	Disadvantages
THERMOCOUPLES	✓ Simple ✓ Rugged ✓ Inexpensive ✓ No external power ✓ Wide temperature range ✓ Variety of styles	× Nonlinear response × Small sensitivity × Small output voltage × Requires CJC × Least stable

National Instruments Company -
http://sine.ni.com/np/app/main/p/ap/daq/lang/en/pg/1/sn/n17:daq,n21:17557/fmid/6681/

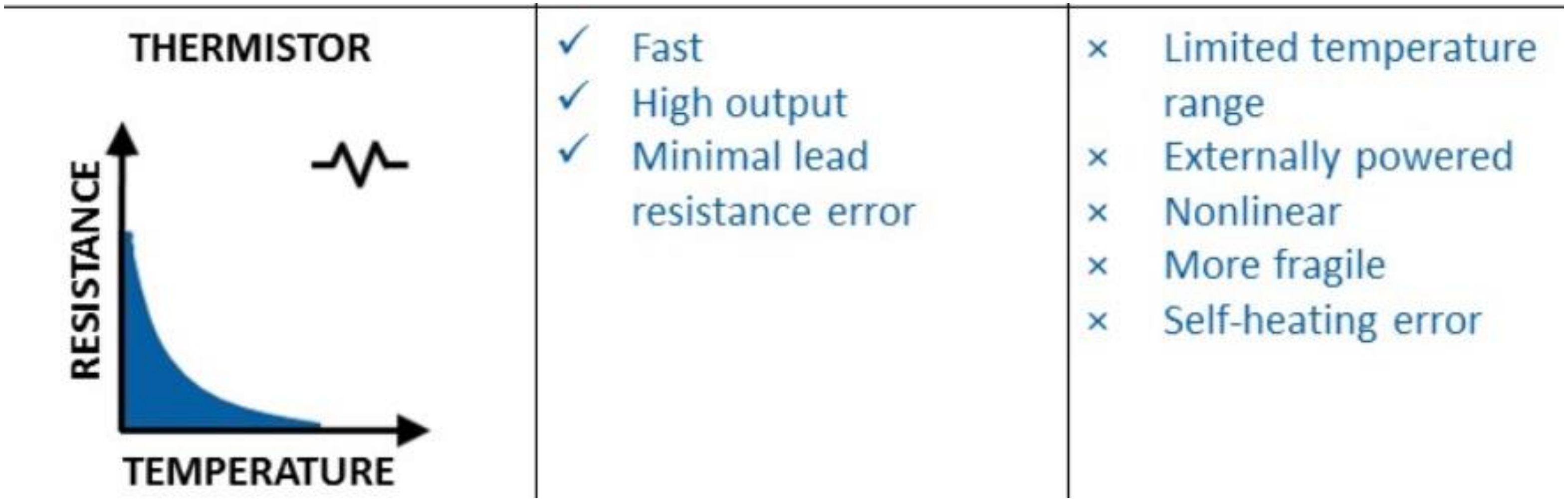
مقایسه حسگرهای دما

مزایا و معایب RTD:



RTD RESISTANCE TEMPERATURE	✓ Most stable ✓ Good Linearity ✓ Most accurate	× Low sensitivity × Externally powered × Costly × Small output resistance × Self-heating error

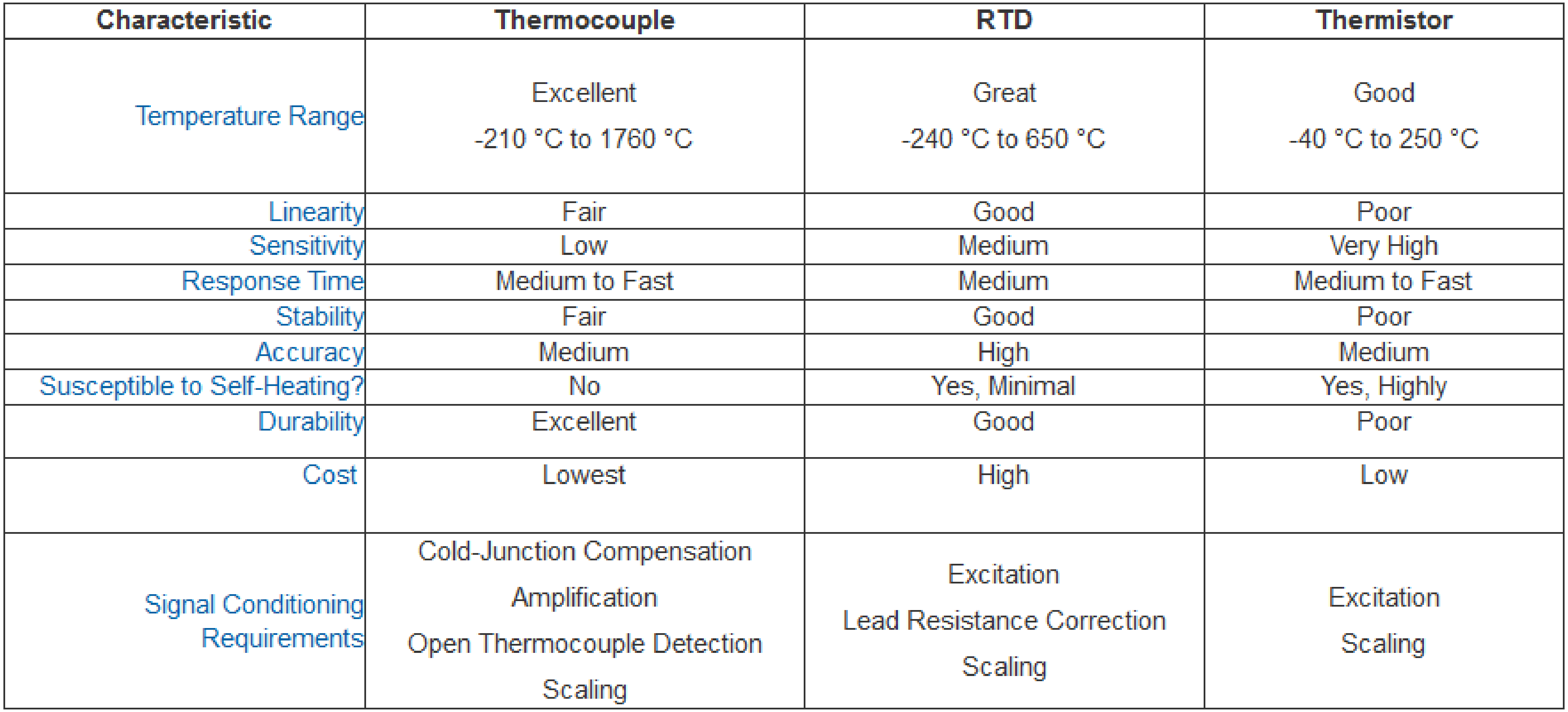
مزایا و معایب Thermistor:



THERMISTOR RESISTANCE TEMPERATURE	✓ Fast ✓ High output ✓ Minimal lead resistance error	× Limited temperature range × Externally powered × Nonlinear × More fragile × Self-heating error

National Instruments Company -
http://sine.ni.com/np/app/main/p/ap/daq/lang/en/pg/1/sn/n17:daq,n21:17557/fmid/6681/

مقایسه حسگرهای دما



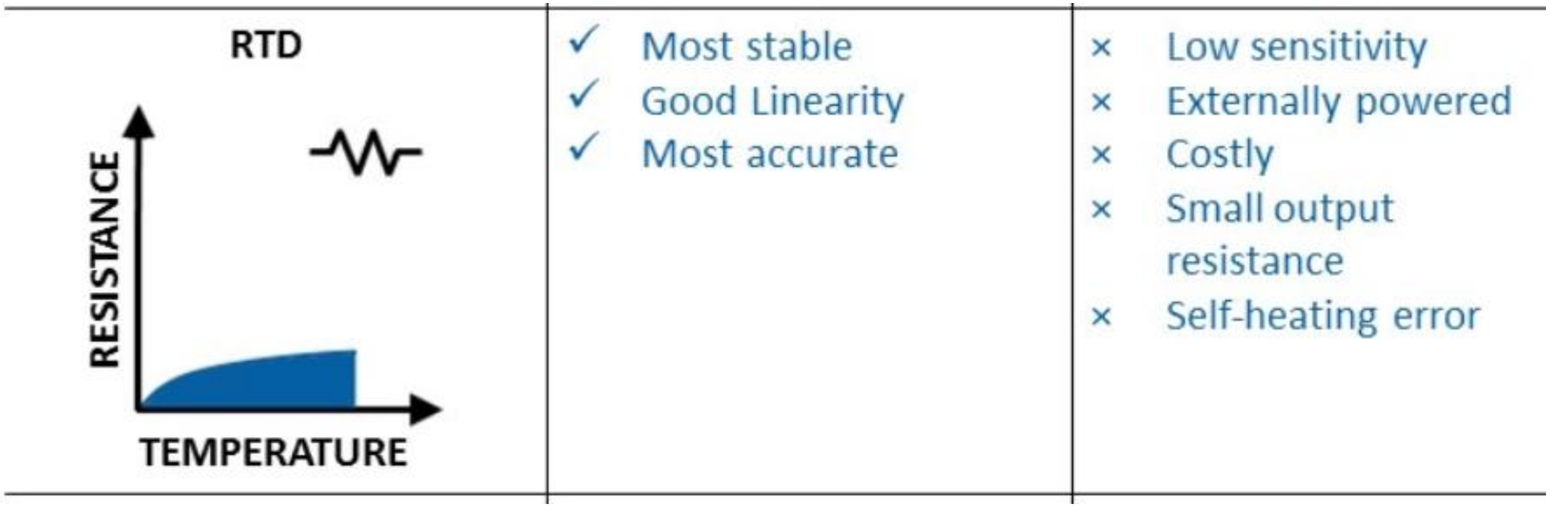
Characteristic	Thermocouple	RTD	Thermistor
Temperature Range	Excellent -210 °C to 1760 °C	Great -240 °C to 650 °C	Good -40 °C to 250 °C
Linearity	Fair	Good	Poor
Sensitivity	Low	Medium	Very High
Response Time	Medium to Fast	Medium	Medium to Fast
Stability	Fair	Good	Poor
Accuracy	Medium	High	Medium
Susceptible to Self-Heating?	No	Yes, Minimal	Yes, Highly
Durability	Excellent	Good	Poor
Cost	Lowest	High	Low
Signal Conditioning Requirements	Cold-Junction Compensation Amplification Open Thermocouple Detection Scaling	Excitation Lead Resistance Correction Scaling	Excitation Scaling

