Theory

2.1 Temperature sensor Pt100 (platinum resistance)

Pt100 platinum resistance is a temperature sensor that utilizes the resistance variation of platinum metal with temperature. Platinum possesses stable physical and chemical characteristics, strong antioxidant ability, good replication, and easy production. Hence, platinum resistors are widely used for precise measurement of temperature in industry. However, the disadvantages are their high cost, small temperature coefficient, and vulnerability to magnetic field perturbation.

According to IEC standards, the range of temperature measurement using a platinum resistance is -200 - 650 °C. Pt100 platinum resistance sensor has a resistance of 100 ohms at 0 °C (i.e. 32 °F). The relationship between resistance R_t and temperature t can be found in the table of Pt100 sensor (Appendix 1), and can be expressed as follows:

$$R_t = R_0\left[1 + At + Bt^2 + C(t - 100^\circ C)t^3\right] \text{, for temperature } t\text{: -200 ~ 0 °C.} \tag{1}$$

and $$R_t = R_0(1 + At + Bt^2) \text{, for temperature } t\text{: 0 ~ 650 °C.} \tag{2}$$

In (1) and (2), R_t and R_0 are respectively the resistance at temperature t and temperature 0 °C. A, B and C are temperature coefficients. For commonly used industrial platinum resistances, we have $A=3.90802\times10^{-3}/^\circ C$, $B=-5.80195\times10^{-7}/^\circ C^2$, $C=-4.27350\times10^{-12}/^\circ C^3$. In between 0 ~ 100 °C, R_t can be approximately expressed in linear as:

$$R_t = R_0(1 + A_1 t) , \tag{3}$$

where A_1 is the temperature coefficient and approximately $3.85\times10^{-3}/^\circ C$. $Rt = 100$ ohm at $t = 0$ °C and $Rt = 138.5$ ohm at $t = 100$ °C.

2.2 Measurement of thermal resistance using a constant voltage source

Figure 1 is the circuit schematic of measuring thermal resistance using a constant voltage.

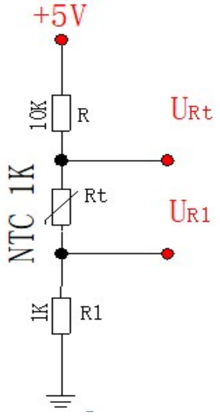

Figure 1 Circuit schematic of measuring thermal resistance using a constant voltage

The power supply is a constant voltage source, R_1 is a fixed resistance of known value, and R_t is a thermal resistance. U_{R1} is the voltage on R_1, U_{Rt} is the voltage on R_T. U_{R1} is used to monitor the current of the circuit. When the circuit voltage and temperature are fixed, U_{R1} is also fixed. The circuit current I_0 is U_{R1}/R_1. As long as the voltage U_{RT} across the thermal resistance is measured, The resistance of the thermal resistance can be determined, i.e. when the circuit current is I_0 and the temperature is T, the thermal resistance R_T is:

$$R_t = \frac{U_{R_t}}{I_O}. \tag{4}$$

2.3 Temperature sensor of semiconductor thermistor (NTC1K)

A semiconductor thermistor measures temperature by using the characteristics of resistance variation with temperature change. According to the resistance increasing or reducing with the increase of temperature, semiconductor thermistors are classified into NTC type (negative temperature coefficient), PTC type (positive temperature coefficient) and CTC type (critical temperature). Semiconductor thermistors have properties of large resistivity and large temperature coefficient, but also drawbacks of large nonlinearity and poor stability. Therefore they are usually only applicable to those general sceneries of high accuracy of temperature measurement unnecessary. Characteristic curves of the above three types of thermistors are shown in Figure 2.

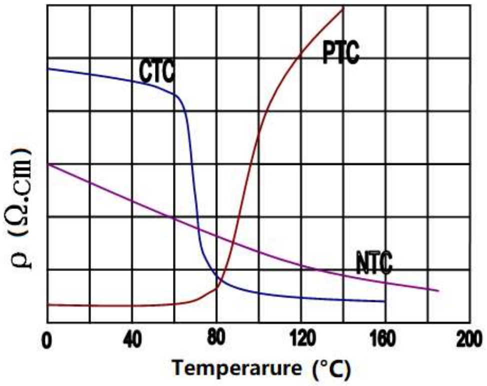

Figure 2 Characteristic curves of three types of thermistors

In a certain temperature range (lower than 150 °C), the resistance R_t of a NTC thermistor has a relationship with temperature T as follows:

$$R_T = R_0 e^{B(\frac{1}{T}-\frac{1}{T_0})}, \tag{5}$$

where R_t and R_0 are respectively the resistance values at temperature $T(K)$ and $T_0(K)$ with K the thermodynamic temperature unit Kelvin; B is a constant and usually $2000 \sim 6000\,K$.

