Electronic thermometer

Simple sensing diode provides accurate and reliable temperature measurement

by A. S. Henderson

Although several designs for electronic thermometers have been published, most of these have either been complicated or low performance devices. This design has been kept simple for reliable operation, and offers an accuracy within 1% of f.s.d.

The most important part of an electronic thermometer is the sensing device which, in most cases, should be small, have a low thermal capacity, generate a large signal, respond linearly to temperature variations, abstract or dissipate very little energy and have a long life. Several devices such as thermistors, transistors and special i.cs were considered, but the most attractive device appeared to be a miniature signal diode. It is generally accepted that, with a constant current, the forward voltage across a silicon diode reduces by 2mV per degree increase in junction temperature. This can be expressed as

$$\Delta V = \frac{kt}{q}\, ln\, V_f$$

where k is Boltzmann's constant and q is the charge on the electron. As k and q are fixed, the change in voltage must be linearly connected to temperature, and the physical constants of silicon give 2mV/°C.

To test this parameter, six batches of 100 miniature signal diodes were evaluated as shown in Fig. 1, using a 9 to 15V d.c supply connected in series with a 10kΩ resistor, a multimeter and a diode. The diode under test was cycled from 0°C to 100°C with a forward current of exactly 1mA at 0°C. As there was no detectable change in forward current, this was assumed to be constant. The forward voltage drop, V_f, of each diode was measured at ambient temperature to record the spread in V_f within a batch. These values were grouped in 5mV steps, and the distribution of V_f within six batches of 100 silicon devices is shown in Fig. 2.

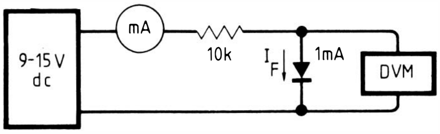

Fig. 1. Test circuit to measure V_f.

From each type, two devices from the outer distribution spread, ignoring the odd wild values, and three from the central concentration were assembled into probes and tested for V_f at 0°C and 100°C. The correlation between V_f at 0°C and the voltage excursion, ΔV, over 100°C for four types is shown in Fig. 3. The 1N3063, 1S44 and 1N4154 showed no apparent correlation and have been omitted.

A batch of germanium diodes, type 1N3470, was also tested and Fig. 4 shows the distribution of V_f(amb) for these devices. An ideal device, indicated in Fig. 3 by a dotted line marked 2mV/°C, has a