Table 2: *Comparison of Temperature Sensor Types*

National Instruments Company -
http://sine.ni.com/np/app/main/p/ap/daq/lang/en/pg/1/sn/n17:daq,n21:17557/fmid/6681/

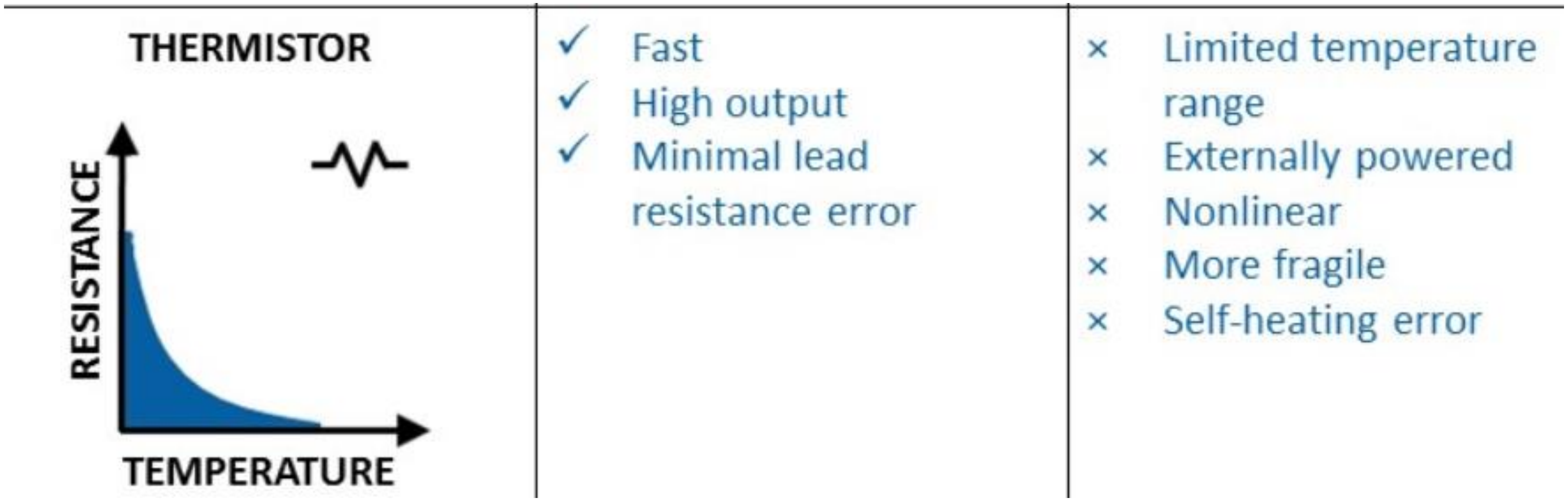
مقایسه حسگرهای دما

مزایا و معایب RTD:



RTD		
	✓ Most stable ✓ Good Linearity ✓ Most accurate	× Low sensitivity × Externally powered × Costly × Small output resistance × Self-heating error

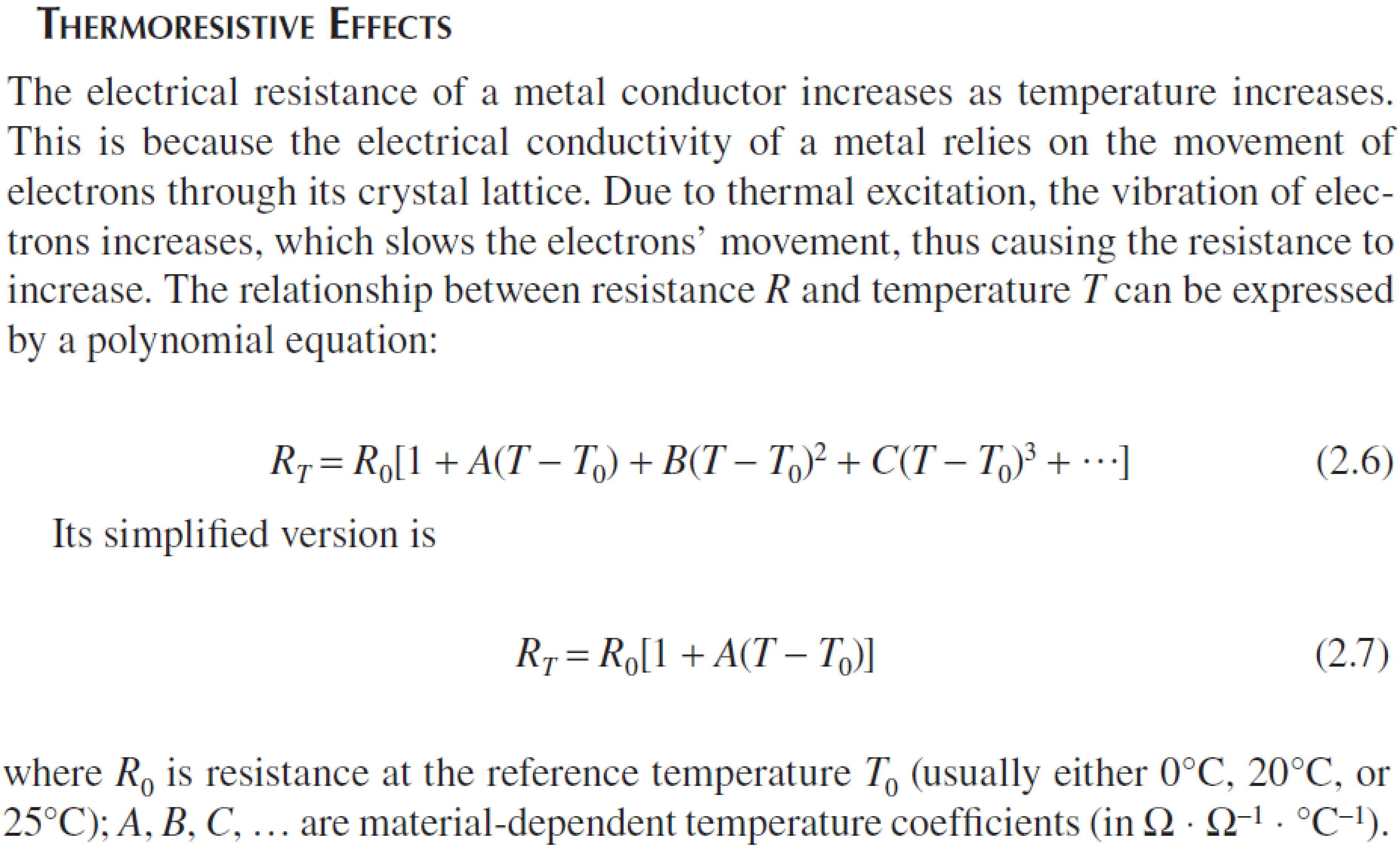
مزایا و معایب Thermistor:



THERMISTOR		
	✓ Fast ✓ High output ✓ Minimal lead resistance error	× Limited temperature range × Externally powered × Nonlinear × More fragile × Self-heating error

National Instruments Company -
http://sine.ni.com/np/app/main/p/ap/daq/lang/en/pg/1/sn/n17:daq,n21:17557/fmid/6681/

اثر گرمامقاوتی در فلزات (اساس کارکرد RTDها)



THERMORESISTIVE EFFECTS

The electrical resistance of a metal conductor increases as temperature increases. This is because the electrical conductivity of a metal relies on the movement of electrons through its crystal lattice. Due to thermal excitation, the vibration of electrons increases, which slows the electrons' movement, thus causing the resistance to increase. The relationship between resistance R and temperature T can be expressed by a polynomial equation:

$$R_T = R_0[1 + A(T - T_0) + B(T - T_0)^2 + C(T - T_0)^3 + \cdots] \tag{2.6}$$

Its simplified version is

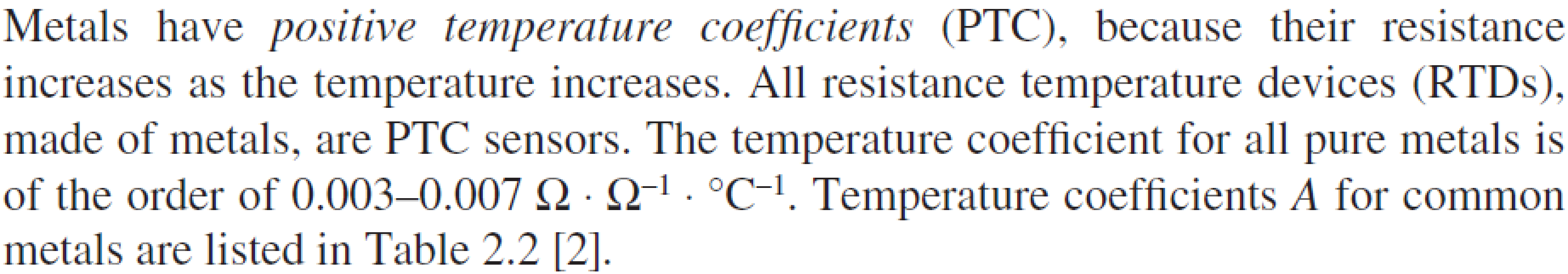
$$R_T = R_0[1 + A(T - T_0)] \tag{2.7}$$

where R_0 is resistance at the reference temperature T_0 (usually either 0°C, 20°C, or 25°C); A, B, C, … are material-dependent temperature coefficients (in $\Omega \cdot \Omega^{-1} \cdot {}^{\circ}\mathrm{C}^{-1}$).

