Solid State Temperature Sensing

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Introduction

The forward bias voltage across a semiconductor junction has a very constant change in voltage with temperature over a wide temperature range if the current through the junction is constant. For silicon semiconductors the constant is around -2 mV per degree Celsius. The constant increases with current and varies from device to device so some method is needed to calibrate the temperature sensing. As this is an introduction for students the calibration issues are ignored so as not to make the problems too difficult. Since we are talking about a straight line then two bits of information are needed. We have the slope. We now need the total diode voltage at some known temperature. For the examples we will use the voltage at 0 C and refer to that voltage as VZ. However, this data is rarely if ever provided in data sheets. More commonly you are given the range of voltage at 25 C and then you have to work backwards with the slope down to 0 C. The following nomenclature is used.

k is the change in diode voltage per degree C
T is the diode temperature in degrees C
VZ is the voltage across the diode when the temperature is 0 C

Circuit 1

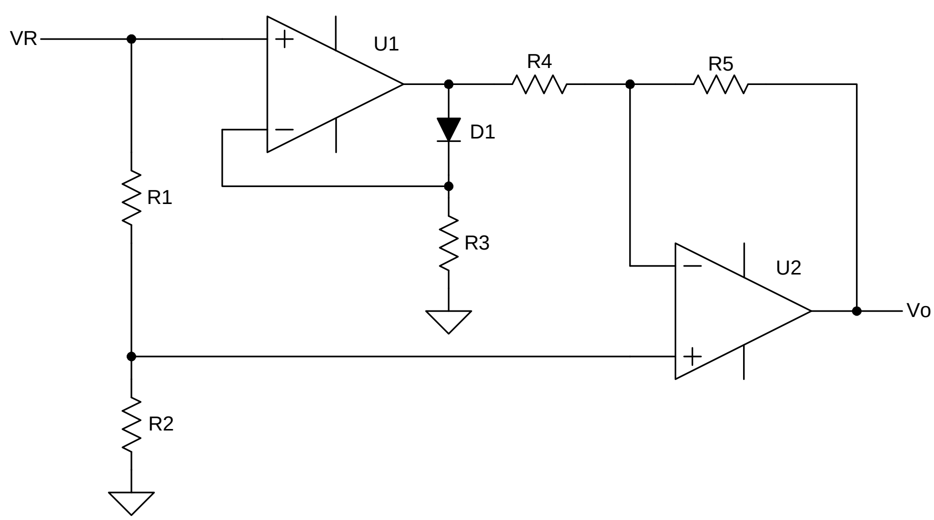

Figure 1: Circuit 1 for solid state thermometer

The reference voltage, VR, is typically a standard temperature stable precision part with a voltage of 5.000 volts. Feedback from U1 makes the voltage across R3 exactly equal to VR so the current through R3 is constant and thus the current through the diode is constant. The constant current is generally in the range of 100 uA to 1 mA. Higher currents will cause some heating of the diode junction – thus causing error. For a 5.000 volt reference R3 might be chosen to be 10K for a current of 500 uA.

The voltage at the output of U1 is VR + VZ + k*T where k is typically -0.002. We often desire for Vo to be 10 mV/C and be 0.000 volts when T is 0. For this example then inverting amplifier, U2, would have to have a gain of 0.01/-0.002 = -5. The ratio, R5/R4, then must be 5. We might choose R4 as 2K and then compute R5 as 10K. We will use VR as 5.000 and VZ as 0.700 as an example. Then at 0 C the output of U1 is 5.700 volts and the output of U2 is -5*5.700 = -28.500 volts. However, this voltage will increase by 10 mV for each degree C the temperature is above 0. We need a method to eliminate the -28.500 volt output offset.

Voltage divider R1 and R2 applies a positive voltage to the non-inverting input of U2. Since the inverting gain is -5 the non-inverting gain is 6. The question now becomes what voltage should be applied to the non-inverting input of U2 to produce a +28.500 volt output which by superposition will neutralize the -28.500 voltage. The answer is simply 28.5/6 = 4.75 volts. R1 and R2 would then be calculated to produce this voltage.

