LM34/LM35 Precision Monolithic Temperature Sensors

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Introduction

Most commonly-used electrical temperature sensors are difficult to apply. For example, thermocouples have low output levels and require cold junction compensation. Thermistors are nonlinear. In addition, the outputs of these sensors are not linearly proportional to any temperature scale. Early monolithic sensors, such as the LM3911, LM134 and LM135, overcame many of these difficulties, but their outputs are related to the Kelvin temperature scale rather than the more popular Celsius and Fahrenheit scales. Fortunately, in 1983 two I.C.'s, the LM34 Precision Fahrenheit Temperature Sensor and the LM35 Precision Celsius Temperature Sensor, were introduced. This application note will discuss the LM34, but with the proper scaling factors can easily be adapted to the LM35.

The LM34 has an output of 10 mV/˚F with a typical nonlinearity of only ±0.35˚F over a –50 to +300˚F temperature range, and is accurate to within ±0.4˚F typically at room temperature (77˚F). The LM34's low output impedance and linear output characteristic make interfacing with readout or control circuitry easy. An inherent strength of the LM34 over other currently available temperature sensors is that it is not as susceptible to large errors in its output from low level leakage currents. For instance, many monolithic temperature sensors have an output of only 1 µA/˚K. This leads to a 1˚K error for only 1 µ-Ampere of leakage current. On the other hand, the LM34 may be operated as a current mode device providing 20 µA/˚F of output current. The same 1 µA of leakage current will cause an error in the LM34's output of only 0.05˚F (or 0.03˚K after scaling).

Low cost and high accuracy are maintained by performing trimming and calibration procedures at the wafer level. The device may be operated with either single or dual supplies. With less than 70 µA of current drain, the LM34 has very little self-heating (less than 0.2˚F in still air), and comes in a TO-46 metal can package, a SO-8 small outline package and a TO-92 plastic package.

Forerunners to the LM34

The making of a temperature sensor depends upon exploiting a property of some material which is a changing function of temperature. Preferably this function will be a linear function for the temperature range of interest. The base-emitter voltage (V_{BE}) of a silicon NPN transistor has such a temperature dependence over small ranges of temperature.

Unfortunately, the value of V_{BE} varies over a production range and thus the room temperature calibration error is not specified nor guaranteeable in production. Additionally, the temperature coefficient of about –2 mV/˚C also has a tolerance and spread in production. Furthermore, while the tempo may appear linear over a narrow temperature, there is a definite nonlinearity as large as 3˚C or 4˚C over a full –55˚C to +150˚C temperature range.

Another approach has been developed where the difference in the base-emitter voltage of two transistors operated at different current densities is used as a measure of temperature. It can be shown that when two transistors, Q1 and Q2, are operated at different emitter current densities, the difference in their base-emitter voltages, ΔV_{BE}, is

$$\Delta V_{BE} = V_{BE1} - V_{BE2} = \frac{kT}{q} \ln \frac{(J_{E1})}{J_{E2}} \quad (1)$$

where k is Boltzman's constant, q is the charge on an electron, T is absolute temperature in degrees Kelvin and J_{E1} and J_{E2} are the emitter current densities of Q1 and Q2 respectively. A circuit realizing this function is shown in *Figure 1*.

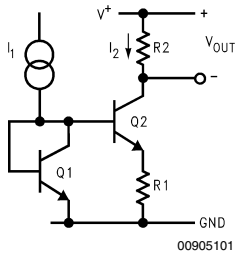


FIGURE 1.

Equation (1) implies that as long as the ratio of I_{E1} to I_{E2} is held constant, then ΔV_{BE} is a linear function of temperature (this is not exactly true over the whole temperature range, but a correction circuit for the nonlinearity of V_{BE1} and V_{BE2} will be discussed later). The linearity of this ΔV_{BE} with temperature is good enough that most of today's monolithic temperature sensors are based upon this principle.

An early monolithic temperature sensor using the above principle is shown in *Figure 2*. This sensor outputs a voltage which is related to the absolute temperature scale by a factor of 10 mV per degree Kelvin and is known as the LM135. The circuit has a ΔV_{BE} of approximately

(0.2 mV/˚K) x (T)

developed across resistor R. The amplifier acts as a servo to enforce this condition. The ΔV_{BE} appearing across resistor R is then multiplied by the resistor string consisting of R and the 26R and 23R resistors for an output voltage of (10 mV/˚K) x (T). The resistor marked 100R is used for offset trimming. This circuit has been very popular, but such Kelvin temperature sensors have the disadvantage of a large constant output voltage of 2.73V which must be subtracted for use as a Celsius-scaled temperature sensor.

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Forerunners to the LM34 (Continued)

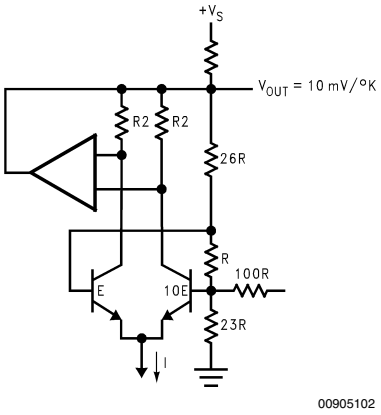


FIGURE 2.