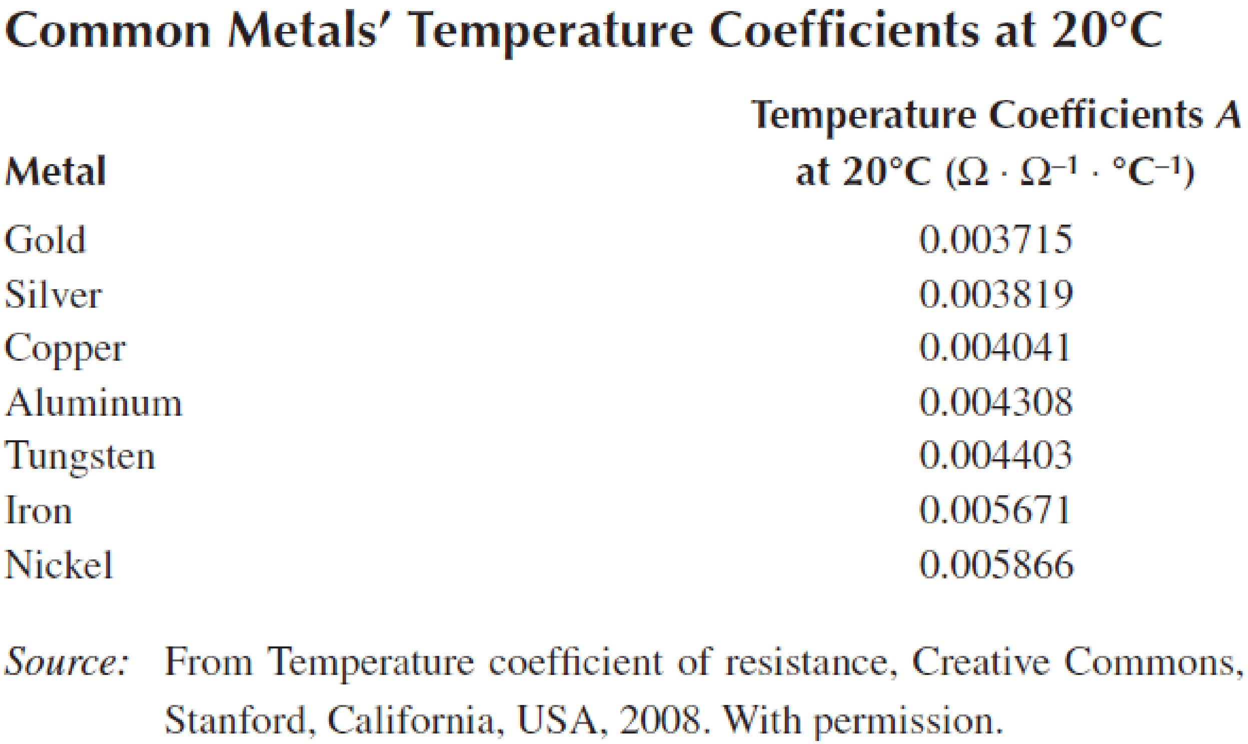
W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.

THERMORESISTIVE EFFECTS

اثر گرمامقاوتی در فلزات (اساس کارکرد RTDها)



Metals have *positive temperature coefficients* (PTC), because their resistance increases as the temperature increases. All resistance temperature devices (RTDs), made of metals, are PTC sensors. The temperature coefficient for all pure metals is of the order of 0.003–0.007 $\Omega \cdot \Omega^{-1} \cdot {}^{\circ}C^{-1}$. Temperature coefficients A for common metals are listed in Table 2.2 [2].



Common Metals' Temperature Coefficients at 20°C

Metal	Temperature Coefficients A at 20°C ($\Omega \cdot \Omega^{-1} \cdot {}^{\circ}C^{-1}$)
Gold	0.003715
Silver	0.003819
Copper	0.004041
Aluminum	0.004308
Tungsten	0.004403
Iron	0.005671
Nickel	0.005866

Source: From Temperature coefficient of resistance, Creative Commons, Stanford, California, USA, 2008. With permission.

W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.

THERMORESISTIVE EFFECTS

EXAMPLE 2.4

A copper wire has a resistance of 5 Ω at 20°C. Calculate its resistance if the temperature is increased to 65°C.

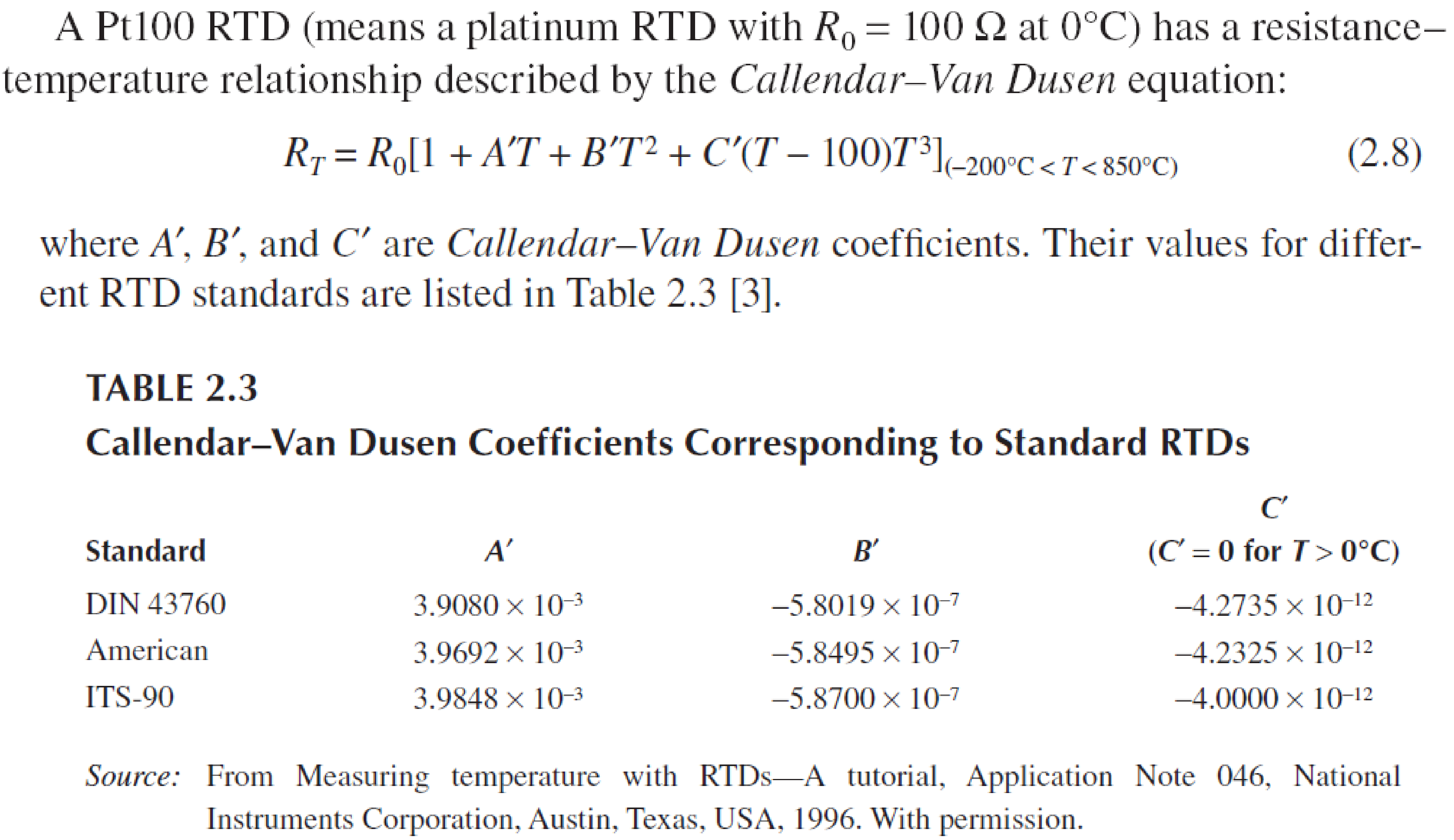
SOLUTION

From Table 2.2, $A = 0.004041\ \Omega \cdot \Omega^{-1} \cdot {}^{\circ}\mathrm{C}^{-1}$ at 20°C. Use Equation 2.7:

$$R_T = R_0[1 + A(T - T_0)] \Rightarrow R_{65} = (5\ \Omega)[1 + 0.004041\ \Omega \cdot \Omega^{-1} \cdot {}^{\circ}\mathrm{C}^{-1}(65^{\circ}\mathrm{C} - 20^{\circ}\mathrm{C})]$$
$$= 5.91\ \Omega$$

THERMORESISTIVE EFFECTS

اثر گرمامقاوتی در فلزات (اساس کارکرد RTDها)



A Pt100 RTD (means a platinum RTD with $R_0 = 100\ \Omega$ at 0°C) has a resistance–temperature relationship described by the *Callendar–Van Dusen* equation:

$$R_T = R_0[1 + A'T + B'T^2 + C'(T - 100)T^3]_{(-200°\mathrm{C} < T < 850°\mathrm{C})} \qquad (2.8)$$

where A', B', and C' are *Callendar–Van Dusen* coefficients. Their values for different RTD standards are listed in Table 2.3 [3].