Homework problems

1. Rework the above example if VR is 1.25, 2.50, and 10.00 volts. For all cases calculate R3 for a diode current of 500 uA. If you end up with a negative resistor value (for R1 or R2) then the circuit can not work for that particular VR.

2. Rework the above example but use VZ = 0.75 and k = -0.0022. If necessary, use a different voltage for VR.

3. For a typical test problem you would be given VR, VZ, k, and either R4 or R5 (you would calculate the other) and R1 or R2 (you would calculate the other), and the output voltage scale factor (typically 10 mV/C but could be other values such as 20 or 50 mV/C, etc.). You might also have to calculate R3 for a specified diode current.

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Circuit 2

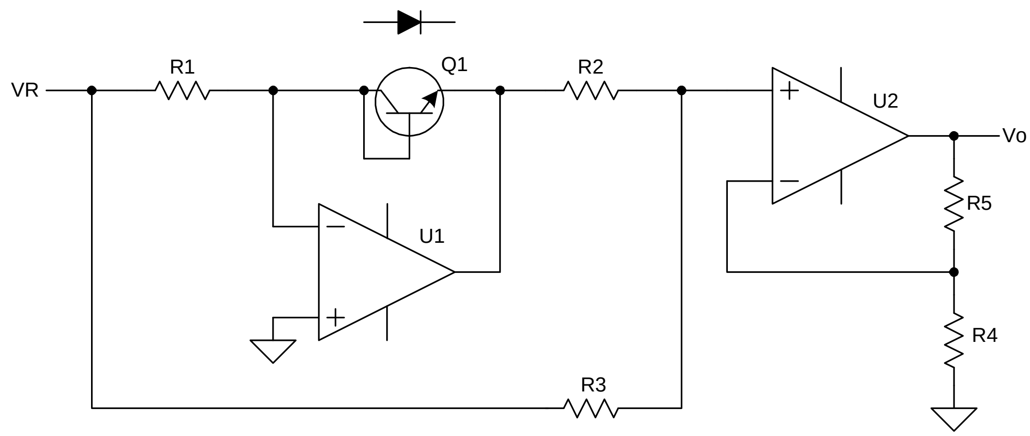

Figure 2: Circuit 2 for solid state thermometer

The circuit in Figure 2 uses a forward biased transistor instead of a diode as the temperature sensor. This connection is known as a transdiode and has better properties than standard diodes. The diode symbol above the transistor is just to illustrate what is going on. A diode could also be used for this circuit instead. Feedback from U1 holds the voltage at the inverting input of U1 at zero. VR is a standard reference voltage as in the previous circuit and is typically 5.000 volts. The current through R1 is constant and is VR/R1. Thus, the current through the transistor is also constant. The output voltage of U1 is –(VZ + k*T). Note that the output voltage will move in a positive direction as temperature is above 0.

The voltage divider formed by R2 and R3 sums a fraction of the positive VR with the negative VZ output of U1 so that at 0 C the voltage at the non-inverting input of U2 is 0. Either R2 or R3 is chosen and then the other is calculated. For this example we will choose R2 to be 10K and we will use the same 5.000 volts for VR, -0.002 for k and 0.7 volts for VZ as in the first circuit example. We use the fact that the voltage at the inverting input of U2 is 0 at 0 C. Under this condition the current through R2 is (-0.7 – 0)/10K = -70 uA. The current through R3 must be the same. So R3 = (0 – 5)/-70uA = 71.43K.

We have satisfied the 0 C point. Now we have to determine the voltage gain for U2. The R2, R3 voltage divider attenuated the -0.002 k factor by (71.43K / 81.43K) = 0.877. Thus, the k factor is now 0.002 * 0.877 = 0.001754. The gain to achieve 10 mV / C is 0.01 / 0.001754 = 5.701. If we choose R4 to be 10K then R5 would be 10K*(5.701-1) = 47K.