Various sensors have been developed with outputs which are proportional to the Celsius temperature scale, but are rather expensive and difficult to calibrate due to the large number of calibration steps which have to be performed. Gerard C.M. Meijer[4] has developed a circuit which claims to be inherently calibrated if properly trimmed at any one temperature. The basic structure of Meijer's circuit is shown in *Figure 3*. The output current has a temperature coefficient of 1 µA/°C. The circuit works as follows: a current which is proportional to absolute temperature, I_{PTAT}, is generated by a current source. Then a current which is proportional to the V_{BE} drop of transistor Q4 is subtracted from I_{PTAT} to get the output current, I_O. Transistor Q4 is biased by means of a PNP current mirror and transistor Q3, which is used as a feedback amplifier. In Meijer's paper it is claimed that the calibration procedure is straightforward and can be performed at any temperature by trimming resistor R4 to adjust the sensitivity, dI_O/dT, and then trimming a resistor in the PTAT current source to give the correct value of output current for the temperature at which the calibration is being performed.

Meijer's Celsius temperature sensor has problems due to its small output signal (i.e., the output may have errors caused by leakage currents). Another problem is the trim scheme requires the trimming of two resistors to a very high degree of accuracy. To overcome these problems the circuits of *Figure 4* (an LM34 Fahrenheit temperature sensor) and *Figure 5* (an LM35 Celsius temperature sensor) have been developed to have a simpler calibration procedure, an output voltage with a relatively large tempco, and a curvature compensation circuit to account for the non-linear characteristics of V_{BE} versus temperature. Basically, what happens is transistors Q1 and Q2 develop a ΔV_{BE} across resistor R1. This voltage is multiplied across resistor nR1. Thus at the non-inverting input of amplifier A2 is a voltage two diode drops below the voltage across resistor nR1. This voltage is then amplified by amplifier A2 to give an output proportional to whichever temperature scale is desired by a factor of 10 mV per degree.

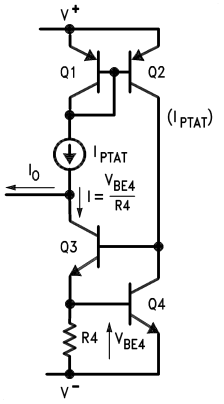


FIGURE 3.

Circuit Operation

Since the two circuits are very similar, only the LM34 Fahrenheit temperature sensor will be discussed in greater detail. The circuit operates as follows:

Transistor Q1 has 10 times the emitter area of transistor Q2, and therefore, one-tenth the current density. From *Figure 4*, it is seen that the difference in the current densities of Q1 and Q2 will develop a voltage which is proportional to absolute temperature across resistor R_1. At 77°F this voltage will be 60 mV. As in the Kelvin temperature sensor, an amplifier, A1, is used to insure that this is the case by servoing the base of transistor Q1 to a voltage level, V_{PTAT}, of ΔV_{BE} x n. The value of n will be trimmed during calibration of the device to give the correct output for any temperature.

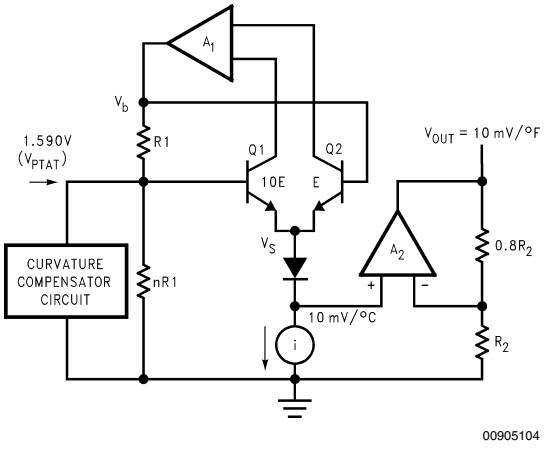


FIGURE 4.

Circuit Operation (Continued)

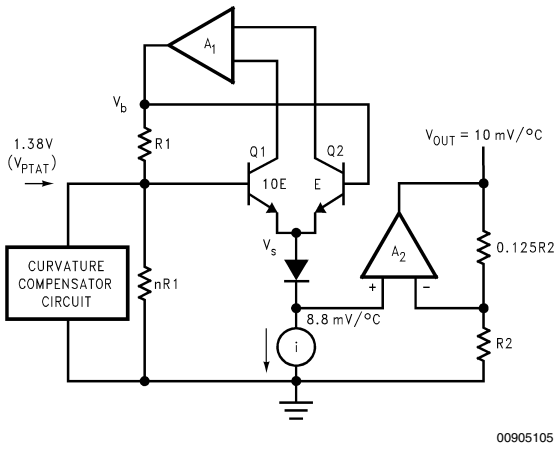


FIGURE 5.

For purposes of discussion, suppose that a value of V_{PTAT} equal to 1.59V will give a correct output of 770 mV at 77˚F. Then n will be equal to $V_{PTAT}/\Delta V_{BE}$ or 1.59V/60 mV = 26.5, and V_{PTAT} will have a temperature coefficient (tempco) of:

$$\frac{nk}{q} \ln \frac{I_1}{I_2} = 5.3 \text{ mV/°C.}$$

Subtracting two diode drops of 581 mV (at 77˚F) with tempcos of −2.35 mV/˚C each, will result in a voltage of 428 mV with a tempco of 10 mV/˚C at the non-inverting input of amplifier A2. As shown, amplifier A2 has a gain of 1.8 which provides the necessary conversion to 770 mV at 77˚F (25˚C). A further example would be if the temperature were 32˚F (0˚C), then the voltage at the input of A2 would be 428 mV−(10 mV/˚C) (25˚C) = 0.178, which would give V_{OUT} = (0.178) (1.8) = 320 mV—the correct value for this temperature.

