used to avoid thermal problems. The junction voltage changes by −1.9 mV/°C, but a semitone change is equivalent to 1.5 mV, therefore a 1°C change could result in a 1.27 semitone change in pitch! Figure 9 shows two temperature effects in operation; there is a large shift and the slope of the line changes.

Figure 10 illustrates the equations that determine the diode operation. Two facts emerge from these equations. First, an 18 mV change in V_{BE} will double the current I_o and second, this parameter has a temperature coefficient of −0.33%/°C. Both the temperature problems can be resolved by using a circuit similar to that shown in Fig. 11. Transistor Q1 is run at constant current (12 uA) by the op-amp. Q2 is used as the exponentiator transistor. The emitter of Q2 is held at a voltage of about −0V6. Any voltage change at the base of Q2 will result in an exponential change in the collector current of Q2. Q1 and Q2 are in thermal contact and so any temperature change will affect both equally. Thus the −1.9 mV/°C factor is cancelled out by Q1 acting as a compensating thermometer for Q2. The slope change is removed by using a temperature sensitive resistance (Q81 — Tel Labs) which has an equal but opposite temperature coefficient to the diode junction. This resistor is often in thermal contact with the matched transistors. If this circuit is connected to a linear current controlled oscillator, a musical VCO is produced.

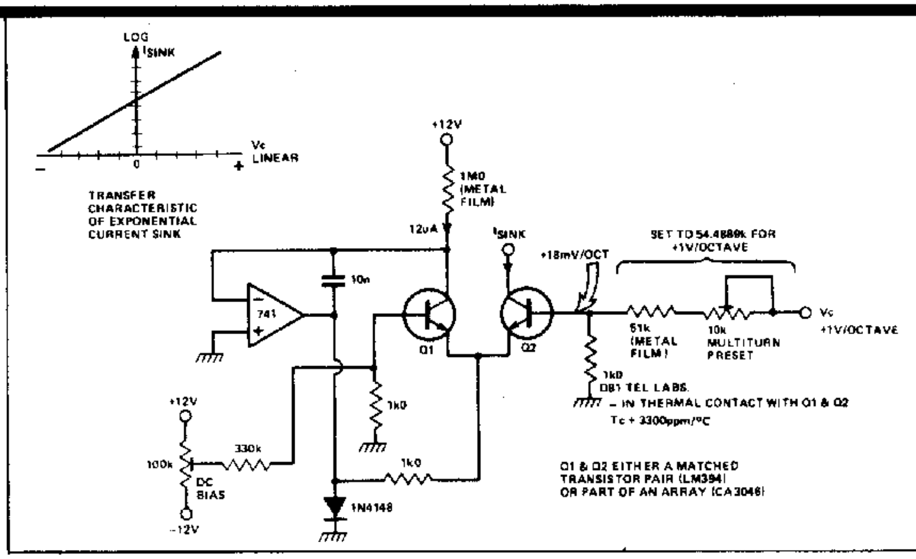


Fig. 11 An exponential current sink.

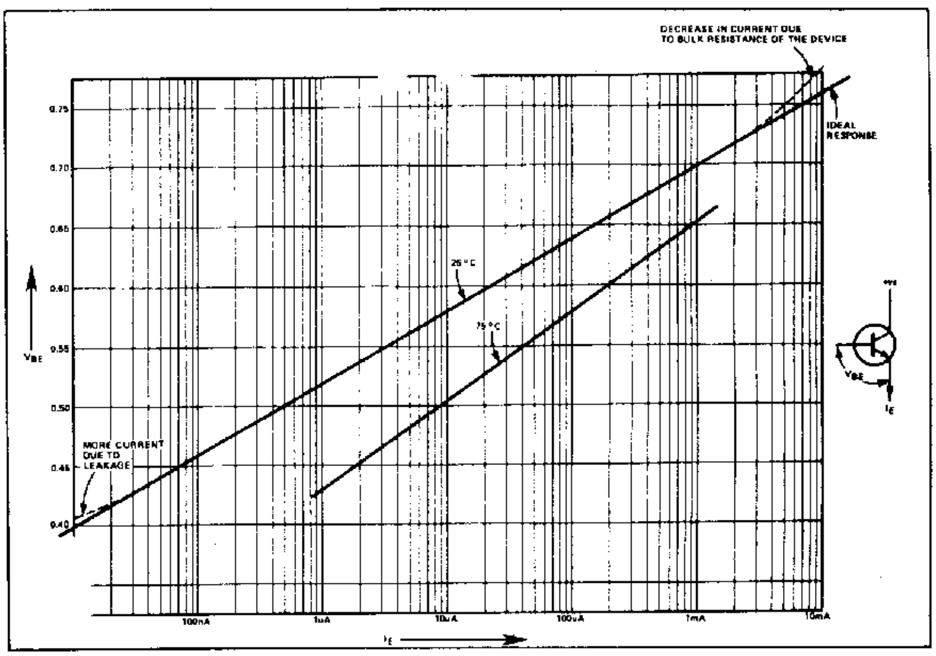
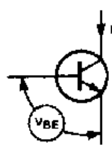


Fig. 9 Silicon diode transfer characteristics.