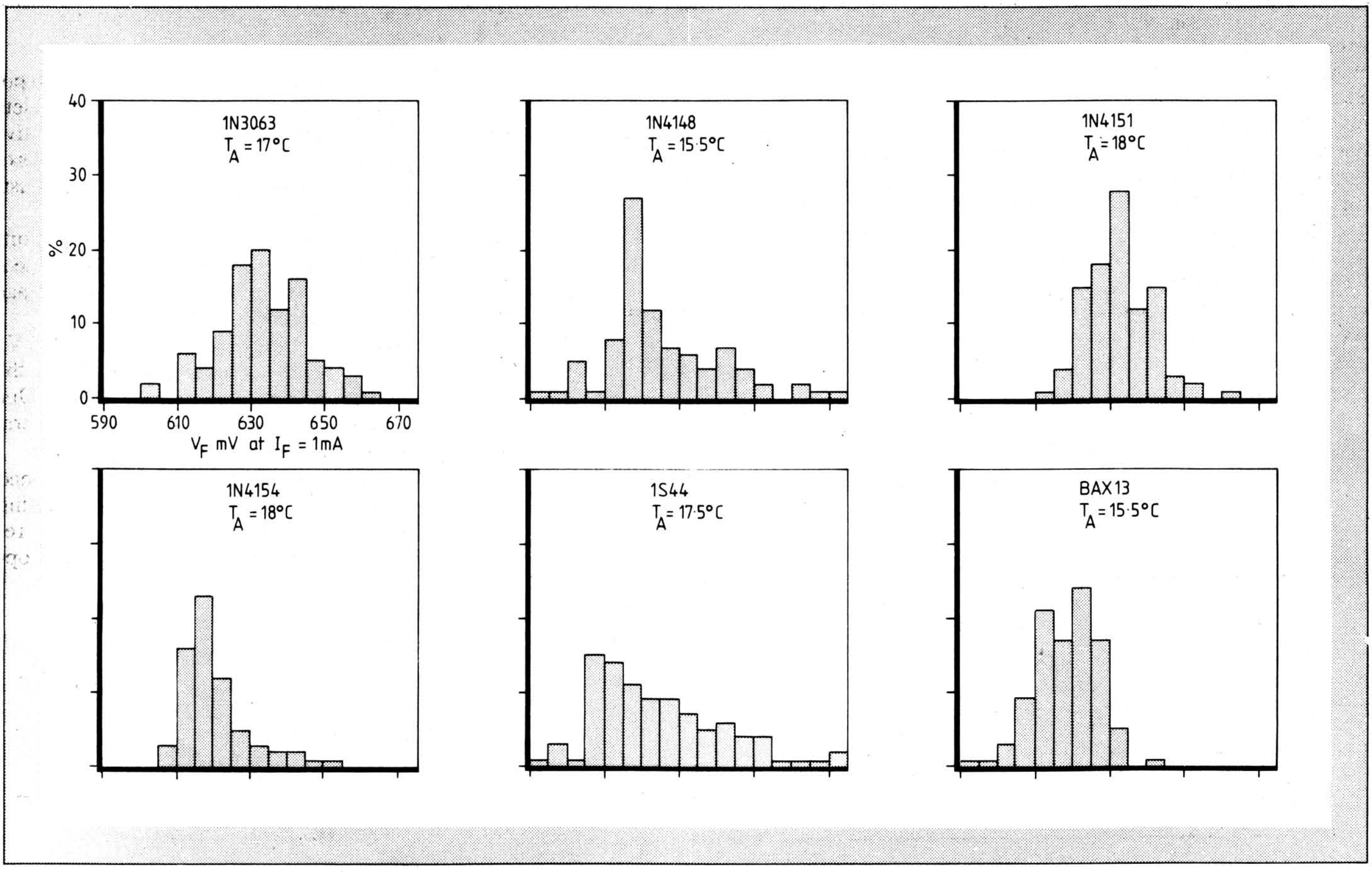

Fig. 2. Distribution of V_f (amb) for six types of silicon diode.

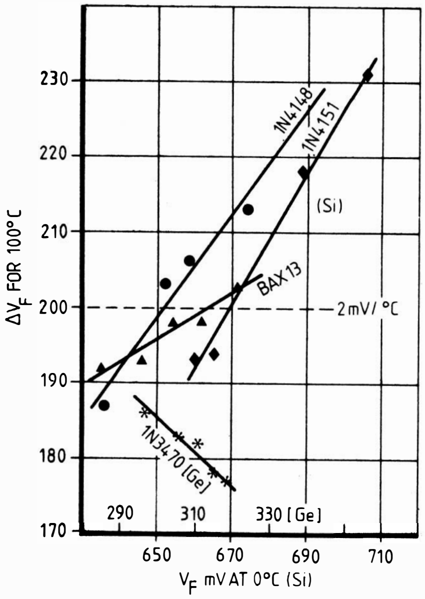

Fig. 3. Correlation between V_f (0°C) and ΔV_f (100°C).

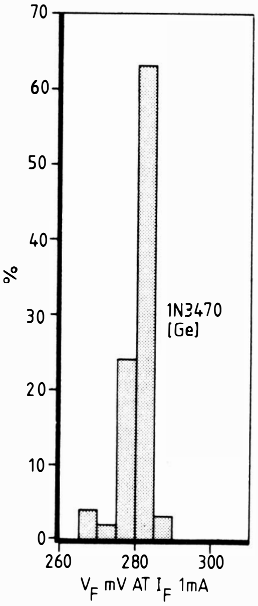

Fig. 4. Distribution of V_f (amb) for a germanium diode.

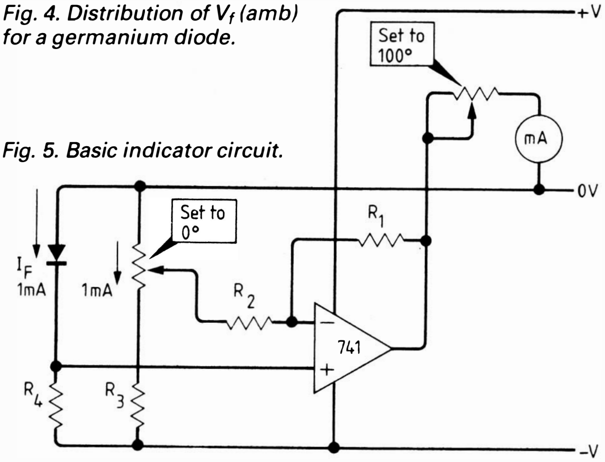

Fig. 5. Basic indicator circuit.

horizontal slope which is independent of V_f at 0°C. The closest slope to the ideal is shared by the BAX13 and 1N3470 silicon and germanium devices respectively.