Easy Calibration Procedure

The circuit may be calibrated at any temperature by adjusting the value of the resistor ratio factor n. Note that the value of n is dependent on the actual value of the voltage drop from the two diodes since n is adjusted to give a correct value of voltage at the output and not to a theoretical value for PTAT. The calibration procedure is easily carried out by opening or shorting the links of a quasi-binary trim network like the one shown in *Figure 6*. The links may be opened to add resistance by blowing an aluminum fuse, or a resistor may be shorted out of the circuit by carrying out a "zener-zap". The analysis in the next section shows that when the circuit is calibrated at a given temperature, then the circuit will be accurate for the full temperature range.

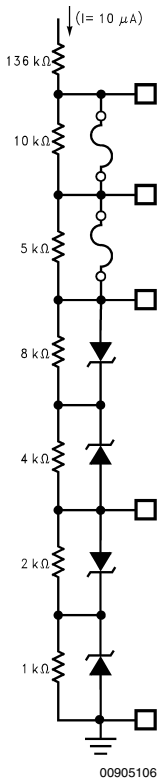


FIGURE 6.

How the Calibration Procedure Works

Widlar[5] has shown that a good approximation for the base-emitter voltage of a transistor is:

$$V_{BE} = V_{G0}\left(1 - \frac{T}{T_0}\right) + V_{beo}\left(\frac{T}{T_0}\right) + \frac{nkT}{q} \ln\left(\frac{T_0}{T}\right) + \frac{kT}{q} \ln \frac{I_C}{I_{co}} \quad (2)$$

where T is the temperature in ˚Kelvin, T_0 is a reference temperature, V_{GO} is the bandgap of silicon, typically 1.22V,

How the Calibration Procedure Works (Continued)

and V_{beo} is the transistor's base-emitter voltage at the reference temperature, T_0. The above equation can be re-written as

$$V_{BE} = (\text{sum of linear temp terms}) + (\text{sum of non-linear temp terms}) \quad (3)$$

where the first two terms of *Equation (1)* are linear and the last two terms are non-linear. The non-linear terms were shown by Widlar to be relatively small and thus will be considered later.

Let us define a base voltage, V_b, which is a linear function of temperature as: $V_b = C_1 \bullet T$. This voltage may be represented by the circuit in *Figure 1*. The emitter voltage is $V_e = V_b - V_{be}$ which becomes:

$$V_e = C_1T - V_{G0}\left(1 - \frac{T}{T_0}\right) - V_{beo}\left(\frac{T}{T_0}\right).$$

If V_e is defined as being equal to C_2 at $T = T_0$, then the above equation may be solved for C_1. Doing so gives:

$$C_1 = \frac{V_{beo} + C_2}{T_0} \quad (4)$$

Using this value for C_1 in the equation for V_e gives:

$$V_e = C_2\frac{T}{T_0} + V_{G0}\left(\frac{T - T_0}{T_0}\right) \quad (5)$$

If V_e is differentiated with respect to temperature, T, *Equation (4)* becomes $dV_e/dT = (C_2 + V_{G0})/T_0$.

This equation shows that if V_b is adjusted at T_0 to give $V_e = C_2$, then the rate of change of V_e with respect to temperature will be a constant, independent of the value of V_b, the transistor's beta or V_{be}. To proceed, consider the case where $V_e = C_2 = 0$ at $T_0 = 0^\circ C$. Then

$$\frac{dV_e}{dT} = \frac{V_{G0}}{273.7} = 4.47\ mV/^\circ C$$

Therefore, if V_e is trimmed to be equal to (4.47 mV) T (in °C) for each degree of displacement from 0°C, then the trimming can be done at ambient temperatures.

In practice, the two non-linear terms in *Equation (1)* are found to be quadratic for positive temperatures. Tsividis[6] showed that the bandgap voltage, V_0, is not linear with respect to temperature and causes nonlinear terms which become significant for negative temperatures (below 0°C). The sum of these errors causes an error term which has an approximately square-law characteristic and is thus compensated by the curvature compensation circuit of *Figure 7*.

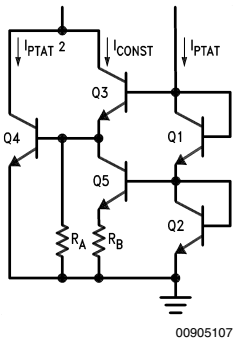


FIGURE 7.

A Unique Compensation Circuit

As mentioned earlier, the base-emitter voltage, V_{BE}, is not a linear function with respect to temperature. In practice, the nonlinearity of this function may be approximated as having a square-law characteristic. Therefore, the inherent non-linearity of the transistor and diode may be corrected by introducing a current with a square-law characteristic into the indicated node of *Figure 4*. Here's how the circuit of *Figure 7* works: transistors Q1 and Q2 are used to establish currents in the other three transistors. The current through Q1 and Q2 is linearly proportional to absolute temperature, I_{PTAT}, as is the current through transistor Q5 and resistor R_B. The current through resistor R_A is a decreasing function of temperature since it is proportional to the V_{BE} of transistor Q4. The emitter current of Q3 is equal to the sum of the current through Q5 and the current through R_A, and thus Q3's collector current is a constant with respect to temperature. The current through transistor Q4, I_{C4}, will be used to compensate for the V_{BE} nonlinearities and is found with the use of the following equation:

$$I_{C4} = I_S\left(e^{\frac{qV_{BE4}}{KT}} - 1\right) \cong I_S\, e^{\frac{qV_{BE4}}{KT}}$$

where $V_{BE4} = V_{BE1} + V_{BE2} - V_{BE3}$.