Homework problems

1. Rework the above example for reference voltages of 1.25, 2.50, and 10.0 volts. It might be that not all of these work. In all cases, calculate the value of R1 for a constant current of 500 uA. Keep in mind that on a test I might specify a different value such as 200 uA or 1 mA, etc.

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2. For a test you might be given R3 and R5 and then you would have to calculate R2 and R4. Use one of your results and work backwards to the given resistors. Be prepared for any permutation.

Circuit 3

The circuit in Figure 3 is yet another method to build a solid state thermometer. This time a negative voltage reference is used and the current through the transdiode (or regular diode) is the reference voltage divided by R1. The output of U1 is simply the forward diode voltage. The inverting gain (-R4/R2) of U2 inverts the negative temperature slope and scales it to the desired output value (typically 10 mV/deg but other values could be used as well). R3 sums current into the virtual ground of U2 so that the output voltage is zero when the temperature is zero.

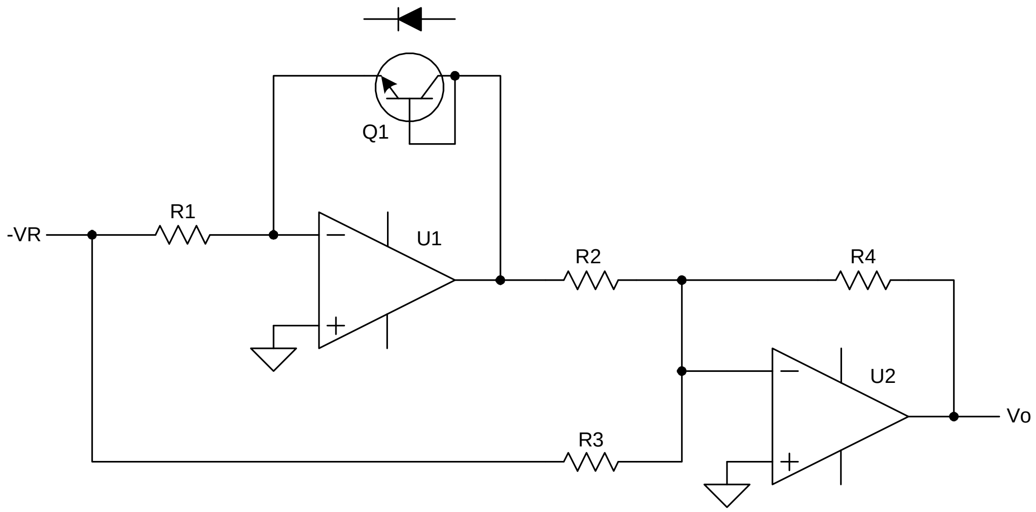

Figure 3: Circuit 3 for solid state thermometer

As an example we will use VR = -5.000 volts, VZ = 0.7 volts, k = -0.002, and we desired Vo to be 10 mV/C. R1 will be selected to be 10K to provide 500 uA through the diode. The ratio, R4/R2, must be 5 to scale the -0.002 factor to +0.01. We will choose R2 as 2K and then calculate R4 to be 10K. At 0 C the current through R2 is (0.7 – 0) / 2K = 350 uA. The current through R3 must then be the same value so that there is no current through R4 and the output voltage is the desired 0 volts. R3 = (0 - -5) / 350 uA = 14.29K.

Homework problems

1. Calculate R1 and R3 for the example circuit for VR = -1.25, -2.5, and -10 volts. All of these will work fine.

2. Modify the example so that the output scale factor is 50 mV / C.

3. For a test you would be given either R2 or R4 and you would calculate the other resistors based on the given diode characteristics and desired diode current.

Conclusions

These are three of a number of circuits to implement a simple solid state thermometer. On a test you might see another variation – should be no problem if you understand how to work the circuits here. Can you invent other methods?

Of the three circuits the third one is clearly the best implementation. You should try to understand why. One important factor is that it is the least sensitive to component tolerance particularly concerning how the effect of VZ is handled.