WHERE
Io IS THE EMITTER SATURATION CURRENT
K IS BOLTZMANNS CONSTANT
q IS THE CHARGE ON AN ELECTRON
T IS THE TEMPERATURE IN °K

HOWEVER, $\frac{KT}{q}$ IS 26mV AT 28.58 °C (301.73 °K IS ROOM TEMPERATURE).
THEREFORE, $I_c \simeq I_o\, e^{V_{BE}/26}$
WHERE V_{BE} IS MEASURED IN mV
REARRANGING THE EQUATION,

$$26.\ \ln\left(\frac{I_c}{I_o}\right) = V_{BE}$$



$$I_c = I_o\left(e^{(qV_{BE}/KT)} - 1\right)$$

$$\therefore I_c \simeq I_o\ e^{qV_{BE}/KT}$$

THEREFORE, AN OCTAVE CHANGE IN Ic IS CAUSED BY A 18.021827mV CHANGE IN V_{BE} (AT 28.58 °C). HOWEVER, IF THE TEMPERATURE WERE +1 °C HIGHER, THEN V_{BE} WOULD HAVE TO BE INCREASED IN SIZE TO A NEW VALUE OF

$$26 \times \left(\frac{302.73}{301.73}\right)$$

SO, FOR AN OCTAVE CHANGE IN Ic AT THE NEW TEMPERATURE, V_{BE} MUST CHANGE BY 18.08155mV, AN INCREASE OF 0.059723mV. THIS CAN BE EXPRESSED AS A PERCENTAGE CHANGE PER °C :–

$$\text{TEMPERATURE SENSITIVITY} = \frac{0.059723 \times 100}{18.021827} = 0.33139\%/°C$$

Fig. 10 Exponential transistor characteristics.

VCO Circuits

Figure 12 is the circuit for an exponential VCO using an exponential current source. The oscillator is a standard triangle-square wave device. IC2 is a current-controlled integrator; the slow rate at its output is equal to I_{ABC}/C. This voltage is buffered by IC3 which drives a Schmitt trigger IC4. The output of IC2 ramps up and down between the two hysteresis levels which are determined by the two clamping diodes connected to the output of IC4. Any stray capacitance on the output of IC4 will slow down the Schmitt trigger and this will make the VCO go flat at high frequencies. Also the propagation time delay around the oscillator will cause a flattening out to the response at high frequencies. These effects can be nulled out but they may not even affect things if the VCO frequency is kept relatively low.

A good VCO is shown in Fig. 13. It is a monolithic device with triangle, sawtooth and pulse outputs, and has a Sync input for slaving it to another

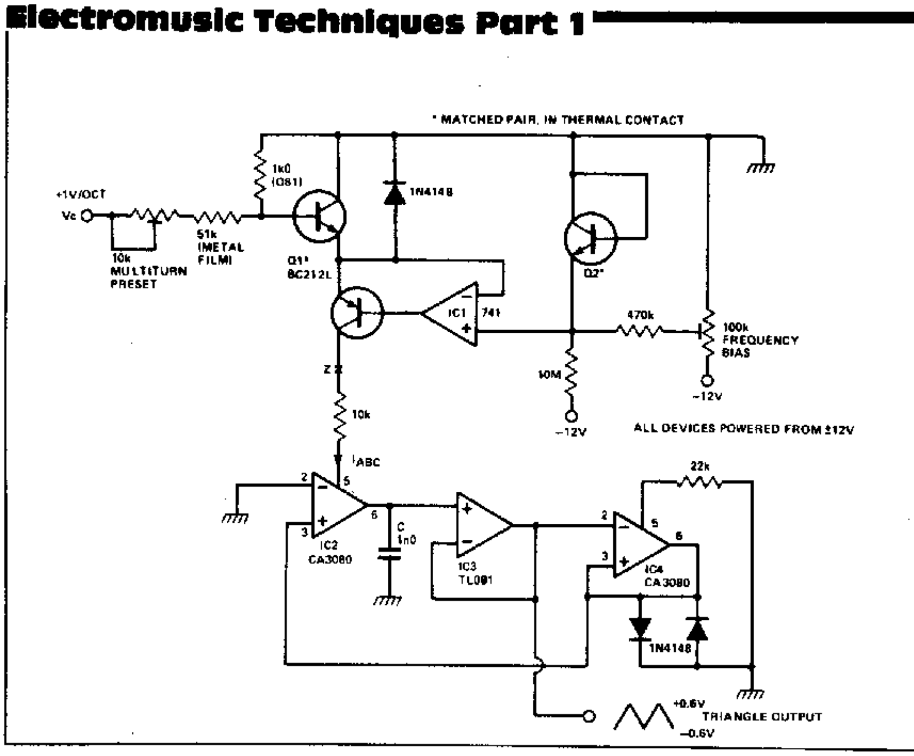


Fig. 12 An exponential VCO.

oscillator. Originally it appeared as the heart of the ETI Synthesiser 1 project, August 1982. (Back issues are available; see the contents page for ordering information.)