From the above logarithmic relationship, it is apparent that I_{C4} becomes

$$I_{C4} = \frac{I_{C1}\, I_{C2}}{I_{C3}} = \frac{I_{PTAT}{}^2}{I_{CONST}}.$$

A Unique Compensation Circuit

(Continued)

Thus, a current which has a square law characteristic and is $PTAT^2$, is generated for use as a means of curvature correction.

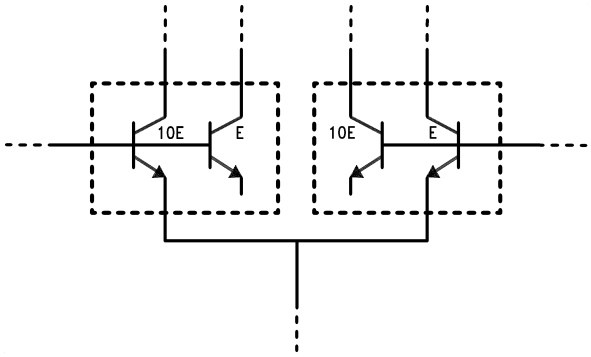
Processing and Layout

The sensor is constructed using conventional bipolar epitaxial linear processing. SiCr thin-film resistors are used in place of their diffused counterparts as a result of their better tempco matching, an important consideration for resistors which must track over temperature. Such resistors include R1 and nR1 of the bandgap circuit.

Another point of interest in the construction of the device centers around transistors Q1 and Q2 of *Figure 4*. In order for the circuit to retain its accuracy over temperature, the leakage currents of each transistor, which can become quite significant at high temperatures, must be equal so that their effects will cancel one another. If the geometries of the two transistors were equivalent, then their leakage currents would be also, but since Q1 has ten times the emitter area of Q2, the accuracy of the device could suffer. To correct the problem, the circuit is built with Q1 and Q2 each replaced by a transistor group consisting of both Q1 and Q2. These transistor groups have equivalent geometries so that their leakage currents will cancel, but only one transistor of each group, representing Q1 in one group and Q2 in the other pair is used in the temperature sensing circuit. A circuit diagram demonstrating this idea is shown in *Figure 8*.

Using the LM34

The LM34 is a versatile device which may be used for a wide variety of applications, including oven controllers and remote temperature sensing. The device is easy to use (there are only three terminals) and will be within 0.02˚F of a surface to which it is either glued or cemented. The TO-46 package allows the user to solder the sensor to a metal surface, but in doing so, the GND pin will be at the same potential as that metal. For applications where a steady reading is desired despite small changes in temperature, the user can solder the TO-46 package to a thermal mass. Conversely, the thermal time constant may be decreased to speed up response time by soldering the sensor to a small heat fin.



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FIGURE 8.

Fahrenheit Temperature Sensors

As mentioned earlier, the LM34 is easy to use and may be operated with either single or dual supplies. *Figure 9* shows a simple Fahrenheit temperature sensor using a single supply. The output in this configuration is limited to positive temperatures. The sensor can be used with a single supply over the full −50˚F to +300˚F temperature range, as seen in *Figure 10*, simply by adding a resistor from the output pin to ground, connecting two diodes in series between the GND pin and the circuit ground, and taking a differential reading. This allows the LM34 to sink the necessary current required for negative temperatures. If dual supplies are available, the sensor may be used over the full temperature range by merely adding a pull-down resistor from the output to the negative supply as shown in *Figure 11*. The value of this resistor should be $|-V_S|/50\ \mu A$.

For applications where the sensor has to be located quite a distance from the readout circuitry, it is often expensive and inconvenient to use the standard 3-wire connection. To overcome this problem, the LM34 may be connected as a two-wire remote temperature sensor. Two circuits to do this are shown in *Figure 12* and *Figure 13*. When connected as a remote temperature sensor, the LM34 may be thought of as a temperature-dependent current source. In both configurations the current has both a relatively large value,

Fahrenheit Temperature Sensors

(Continued)

$$(20\ \mu A/^{\circ}F) \times (T_A + 3^{\circ}F),$$

and less offset when compared to other sensors. In fact, the current per degree Fahrenheit is large enough to make the output relatively immune to leakage currents in the wiring.

Temperature to Digital Converters

For interfacing with digital systems, the output of the LM34 may be sent through an analog to digital converter (ADC) to provide either serial or parallel data outputs as shown in *Figure 14* and *Figure 15*. Both circuits have a 0 to +128˚F scale. The scales are set by adjusting an external voltage reference to each ADC so that the full 8 bits of resolution will be applied over a reduced analog input range. The serial output ADC uses an LM385 micropower voltage reference diode to set its scale adjust (V_{REF} pin) to 1.28V, while the parallel output ADC uses half of an LM358 low power dual op amp configured as a voltage follower to set its $V_{REF}/2$ pin to 0.64V. Both circuits are operated with standard 5V supplies.

Basic Fahrenheit Temperature Sensor (+5˚ to +300˚F)

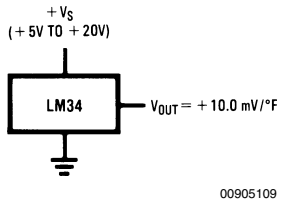


FIGURE 9.

Temperature Sensor, Single Supply, –50˚ to +300˚F

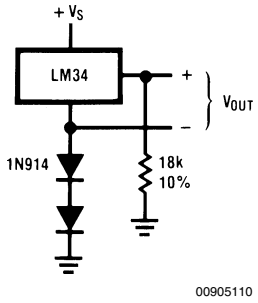


FIGURE 10.