Take a logarithm operation on both sides of the above formula, we get:

$$\ln R_T = B(\frac{1}{T} - \frac{1}{T_0}) + \ln R_0 . \tag{6}$$

From (6), we know $\ln R_T$ and $1/T$ is in linear relationship. By plotting $\ln R_T$ - ($1/T$) curve and doing a straight line fitting, the slope of the line, i.e. constant B, can be acquired.

2.4 Temperature sensor of voltage-mode IC (LM35)

The temperature sensor LM35 is packed following industrial standard T_0-92 with an accuracy usually ± 0.5 °C. Since its output is a voltage signal of good linearity, it is easy to build a precision digital temperature measurement system as long as a DC voltage source and a digital voltmeter are supplied. Internal laser calibration ensures high accuracy and consistency without external calibration. The temperature coefficient of output voltage is $K_V = 10.0$ mV/°C. Figure 3 shows the schematic of LM35. By measuring its output voltage V_0, the measured temperature can be calculated using the following formula:

$$t\ (^\circ C) = V_0/10\ mV. \tag{7}$$

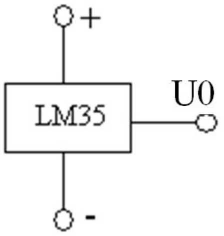

Figure 3 Schematic of temperature sensor LM35.

2.5 Temperature sensor of PN junction

A PN-junction temperature sensor measures temperature utilizing the characteristics of temperature dependency of the junction voltage of a PN junction. Experiments have proven that under a certain current flowing through, there is a good linear relationship between the forward voltage of the PN junction and the temperature. Usually, by making short circuit between terminals *b* and *c* of a transistor, the PN junction between terminals *b* and *e* is used as a temperature sensor for temperature measurement. The forward voltage V_{be} between terminals *b* and *e* of a silicon transistor is typically approximate 600 mV (at 25 °C), and is inversely proportional to the temperature with good linearity of temperature coefficient about -2.3 mV/°C. Temperature measurement range is -50 ~ 150 °C.

Normally, the relationship between current *I* and voltage *U* of a diode PN junction satisfies the following expression:

$$I = I_S\left[e^{qU/kT} - 1\right]. \tag{8}$$

Under conditions of room temperature and U > 0.1V, $e^{qU/KT}$ far larger than 1, equation (5) can be approximated as:

$$I = I_S e^{qU/kT}. \tag{9}$$

In (8) and (9), $q = 1.602\times10^{-19}C$, is the charge of electron, $k = 1.381\times10^{-23}$J/K, is the Boltzmann constant, *T* is thermodynamic temperature, and I_s is the reverse saturation current.

Under the condition of applying a constant forward current, the relationship between forward voltage *U* and temperature *t* is approximately linear as follow:

$$U = Bt + U_{go}, \tag{10}$$

where U_{go} is the semiconductor material parameter and *B* is the junction voltage temperature coefficient of the PN junction. A schematic of experimental measurement of temperature using a PN junction is shown in Figure 4. When the constant voltage source is +5 V, the current flowing through the PN junction is about 400 μA at 25 °C. Measure U_{be} between terminals U_{be1} and U_{be2}. When used as an temperature sensor, use terminal U_{be2}/U_r as the output port.

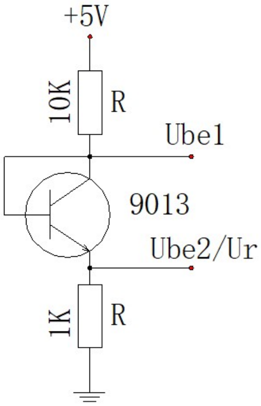

Figure 4 Schematic of experimental measurement of temperature using PN junction