TABLE 2.3

Callendar–Van Dusen Coefficients Corresponding to Standard RTDs

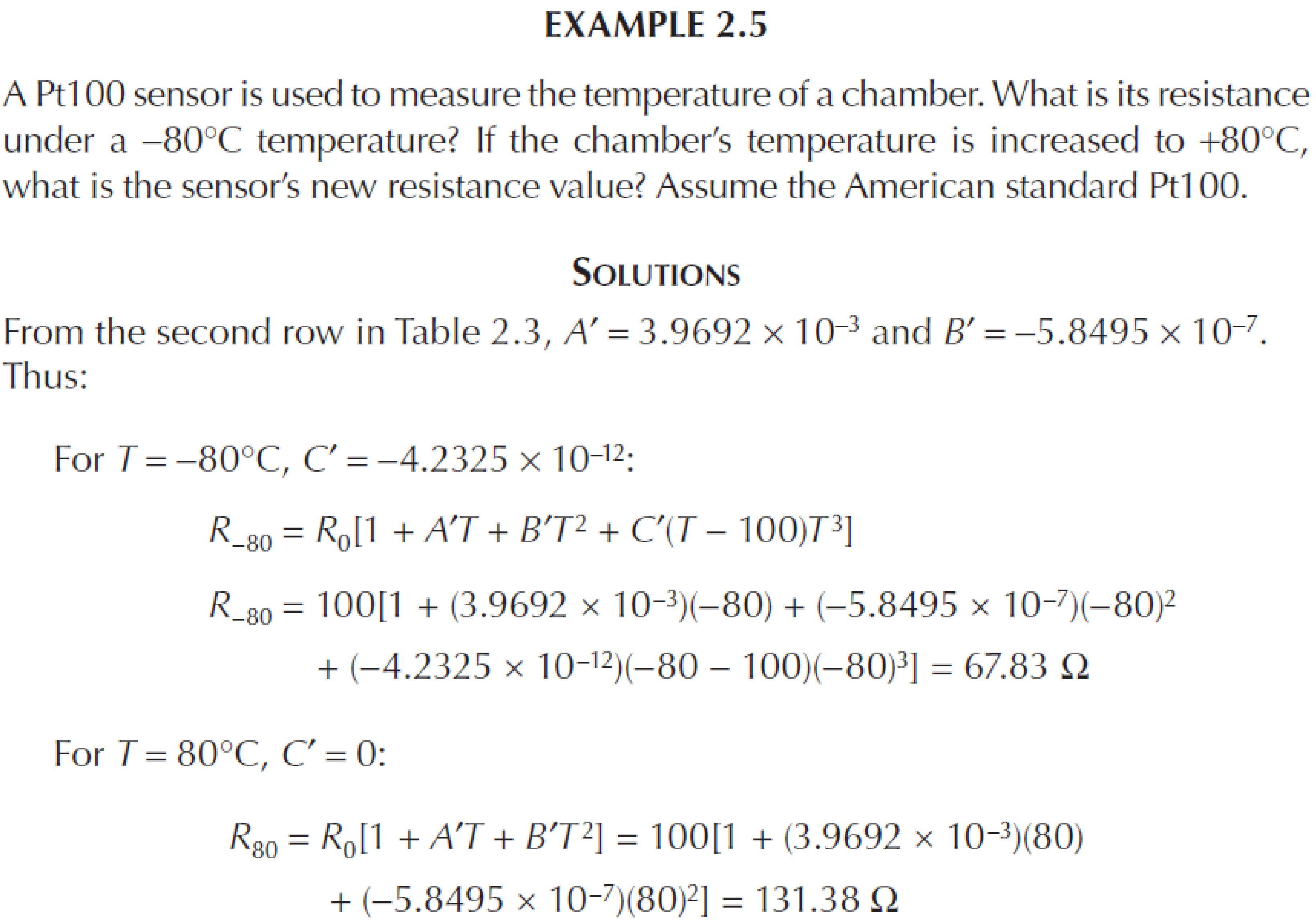
Standard	A'	B'	C' ($C' = 0$ for $T > 0°\mathrm{C}$)
DIN 43760	3.9080×10^{-3}	-5.8019×10^{-7}	-4.2735×10^{-12}
American	3.9692×10^{-3}	-5.8495×10^{-7}	-4.2325×10^{-12}
ITS-90	3.9848×10^{-3}	-5.8700×10^{-7}	-4.0000×10^{-12}

Source: From Measuring temperature with RTDs—A tutorial, Application Note 046, National Instruments Corporation, Austin, Texas, USA, 1996. With permission.

W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.

THERMORESISTIVE EFFECTS

اثر گرمامقاوتی در فلزات (اساس کارکرد RTDها)



EXAMPLE 2.5

A Pt100 sensor is used to measure the temperature of a chamber. What is its resistance under a –80°C temperature? If the chamber's temperature is increased to +80°C, what is the sensor's new resistance value? Assume the American standard Pt100.

SOLUTIONS

From the second row in Table 2.3, $A' = 3.9692 \times 10^{-3}$ and $B' = -5.8495 \times 10^{-7}$. Thus:

For $T = -80°\text{C}$, $C' = -4.2325 \times 10^{-12}$:

$$R_{-80} = R_0[1 + A'T + B'T^2 + C'(T - 100)T^3]$$

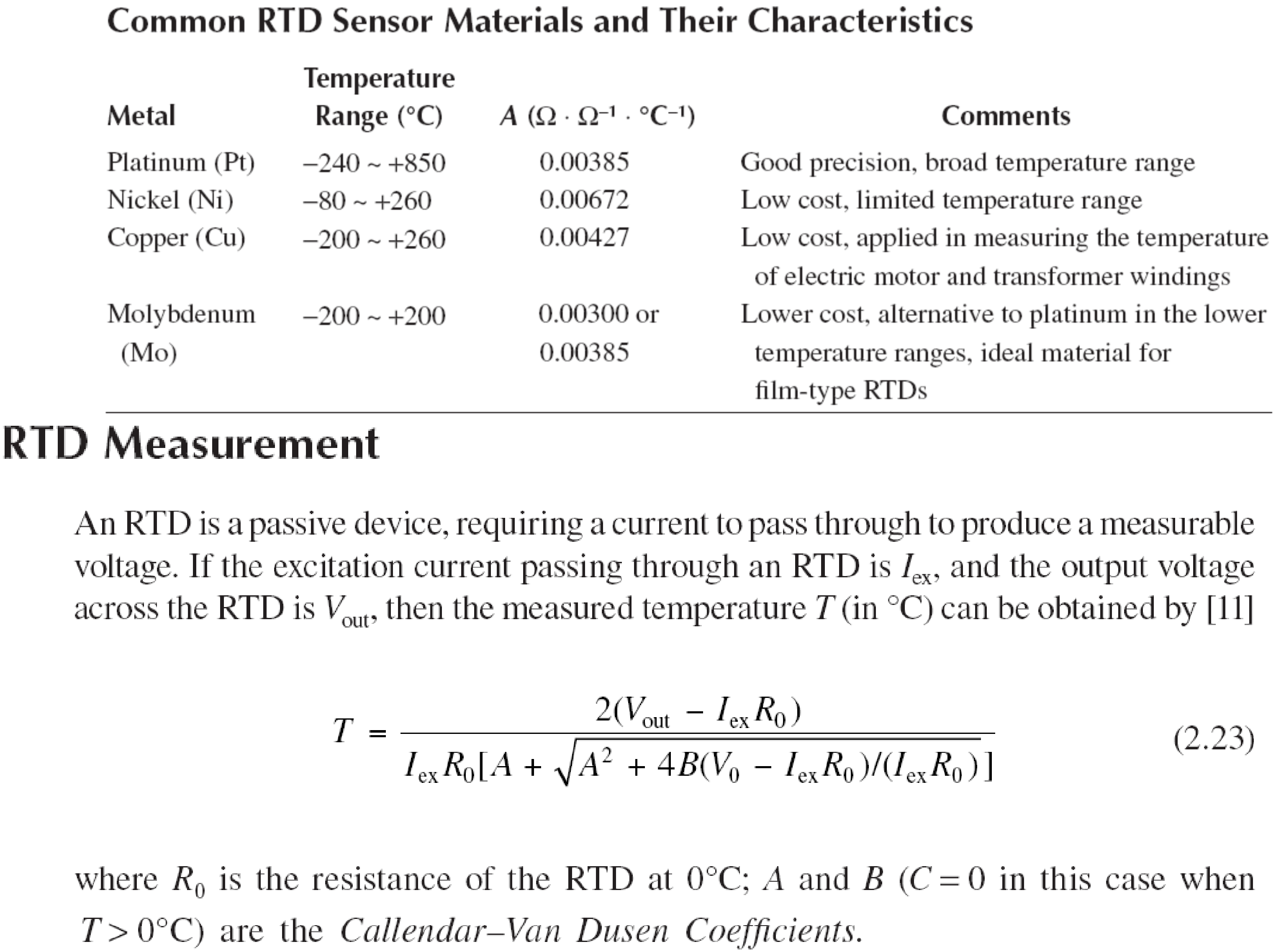
$$R_{-80} = 100[1 + (3.9692 \times 10^{-3})(-80) + (-5.8495 \times 10^{-7})(-80)^2 + (-4.2325 \times 10^{-12})(-80 - 100)(-80)^3] = 67.83\ \Omega$$

For $T = 80°\text{C}$, $C' = 0$:

$$R_{80} = R_0[1 + A'T + B'T^2] = 100[1 + (3.9692 \times 10^{-3})(80) + (-5.8495 \times 10^{-7})(80)^2] = 131.38\ \Omega$$

W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.