Full-Range Fahrenheit Temperature Sensor

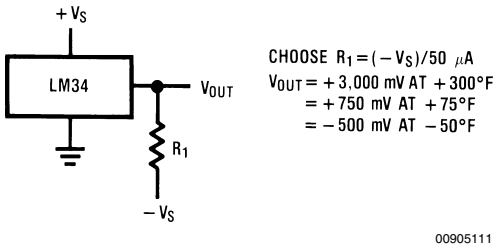
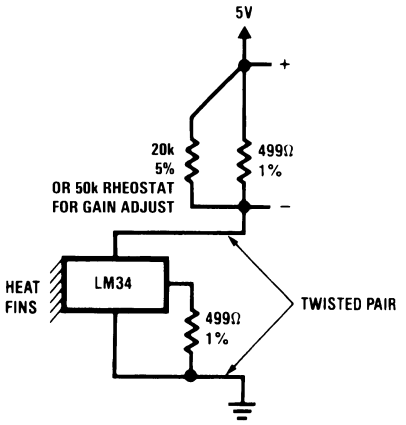


FIGURE 11.

Temperature to Digital Converters (Continued)

Two-Wire Remote Temperature Sensor
(Grounded Sensor)



V_{OUT} = 10 mV/°F (T_A + 3°F)
from +3°F to +100°F

FIGURE 12.

Two-Wire Temperature Sensor
(Output Referred to Ground)

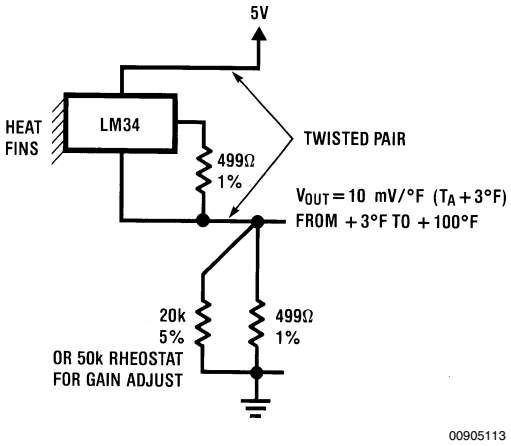


FIGURE 13.

Temperature to Digital Converters (Continued)

Temperature-to-Digital Converter (Serial Output, +128˚F Full Scale)

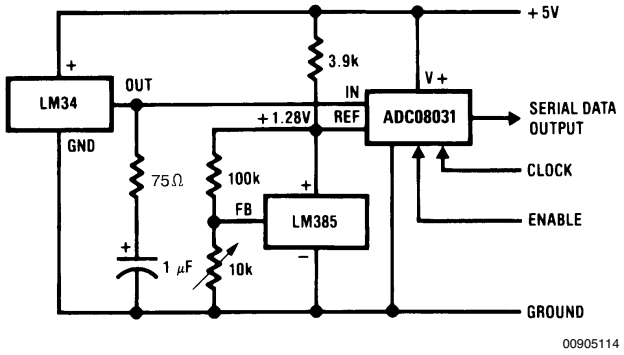


FIGURE 14.

Temperature-to-Digital Converter
(Parallel TRI-STATE Outputs for Standard Data Bus to µP Interface, 128˚F Full Scale)

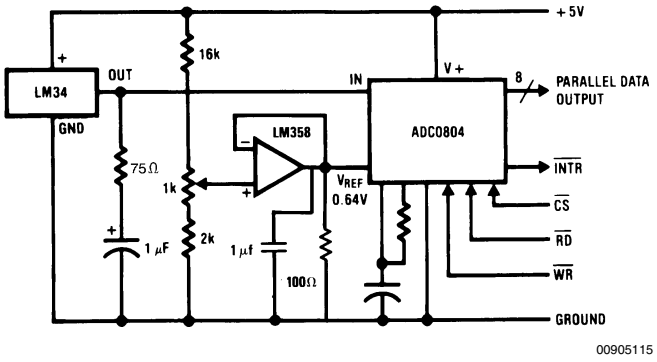


FIGURE 15.

LM34 with Voltage-to-Frequency Converter and Isolated Output
(3˚F to +300˚F; 30 Hz to 3000 Hz)