From the distribution figures it is clear that very few diodes in a batch of 100 will give an exact 200mV excursion for a 100°C change in temperature (180mV for the 1N3470), therefore the range of the indicator needs to be adjustable. If the 0° and 100° readings are set by potentiometers, it is possible to achieve accurate and reliable temperature measurement.

The circuit shown in Fig. 5 uses a diode sensor with its anode connected to 0V and a 1mA bleed resistor to the negative supply. The junction of the diode and resistor feeds the non-inverting input of an op-amp, and the inverting input is connected to an identical negative voltage from the set −0°C cermet potentiometer. Therefore, with the circuit adjusted, when the diode is at 0°C the output from the op-amp is 0V. As the temperature is increased V_f at the non-inverting input reduces, i.e. becomes more positive, and the output goes positive. A closed-loop gain of around 5 gives an output of about 1V. If a 1mA meter is connected from the output via a 1kΩ potentiometer to 0V, the 100°C signal can be adjusted for f.s.d. Alternatively, f.s.d. can be set for any intermediate output to give a wide choice of scale values. Other meter sensitivities can easily be used by altering the value of the set −100°C potentiometer.

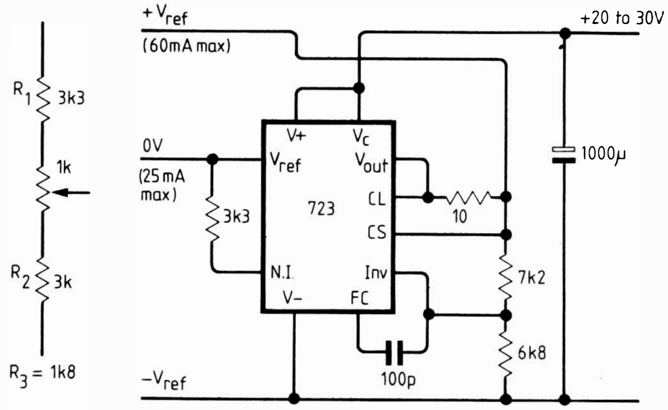

Fig. 6. Stabilized power supply. The resistor network allows adjustment of the positive rail to exactly twice V_{ref}.

To avoid problems with drift, the instrument requires a regulated power supply as shown in Fig. 6, which also provides a temperature-stabilized reference voltage of around 7V. The V_{ref} terminal is used for 0V and is connected to earth. The main regulator controls the positive rail at double V_{ref}. The complete circuit shown in Fig. 7 uses an alternative voltage adjustment network which provides a smoother and less critical adjustment of the output voltage.

For battery operation in a portable unit, the 723 regulator cannot be used because it requires a 9V input and a slight voltage drop causes trouble. The circuit in Fig. 8 overcomes this problem by using a 7V2 and a 3V6 Zener diode for stabilizing the positive and 0V rails respectively. One drawback, however, is the loss of temperature compensation provided by the 723.

In applications which require a switched output, such as the control of a heating element, a simple modification is to remove the feedback network from the op-

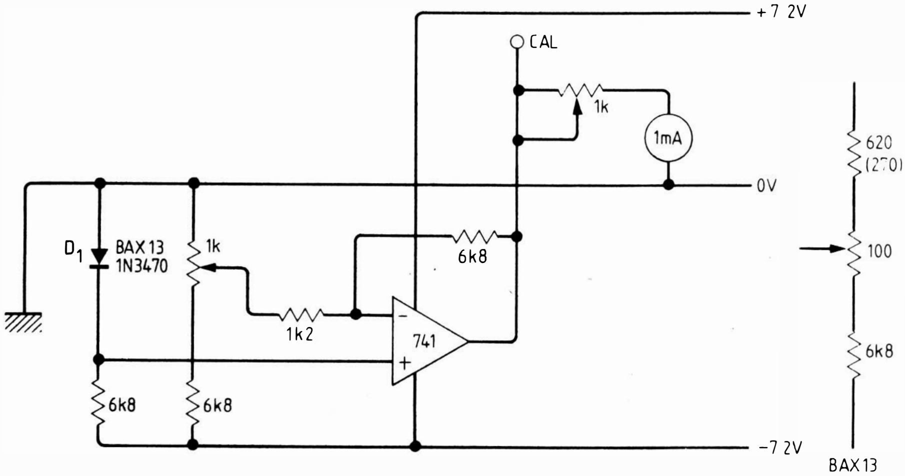

Fig. 7. Prototype circuit using a silicon or germanium diode.