RTDs



Common RTD Sensor Materials and Their Characteristics

Metal	Temperature Range (°C)	A ($\Omega \cdot \Omega^{-1} \cdot {}^\circ C^{-1}$)	Comments
Platinum (Pt)	–240 ~ +850	0.00385	Good precision, broad temperature range
Nickel (Ni)	–80 ~ +260	0.00672	Low cost, limited temperature range
Copper (Cu)	–200 ~ +260	0.00427	Low cost, applied in measuring the temperature of electric motor and transformer windings
Molybdenum (Mo)	–200 ~ +200	0.00300 or 0.00385	Lower cost, alternative to platinum in the lower temperature ranges, ideal material for film-type RTDs

RTD Measurement

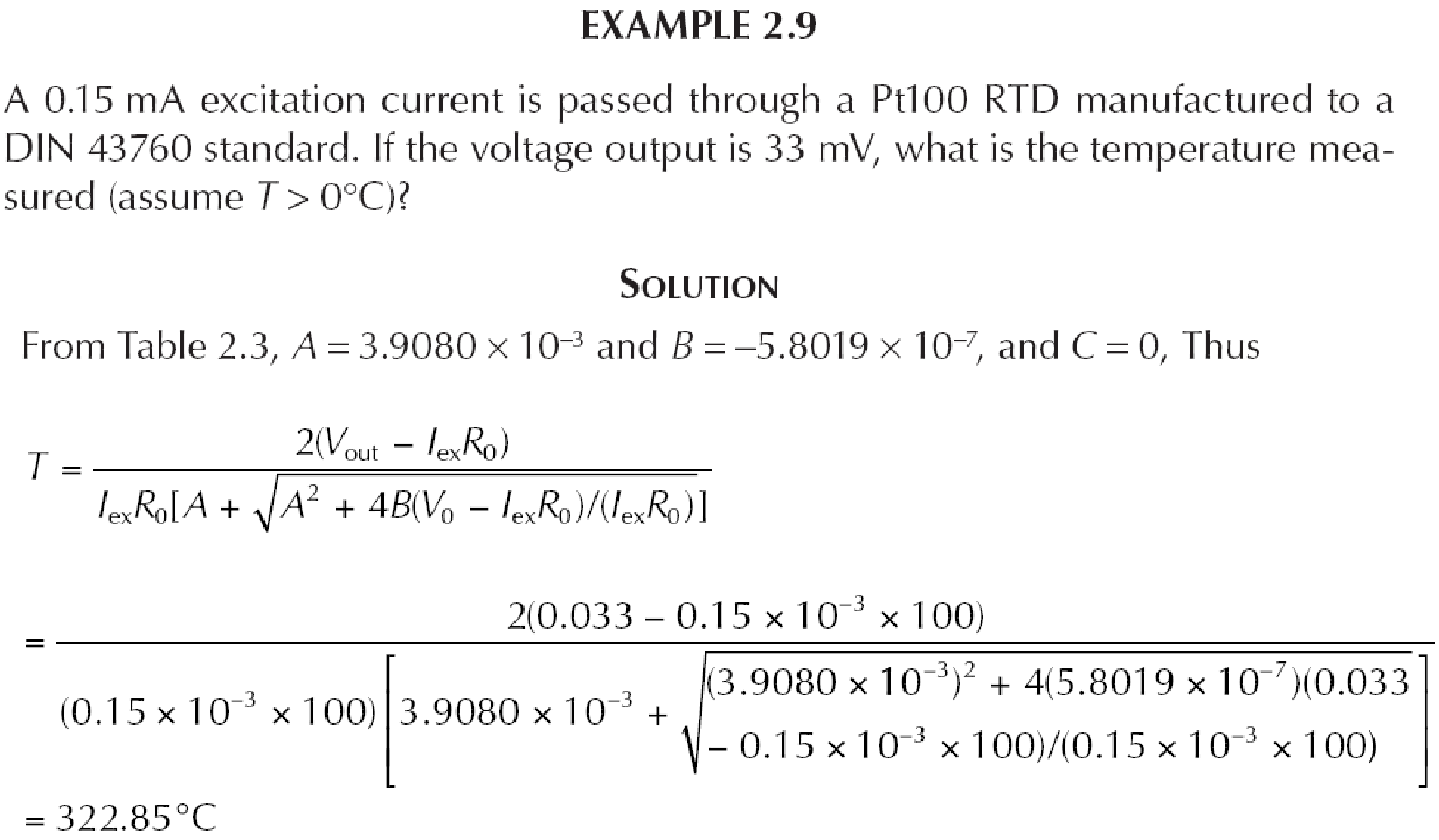
An RTD is a passive device, requiring a current to pass through to produce a measurable voltage. If the excitation current passing through an RTD is I_{ex}, and the output voltage across the RTD is V_{out}, then the measured temperature T (in °C) can be obtained by [11]

$$T = \frac{2(V_{out} - I_{ex}R_0)}{I_{ex}R_0[A + \sqrt{A^2 + 4B(V_0 - I_{ex}R_0)/(I_{ex}R_0)}]} \qquad (2.23)$$

where R_0 is the resistance of the RTD at 0°C; A and B ($C = 0$ in this case when $T > 0$°C) are the *Callendar–Van Dusen Coefficients.*

W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.

RTDs



EXAMPLE 2.9

A 0.15 mA excitation current is passed through a Pt100 RTD manufactured to a DIN 43760 standard. If the voltage output is 33 mV, what is the temperature measured (assume $T > 0°C$)?

SOLUTION

From Table 2.3, $A = 3.9080 \times 10^{-3}$ and $B = -5.8019 \times 10^{-7}$, and $C = 0$, Thus

$$T = \frac{2(V_{out} - I_{ex}R_0)}{I_{ex}R_0[A + \sqrt{A^2 + 4B(V_0 - I_{ex}R_0)/(I_{ex}R_0)}]}$$

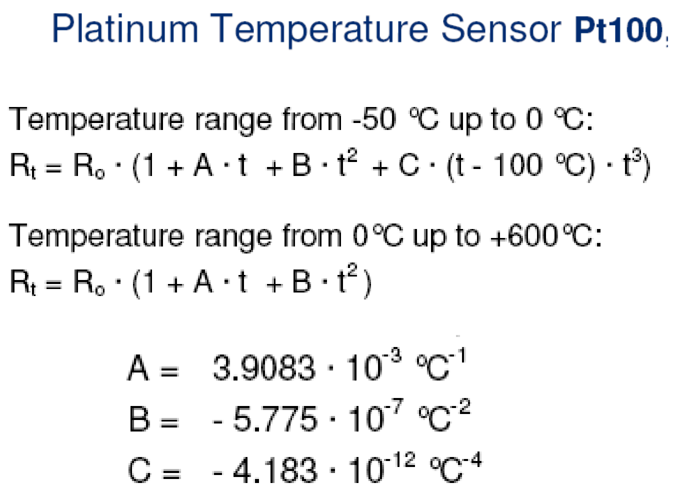
$$= \frac{2(0.033 - 0.15 \times 10^{-3} \times 100)}{(0.15 \times 10^{-3} \times 100)\left[3.9080 \times 10^{-3} + \sqrt{\begin{array}{l}(3.9080 \times 10^{-3})^2 + 4(5.8019 \times 10^{-7})(0.033 \\ - 0.15 \times 10^{-3} \times 100)/(0.15 \times 10^{-3} \times 100)\end{array}}\right]}$$

$$= 322.85°C$$

W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.

مشکل خود گرمایشی در RTD ها

An RTD is a passive device, requiring a current to pass through to produce a measurable voltage. The excitation current also causes the RTD to heat internally (self-heating), which can result in a measurement error. Self-heating is typically specified as the amount of power that will raise the RTD’s temperature by 1°C (in mW / °C). To minimize self-heating-caused error, the smallest possible excitation current (1 mA or less) should be used in measurement. The amount of self-heating also depends greatly on the medium in which the RTD is immersed. For example, an RTD can self-heat up to 100 times higher in still air than in moving water.