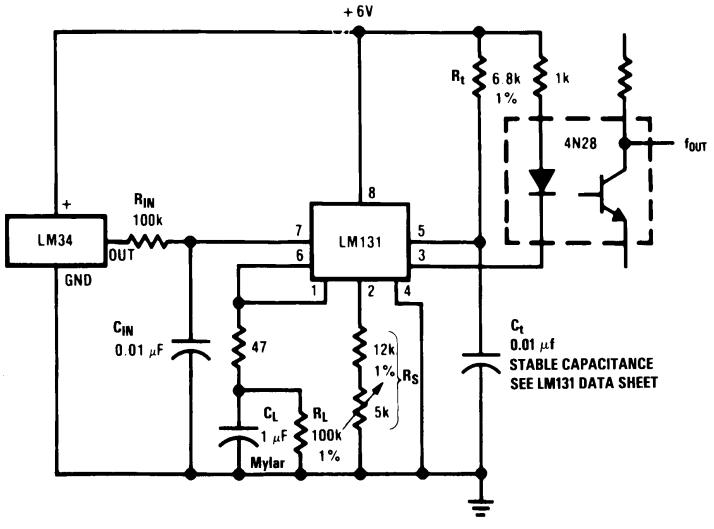
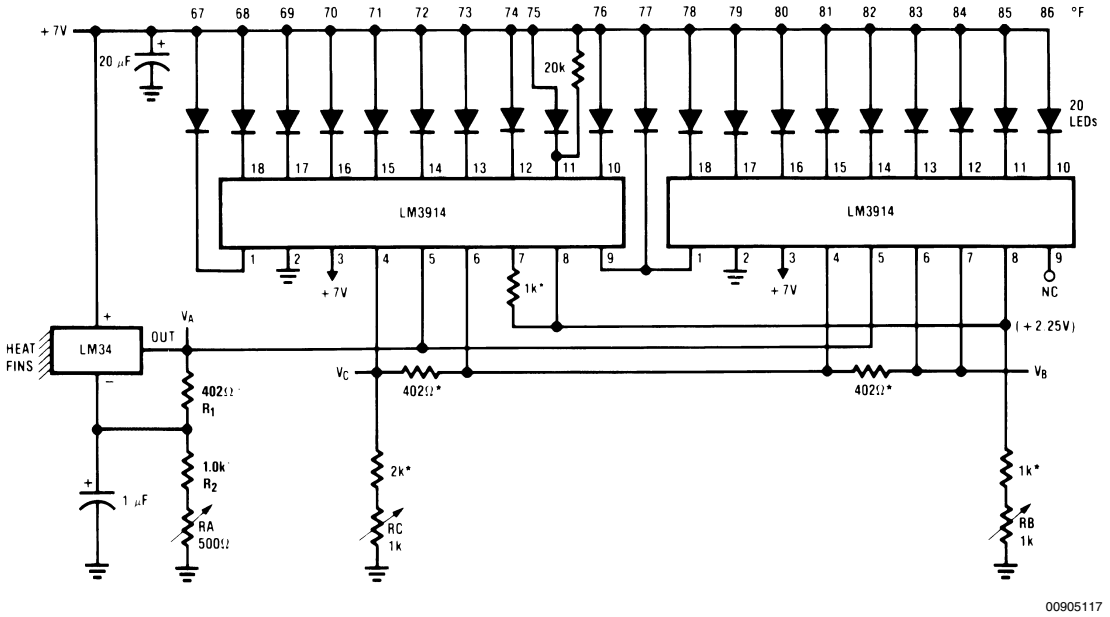


FIGURE 16.

Temperature to Digital Converters (Continued)

Bar-Graph Temperature Display (Dot Mode)



• = 1% or 2% film resistor

— Trim R_B for V_B = 3.525V

— Trim R_C for V_C = 2.725V

— Trim R_A for V_A = 0.085V + 40 mV/˚F x $T_{Ambient}$

— Example: V_A = 3.285V at 80˚F

FIGURE 17.

Temperature-to-Frequency Converter for Remote Sensing

If a frequency proportional to temperature is needed, then the LM34 can be used in conjunction with an LM131 voltage-to-frequency converter to perform the desired conversion from temperature to frequency. A relatively simple circuit which performs over a +3˚F to +300˚F temperature range is shown in *Figure 16*. The output frequency of this circuit can be found from the equation:

$$f_{OUT} = \left(\frac{V_{IN}}{2.09V}\right)\left(\frac{R_S}{R_L}\right)\left(\frac{1}{R_t\, C_t}\right)$$

where resistor R_S is used to adjust the gain of the LM131. If R_S is set to approximately 14.2 kΩ, the output frequency will have a gain of 10 Hz/˚F. Isolation from high common mode levels is provided by channeling the frequency through a photoisolator. This circuit is also useful for sending temperature information across long transmission lines where it can be decoded at the receiving station.

LED Display for Easy Temperature Reading

It is often beneficial to use an array of LED's for displaying temperature. This application may be handled by combining the LM34 with an LM3914 dot/display driver. The temperature may then be displayed as either a bar of illuminated LED's or as a single LED by simply flipping a switch. A wide range of temperatures may be displayed at once by cascading several LM3914's as shown in *Figure 17*.

Without going into how the LM3914 drivers function internally, the values for V_A, V_B, and V_C can be determined as follows:

V_A is the voltage appearing at the output pin of the LM34. It consists of two components, 0.085V and (40 mV/˚F) (T_A).

The first term is due to the LM34's bias current (approximately 70 μA) flowing through the 1 kΩ resistor in series with R_A. The second term is a result of the multiplication of the LM34's output by the resistive string composed of R_1, R_2, and R_A, where R_A is set for a gain factor of 4 (i.e.; 40 mV/˚F).

V_B represents the highest temperature to be displayed and is given by the equation V_B = 0.085V + (40 mV/˚F) (T_{HIGH}). For the circuit in *Figure 17* , V_B = 0.085V + (40 mV/˚F) (86˚F) = 3.525V.

V_C represents the lowest temperature to be displayed minus 1˚F. That is, V_C = 0.085V + (T_{LOW} −1˚F) (40 mV/˚F) which in this case becomes V_C = 0.085V + (67˚F −1˚F) (40 mV/˚F) = 2.725V.

With a few external parts, the circuit can change from dot to bar mode or flash a bar of LED's when the temperature sensed reaches a selected limit (see LM3914 data sheet).

Indoor/Outdoor Thermometer

An indoor/outdoor thermometer capable of displaying temperatures all the way down to –50˚F is shown in *Figure 18*.