LFO Circuits

A couple of LFO units are shown in Fig. 14. All four output waveforms can be usefully employed to sweep VCOs and VCFs. Often the waveforms are mixed together to produce strange frequency modulations. When the sawtooth is fed into one side of a ring modulator and noise into the other, a beat track can be generated; it sounds a bit like a cymbal being hit.

Noise Generators

In 'the old days' noise sources were made by amplifying the noise current of a diode junction that was zenering. These were a bit unreliable, and always involved selecting the device. However, noise can be generated

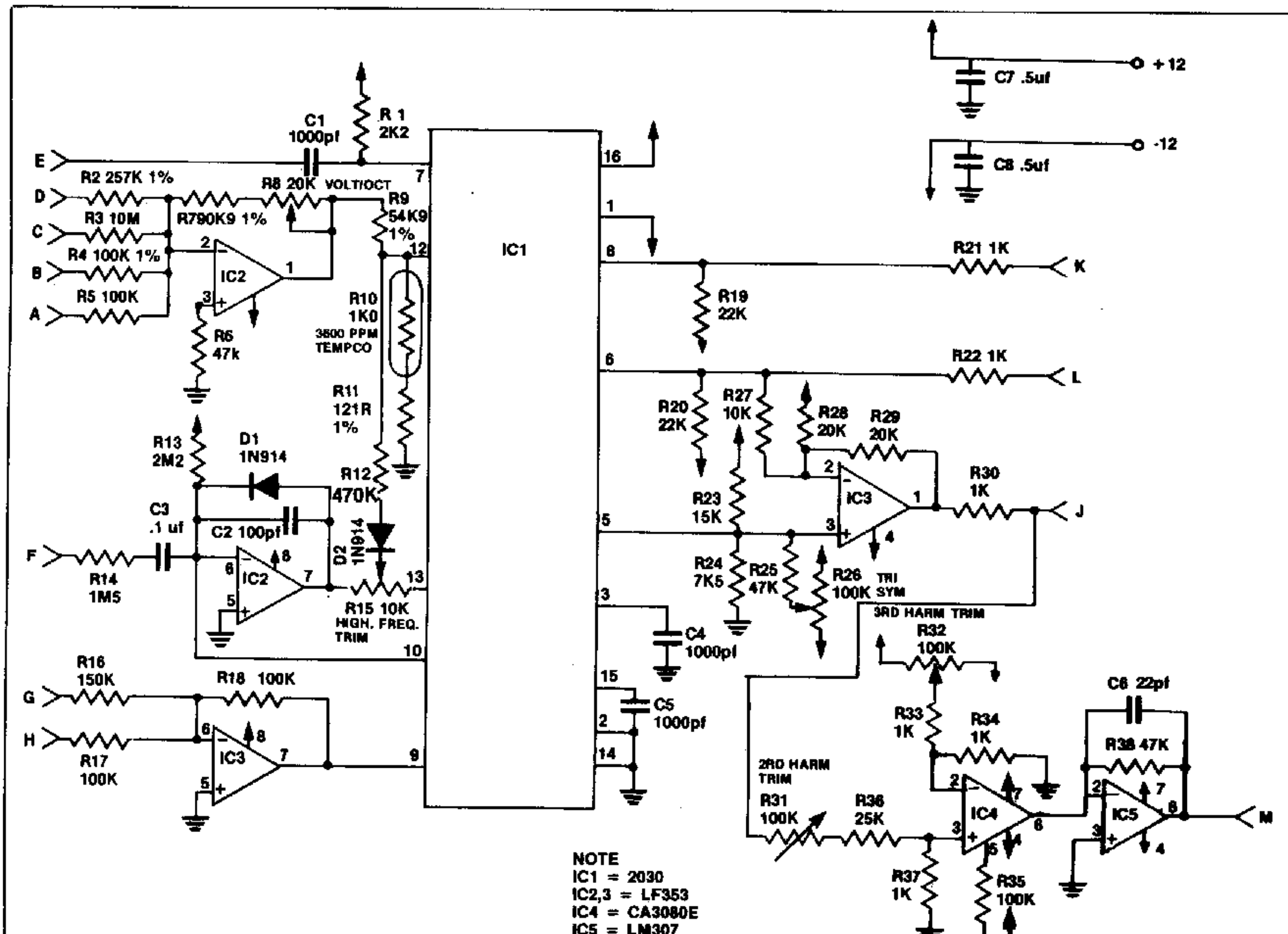


Fig. 13 A VCO using a monolithic device.