Platinum Temperature Sensor **Pt100**

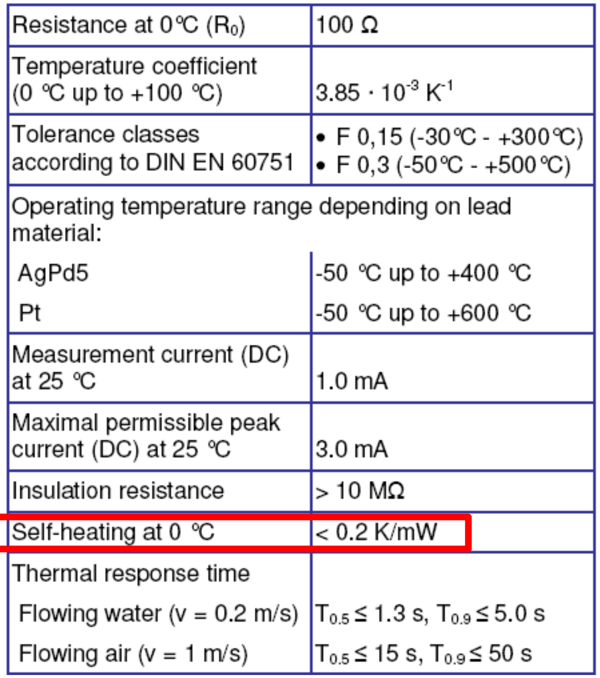
Temperature range from -50 °C up to 0 °C:

$$R_t = R_o \cdot (1 + A \cdot t + B \cdot t^2 + C \cdot (t - 100\ °C) \cdot t^3)$$

Temperature range from 0 °C up to +600 °C:

$$R_t = R_o \cdot (1 + A \cdot t + B \cdot t^2)$$

$$A = 3.9083 \cdot 10^{-3}\ °C^{-1}$$
$$B = -5.775 \cdot 10^{-7}\ °C^{-2}$$
$$C = -4.183 \cdot 10^{-12}\ °C^{-4}$$



Resistance at 0 °C (R_0)	100 Ω
Temperature coefficient (0 °C up to +100 °C)	$3.85 \cdot 10^{-3}\ K^{-1}$
Tolerance classes according to DIN EN 60751	• F 0,15 (-30 °C - +300 °C) • F 0,3 (-50 °C - +500 °C)
Operating temperature range depending on lead material:	
AgPd5	-50 °C up to +400 °C
Pt	-50 °C up to +600 °C
Measurement current (DC) at 25 °C	1.0 mA
Maximal permissible peak current (DC) at 25 °C	3.0 mA
Insulation resistance	> 10 MΩ
Self-heating at 0 °C	< 0.2 K/mW
Thermal response time	
Flowing water (v = 0.2 m/s)	$T_{0.5} \leq 1.3$ s, $T_{0.9} \leq 5.0$ s
Flowing air (v = 1 m/s)	$T_{0.5} \leq 15$ s, $T_{0.9} \leq 50$ s

W. Y. Du ”*Resistive, capacitive, inductive, and magnetic sensor technologies*”, CRC Press, 2014.

RTD ساخت

RTDs are constructed in two forms: *wire-wound* (Figure 2.11a) and *thin film* (Figure 2.11b). Wire-wound RTDs are made by winding a very fine strand of metal wire (platinum, typically 0.0005–0.0015 in. diameter). Thin-film RTDs are produced using *thin-film lithography* that deposits a thin film of metal (e.g., 1 μm platinum) onto a ceramic substrate through the *cathodic atomization* or *sputtering* process.

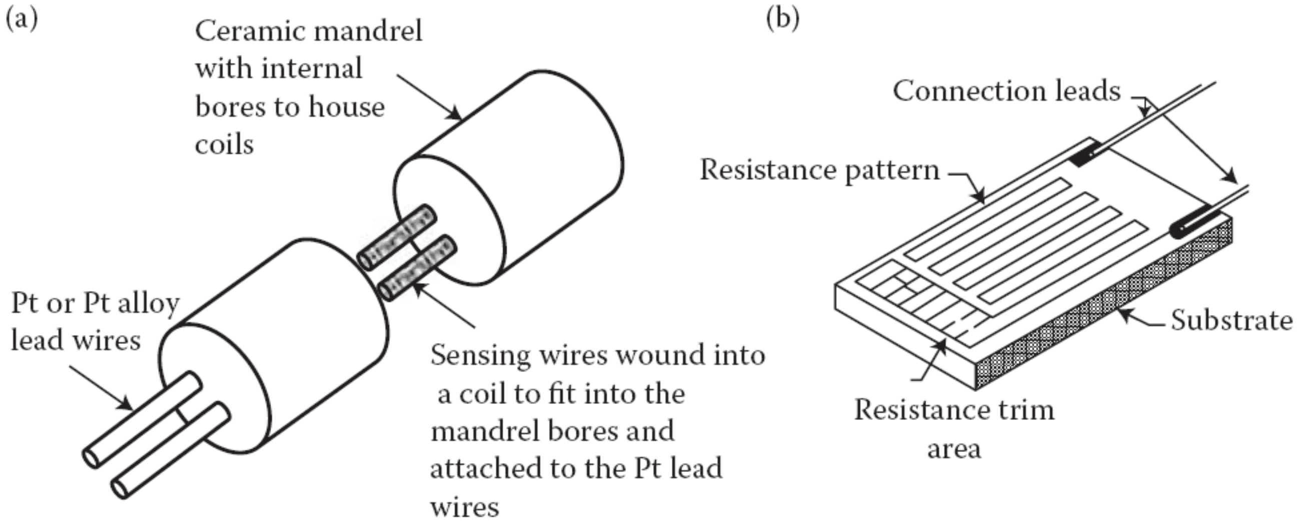


FIGURE 2.11 (a) Wire-wound RTD; (b) thin-film RTD. (Courtesy of *RdF Corporation*, Hudson, New Hampshire, USA.)

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روش اندازه گیری مقاومت RTD

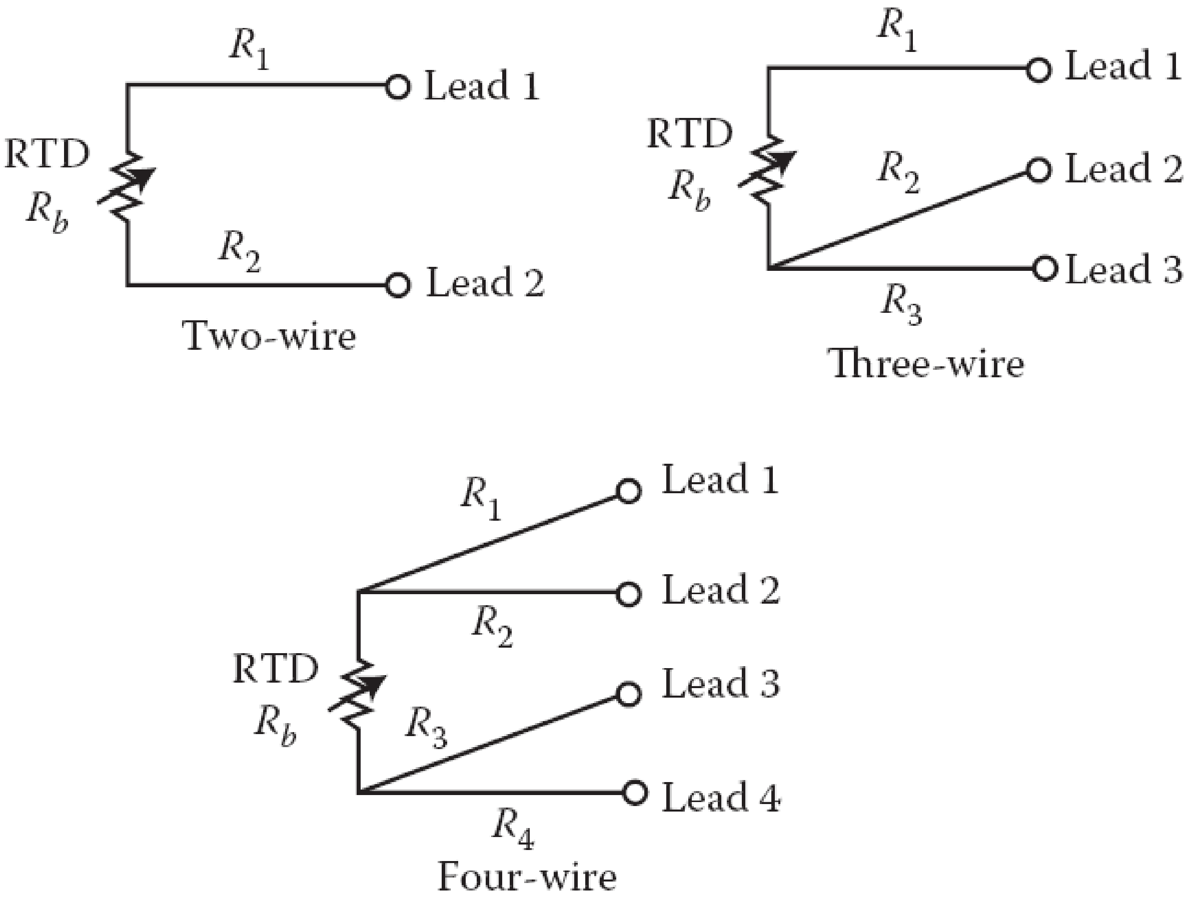
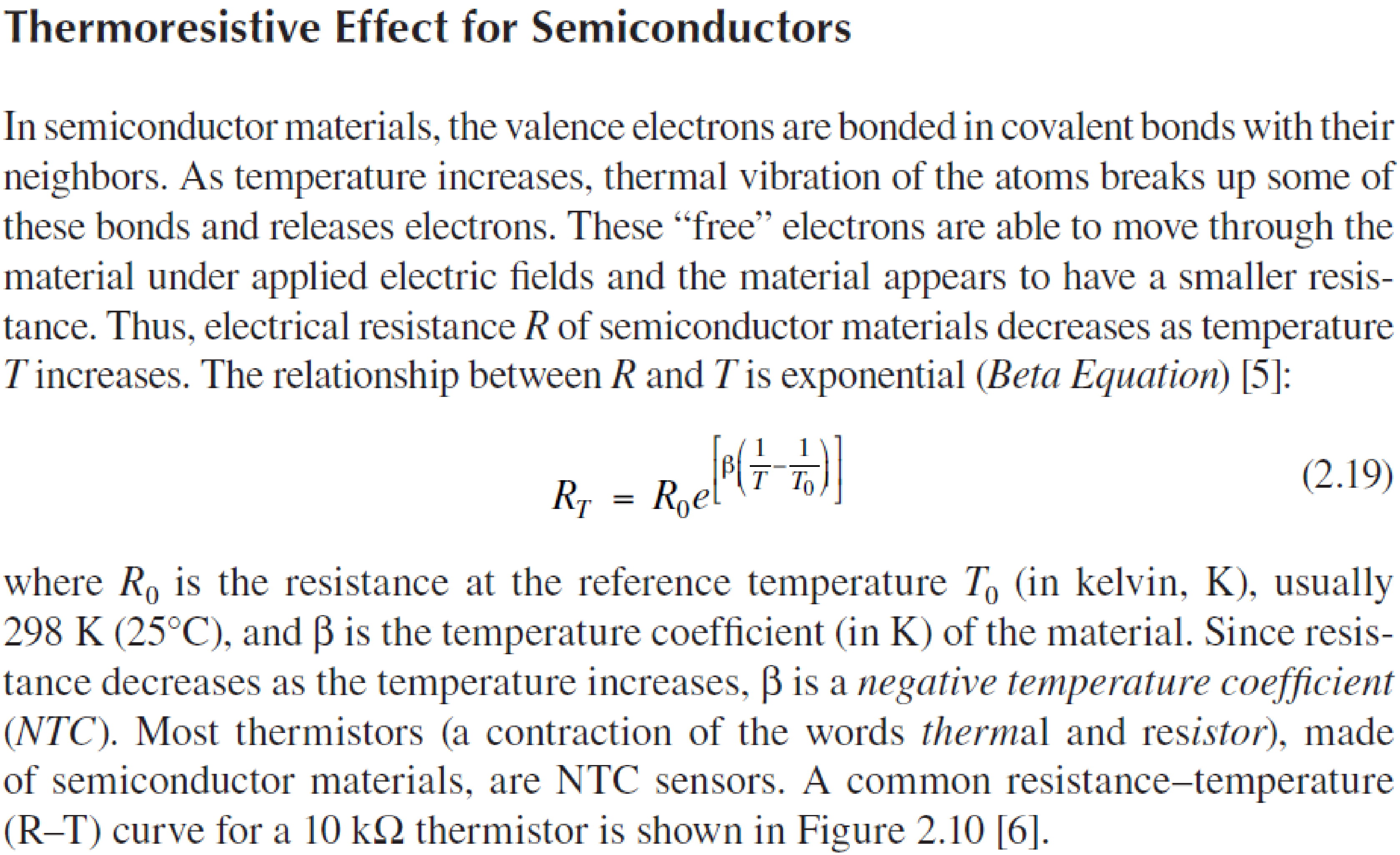