Indoor/Outdoor Thermometer

(Continued)

Two sensor outputs are multiplexed through a CD4066 quad bilateral switch and then displayed one at a time on a DVM such as Texmate's PM-35X. The LMC555 timer is run as an astable multivibrator at 0.2 Hz so that each temperature reading will be displayed for approximately 2.5 seconds. The RC filter on the sensors outputs are to compensate for the capacitive loading of the cable. An LMC7660 can be used to provide the negative supply voltage for the circuit.

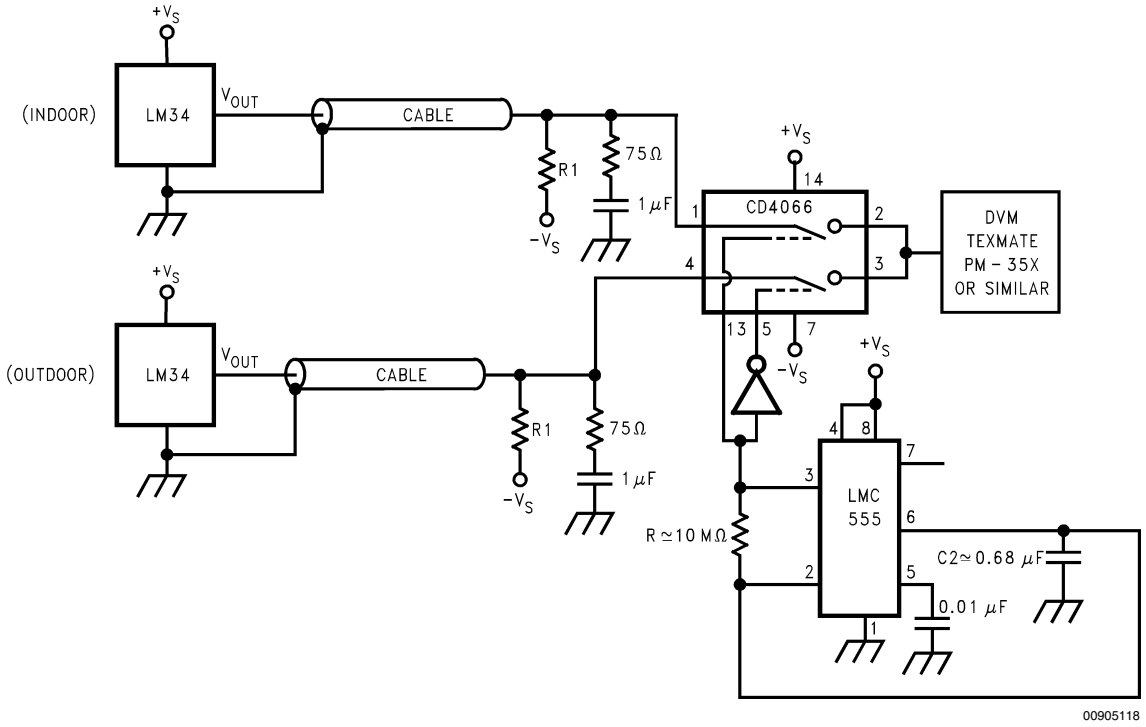


FIGURE 18.

Temperature Controller

A proportional temperature controller can be made with an LM34 and a few additional parts. The complete circuit is shown in *Figure 19*. Here, an LM10 serves as both a temperature setting device and as a driver for the heating unit (an LM395 power transistor). The optional lamp, driven by an LP395 Transistor, is for indicating whether or not power is being applied to the heater.

When a change in temperature is desired, the user merely adjusts a reference setting pot and the circuit will smoothly make the temperature transition with a minimum of overshoot or ringing. The circuit is calibrated by adjusting R2, R3 and C2 for minimum overshoot. Capacitor C2 eliminates DC offset errors. Then R1 and C1 are added to improve loop stability about the set point. For optimum performance, the temperature sensor should be located as close as possible to the heater to minimize the time lag between the heater application and sensing. Long term stability and repeatability are better than 0.5˚F.

Differential Thermometer

The differential thermometer shown in *Figure 20* produces an output voltage which is proportional to the temperature difference between two sensors. This is accomplished by using a difference amplifier to subtract the sensor outputs from one another and then multiplying the difference by a factor of ten to provide a single-ended output of 100 mV per degree of differential temperature.

Differential Thermometer (Continued)

Temperature Controller

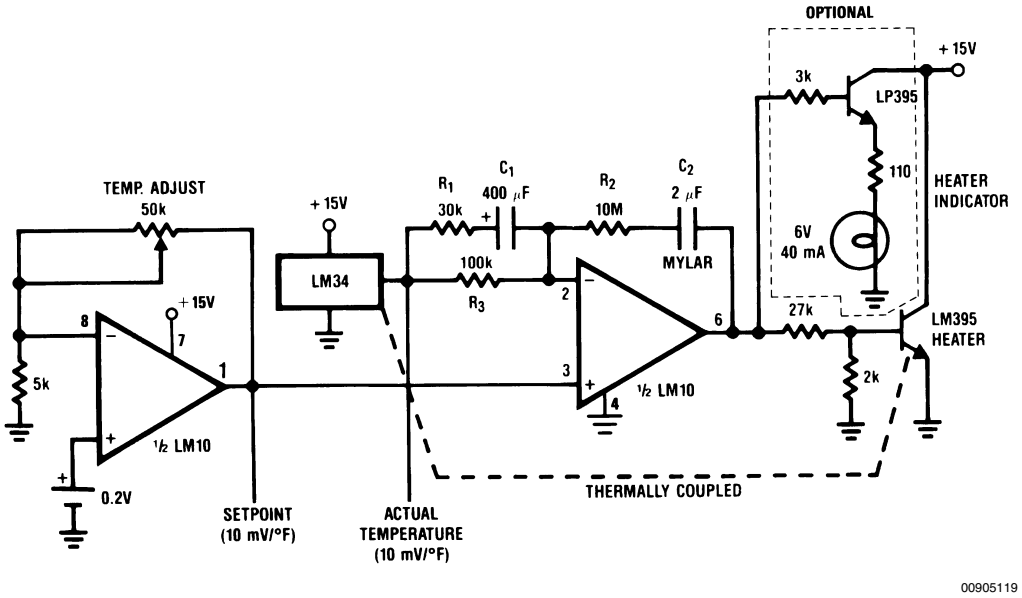


FIGURE 19.