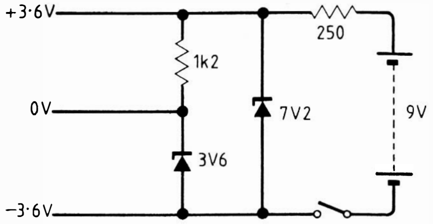

Fig. 8. Simple regulator for a battery supply.

amp in Fig. 7 and use it as a comparator. However, because the change in temperature is proportional to temperature difference, the probe will not quite reach the ambient temperature and over the last fraction of a degree the output changes very slowly. This will cause the op-amp to oscillate for several seconds before switching and may permit switching by thermal noise. Introducing hysteresis by positive feedback is an effective way to stop the oscillation, but this produces an unacceptable dead band. The problem can be overcome by using a dual op-amp with one half connected as in the original circuit and the output signal fed to the second half connected as a comparator with positive feedback. As the output signal is more than five times greater than the input, the dead band is reduced to less than 0.5°C. The combined indicator and comparator circuit is shown in Fig. 9. In the prototype some 741 op-amps did not switch off the transistor. If this occurs, a signal diode should be connected in series with the emitter to raise the base voltage.

Because this is a low-gain, low-impedance circuit, construction is not critical and earthing the 0V line enables a cheap and simple probe to be assembled as shown in Fig. 10. To prevent mains hum a screened lead should be used with the probe.

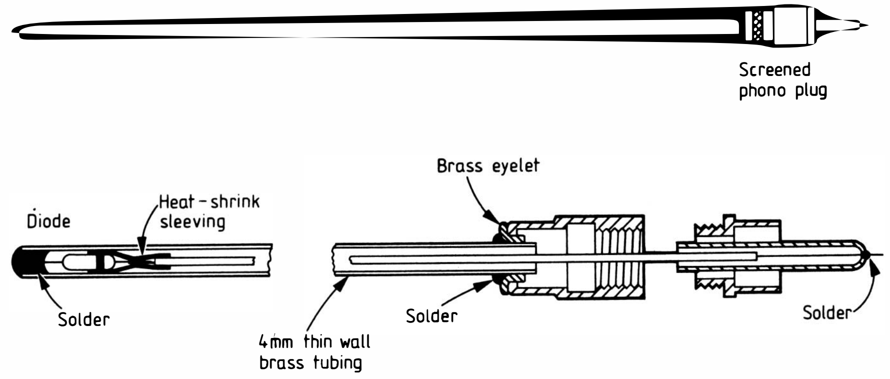

Fig. 10. Temperature probe assembly.

Multi-channel operation

As explained earlier, diodes of the same type do not exhibit exactly similar characteristics so multi-channel operation is not straightforward. Using several meters or cermet potentiometers is expensive, and wire-wound types suffer from poor resolution. Matching the diodes provides a low-cost solution and the test circuit in Fig. 11 enables the devices to be sorted into 0.5mV or 0.25°C groups very quickly. The test circuit does not measure V_F directly but the differences in V_F compared with a preset value, which permits the use of the most sensitive voltage range.

When switching two or more probes at the input to the indicator circuit, the switch must be a make-before-break type so that the op-amp input is always connected. For special applications it is easy to modify the circuit. Closely matched op-amps as in the 747 minimise temperature drift even in a high-sensitivity differential circuit.

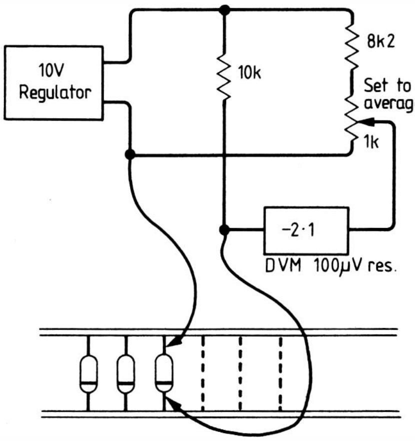

Fig. 11. Test circuit for matching sensing diodes.