FIGURE 2.12 Two-, three-, and four-wire configurations.

W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.

اثر گرمامقاومتی برای نیمه رسانا (اساس کارکرد ترمیستور)



Thermoresistive Effect for Semiconductors

In semiconductor materials, the valence electrons are bonded in covalent bonds with their neighbors. As temperature increases, thermal vibration of the atoms breaks up some of these bonds and releases electrons. These "free" electrons are able to move through the material under applied electric fields and the material appears to have a smaller resistance. Thus, electrical resistance R of semiconductor materials decreases as temperature T increases. The relationship between R and T is exponential (*Beta Equation*) [5]:

$$R_T = R_0 e^{\left[\beta\left(\frac{1}{T}-\frac{1}{T_0}\right)\right]} \tag{2.19}$$

where R_0 is the resistance at the reference temperature T_0 (in kelvin, K), usually 298 K (25°C), and β is the temperature coefficient (in K) of the material. Since resistance decreases as the temperature increases, β is a *negative temperature coefficient* (*NTC*). Most thermistors (a contraction of the words *therm*al and resi*stor*), made of semiconductor materials, are NTC sensors. A common resistance–temperature (R–T) curve for a 10 kΩ thermistor is shown in Figure 2.10 [6].

W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.

اثر ترمورزیستیو برای نیمه رسانا

EXAMPLE 2.7

Find β of a thermistor whose values are $R_0 = 10\ \mathrm{k\Omega}$ at $T_0 = 25°\mathrm{C}$; $R_{50} = 3.3\ \mathrm{k\Omega}$ at $T = 50°\mathrm{C}$.

SOLUTION

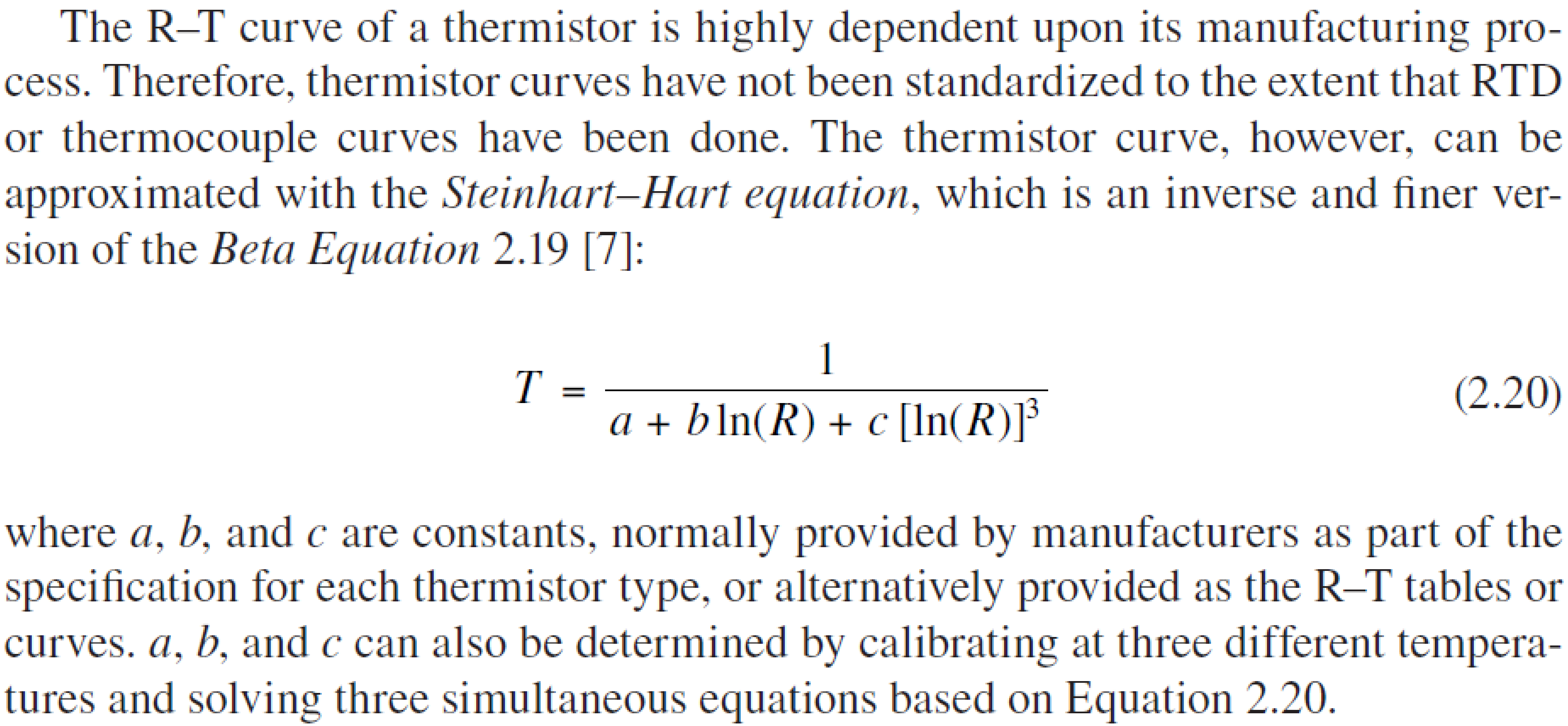
From Equation 2.19

$$\beta = \frac{\ln R_T - \ln R_0}{1/T - 1/T_0} = \frac{\ln R_{50} - \ln R_{25}}{1/(273.15 + 50) - 1/(273.15 + 25)}$$

$$= \frac{\ln(3300) - \ln(10{,}000)}{1/(273.15 + 50) - 1/(273.15 + 25)} = 4272.66\ (\mathrm{K})$$

W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.

اثر ترمورزیستیو برای نیمه رسانا



The R–T curve of a thermistor is highly dependent upon its manufacturing process. Therefore, thermistor curves have not been standardized to the extent that RTD or thermocouple curves have been done. The thermistor curve, however, can be approximated with the *Steinhart–Hart equation*, which is an inverse and finer version of the *Beta Equation* 2.19 [7]:

$$T = \frac{1}{a + b\ln(R) + c\,[\ln(R)]^3} \tag{2.20}$$

where a, b, and c are constants, normally provided by manufacturers as part of the specification for each thermistor type, or alternatively provided as the R–T tables or curves. a, b, and c can also be determined by calibrating at three different temperatures and solving three simultaneous equations based on Equation 2.20.

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اثر ترمورزیستیو برای نیمه رسانا

The Steinhart–Hart Equation 2.20 has a third-order polynomial term, which provides excellent curve fitting for temperature spans within the range of –80°C to 260°C, and it has replaced the beta equation as the most useful tool for interpolating the NTC thermistor's R–T characteristics. If the full temperature range extends beyond the –80°C to 260°C range, the Steinhart–Hart equation can be used to fit a series of narrow temperature ranges, and then splice them together to cover the full range. Table 2.4 shows a typical thermistor data sheet (from *YSI Inc.*, Yellow Springs, Ohio, USA, for its 44004 thermistor).