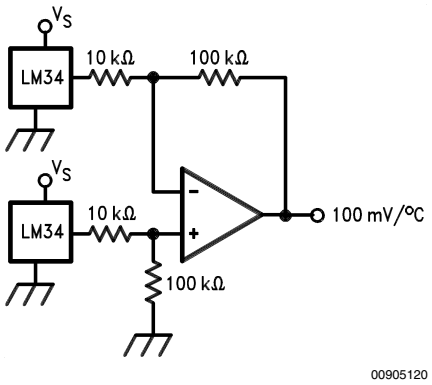
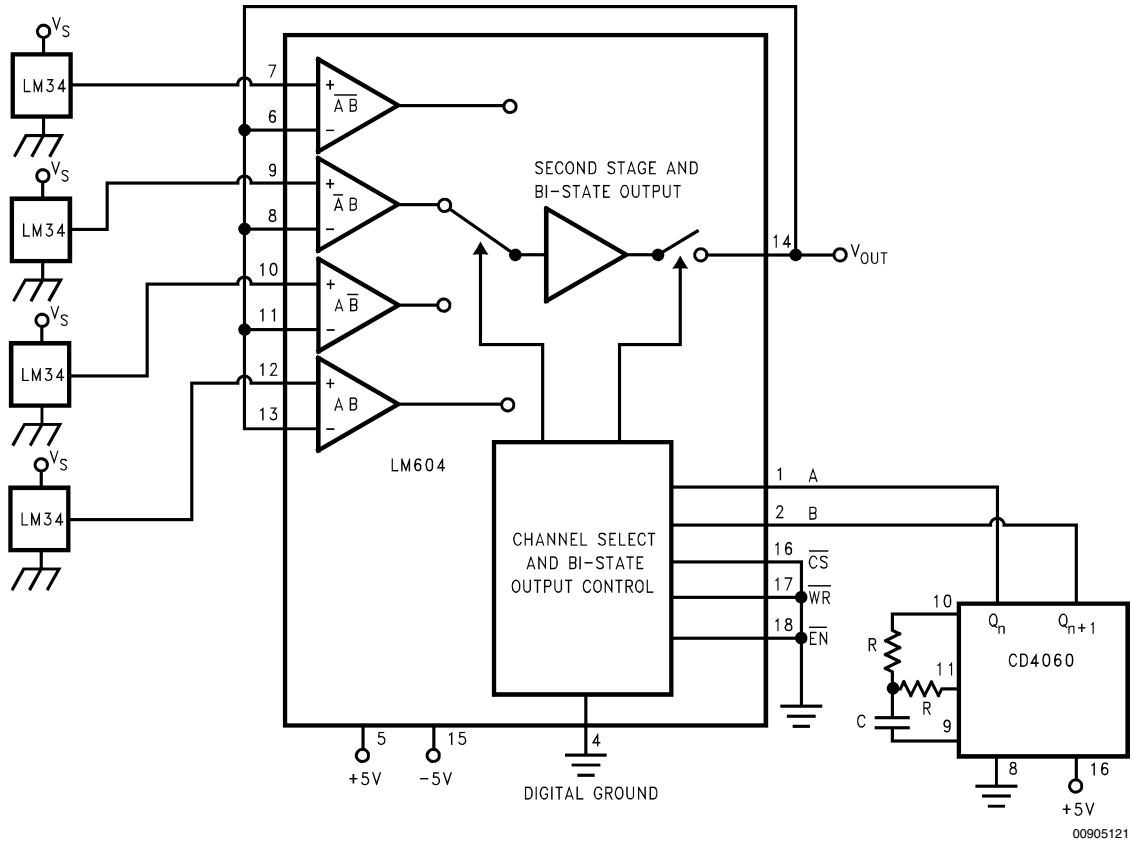


FIGURE 20.

Differential Thermometer (Continued)



Temperature monitoring

$$\text{rate} = \frac{0.56}{RC}\left(\frac{1}{2^{n-1}}\right)$$

If Q_4 and Q_5 are used with R = 13k and C = 510 pF the rate will be 10 kHz.

FIGURE 21.

Temperature Scanner

In some applications it is important to monitor several temperatures periodically, rather than continuously. The circuit shown in *Figure 21* does this with the aid of an LM604 Mux Amp. Each channel is multiplexed to the output according to the AB channel select. The CD4060 ripple binary counter has an on-board oscillator for continuous updating of the channel selects.

Conclusion

As can be seen, the LM34 and LM35 are easy-to-use temperature sensors with excellent linearity. These sensors can be used with minimal external circuitry for a wide variety of applications and do not require any elaborate scaling schemes nor offset voltage subtraction to reproduce the Fahrenheit and Celsius temperature scales respectively.

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Телефон: 8 (495) 268-14-82
Email: n@nsistems.ru

ИНН: 7735154786
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