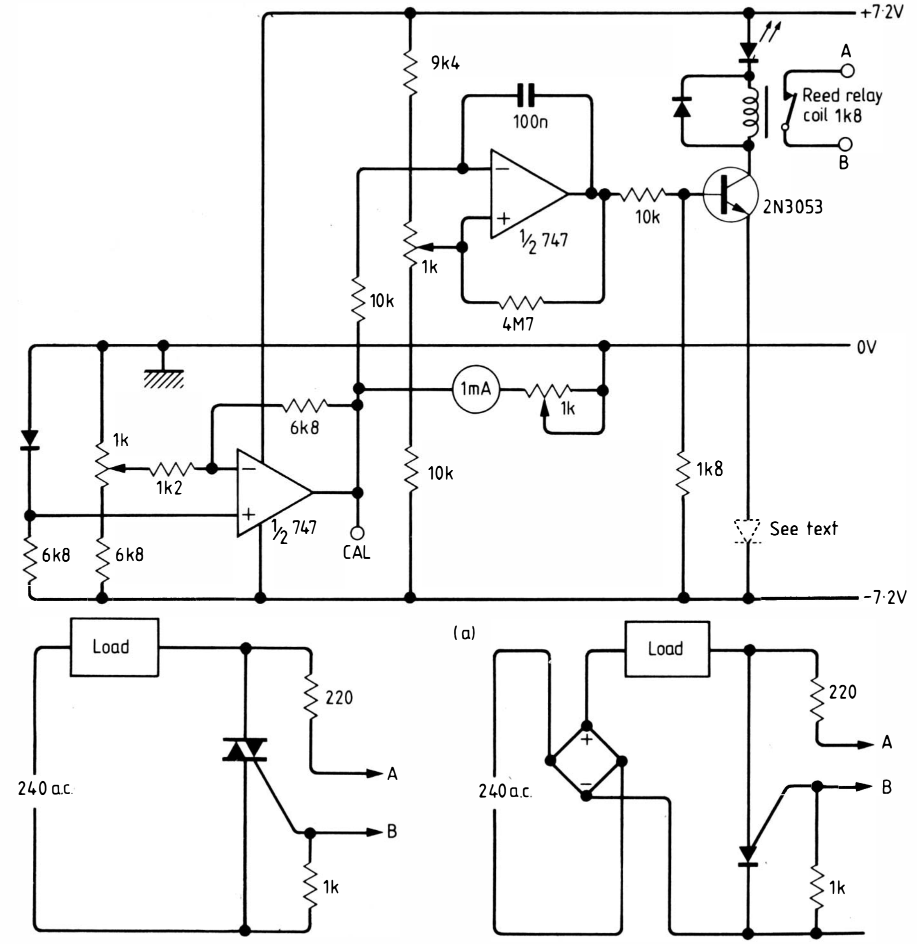

Fig. 9. Temperature indicator and comparator switch. The relay contacts can switch a small load or trigger the optional triac/s.c.r. circuits.

Calibration

Calibration is simple and only requires distilled water. Prepare a tray of ice cubes from the distilled water, half fill a suitable container with the ice cubes and add the same amount of cold tap water. Stir thoroughly until the ice cubes are about half their original size, insert the probe and, when the meter reading stabilizes, adjust the 0°C control so that the meter reads zero. The mixture should be stirred again and the adjustment checked. Next, boil some distilled water, insert the probe and repeat the procedure for the 100°C control.

For intermediate scale lengths such as 0 to 40°C, proceed as above with a voltmeter connected between the cal point and 0V. Note the voltages at 0°C and 100°C, the output voltages at intermediate temperatures will be exactly proportional. Although diodes do not have the same temperature coefficient of forward voltage, the voltage changes linearly with temperature. When calibrating an intermediate scale always start at the bottom end with water about 5°C hotter than the minimum value. Insert the probe and calculate from the calibration cycle the output voltage at the minimum value. When the voltmeter agrees with the calculated value, adjust the 0°C control for zero. Repeat for the maximum value and adjust the 100°C control for full scale. It is better to use the cooling cycle rather than the heating cycle because cooling takes place more smoothly and uniformly. ☐