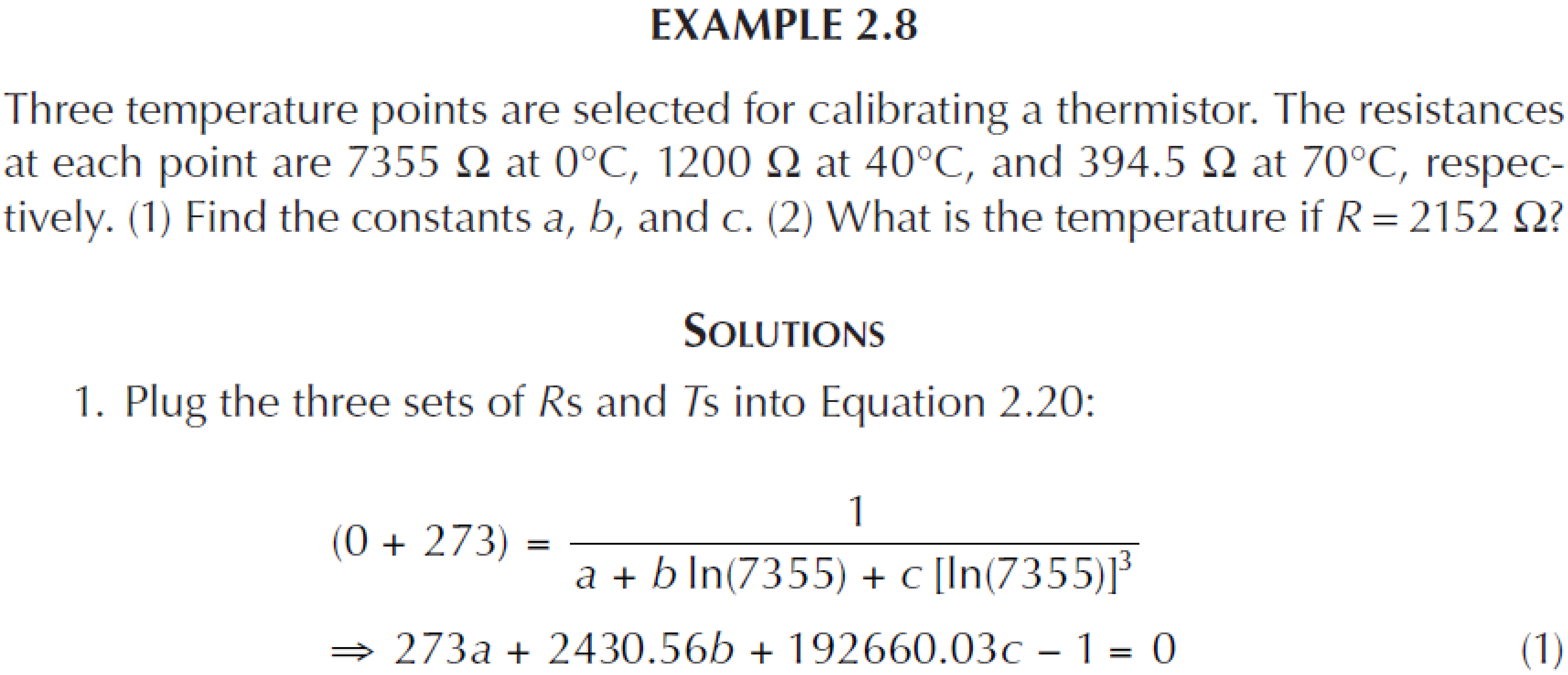
TABLE 2.4

Specifications of the 44004 Thermistor by *YSI Inc.*

Parameter	Specification
Resistance at 25°C	2252 Ω (100 Ω to 1 MΩ available)
Measurement range	–80°C to +120°C typical (250°C maximum)
Interchangeability (tolerance)	±0.1°C or ±0.2°C
Stability over 12 months	<0.02°C at 25°C, <0.25°C at 100°C
Time constant	<1.0 s in oil, <60 s in still air
Self-heating	0.13°C · (mW)$^{-1}$ in oil, 1.0°C · (mW)$^{-1}$ in air
Coefficients	$a = 1.4733 \times 10^{-3}$, $b = 2.372 \times 10^{-3}$, $c = 1.074 \times 10^{-7}$
Dimensions	Ellipsoid bead 2.5 mm × 4 mm

W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.

اثر ترمورزیستیو برای نیمه رسانا



EXAMPLE 2.8

Three temperature points are selected for calibrating a thermistor. The resistances at each point are 7355 Ω at 0°C, 1200 Ω at 40°C, and 394.5 Ω at 70°C, respectively. (1) Find the constants *a*, *b*, and *c*. (2) What is the temperature if $R = 2152\ \Omega$?

SOLUTIONS

1. Plug the three sets of *R*s and *T*s into Equation 2.20:

$$(0 + 273) = \frac{1}{a + b\ln(7355) + c\,[\ln(7355)]^3}$$

$$\Rightarrow 273a + 2430.56b + 192660.03c - 1 = 0 \qquad (1)$$

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اثر ترمورزیستیو برای نیمه رسانا

$$(40+273)=\frac{1}{a+b\ln(1200)+c\,[\ln(1200)]^3}$$

$$\Rightarrow 313a+2219.19b+111557.09c-1=0 \qquad (2)$$

$$(70+273)=\frac{1}{a+b\ln(394.5)+c\,[\ln(394.5)]^3}$$

$$\Rightarrow 343a+2050.32b+73262.01c-1=0 \qquad (3)$$

Solving the three simultaneous Equations (1) through (3) yields

$$a=1.47408\times10^{-3} \quad b=2.3704159\times10^{-4} \quad c=1.0839894\times10^{-7}$$

2. When $R=2152\ \Omega$, the temperature is

$$T=\frac{1}{1.47408\times10^{-3}+2.3704159\times10^{-4}\ln(2152)+1.0839894\times10^{-7}\ [\ln(2152)]^3}$$

$$=299.21\,\mathrm{K}\left(\text{or } 26.21^\circ\mathrm{C}\right)$$

انواع ترمیستور

۱- ترمیستور با ضریب تغییرات حرارتی منفی (NTC)

۲- ترمیستور با ضریب تغییرات مثبت (PTC)

- ☐ Thermally sensitive silicon resistors (*silistors*)
- ☐ Switching PTC thermistors

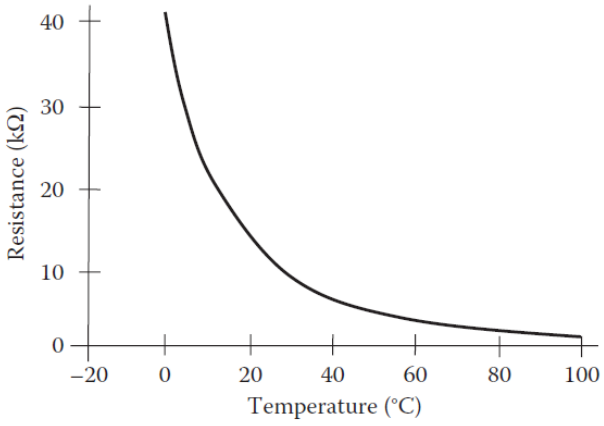

FIGURE 2.10 An NTC thermistor R–T curve.

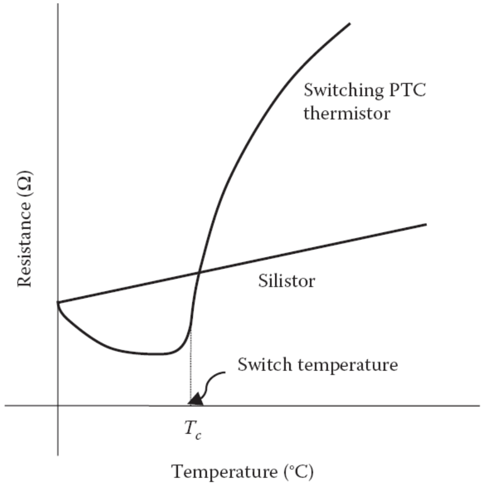

FIGURE 2.14 R–T curves of silistor and switching PTC thermistors.

W. Y. Du ”*Resistive, capacitive, inductive, and magnetic sensor technologies*”, CRC Press, 2014.

انواع ترمیستور

- NTC thermistors are more commonly used than PTC type, especially in temperature measurement applications. NTC thermistors are made using basic ceramics technology and semiconductor metal oxide materials (e.g., oxides of manganese, nickel, cobalt, iron, copper, and titanium). In some thermistors, the decrease in resistance is as great as 6% for each 1°C of temperature increase although 1% changes are more typical. NTC thermistors can provide good accuracy and resolution when measuring temperatures between −100°C and +300°C. If inserted into a Wheatstone bridge, a thermistor can detect temperature changes as small as ±0.005°C.

W. Y. Du ”*Resistive, capacitive, inductive, and magnetic sensor technologies*”, CRC Press, 2014.

انواع ترمیستور

- Silistors exhibit a fairly uniform PTC (about +0.0077°C−1) through most of their operational range, but can also exhibit an NTC region at temperatures higher than 150°C. This type of thermistors is often used for temperature compensation of silicon semiconducting devices in the range of −60°C to +150°C.

- The switching PTC thermistors are made from polycrystalline ceramic materials that are normally highly resistive but become semiconductive by adding dopants. They are often manufactured using compositions of barium, lead, and strontium with additives such as yttrium, manganese, tantalum, and silica. The R–T curves of switching PTC thermistors exhibit very small NTC regions until they reach a critical temperature *Tc*—"*Curie*," "*Switch*" or "*Transition*" *temperature*. After *Tc*, the curve exhibits a rapidly increasing PTC resistance. These resistance changes can be as much as several orders of magnitude within a temperature span of a few degrees.

W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.