

# Logarithmic current electrometer using light emitting diodes

Y B Acharya† and A K Aggarwal‡

† Physical Research Laboratory, Ahmedabad 380009, India

‡ Rollwala Computer Centre, Gujarat University, Ahmedabad 380009, India

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**Abstract.** The limit of low current measurement using logarithmic current to voltage converter is improved by 6–7 orders of magnitude with the use of diodes of large band gap as compared with silicon diodes. Low cost commercially available light emitting diodes (LEDs) have been used for this purpose. A theoretical study and experimental measurement of device constant and reverse saturation currents of the whole class of commercially available LEDs has been carried out. A circuit has been developed which makes use of a new technique for temperature compensation and its performance is compared with the technique in common use. The performance of the amplifier is found to be stable in the temperature range 5–60 °C for both polarity of signals from  $10^{-12}$  to  $10^{-5}$  A.

## 1. Introduction

In general, transducers used for the measurement of various ionospheric parameters and nuclear instruments produce currents (unipolar or bipolar) having a large dynamic range. Electrometers for current measurements of large dynamic range are therefore needed for such applications. Electrometers are commercially available for some current ranges. However, these may not work for all environmental conditions under which the instrument has to work. Hence specific current measuring transimpedance amplifiers have to be designed for many applications. A bipolar log ratio amplifier, which in principle has a large dynamic range, has been designed using light emitting diodes. Since the diode characteristics are prone to change with ambient temperature, temperature compensation using a thermistor to improve the performance of the log amplifier has been used. A new ratio technique for temperature compensation is also described and its performance is compared with the thermistor technique normally used for such applications.

## 2. Theoretical background

A number of papers concerning low dc current measurements have been published (Barker 1979, Anso *et al* 1989). Gain switching amplifier and logarithmic amplifiers are two common methods for measuring currents or voltages having a large dynamic range. Each has its own advantages and disadvantages. Gain switched amplifiers are linear in nature and are well behaved over a wide temperature range, but use switches which contribute to leakage current and also introduce abrupt changes in the output signal which cause difficulty in data analysis. On the other hand, a logarithmic

amplifier compresses the signal and provides a large dynamic range. However, such amplifiers are very sensitive to temperature variations. Therefore, appropriate temperature compensation techniques have to be used with logarithmic amplifiers (El-Ibiary 1963, Izumi and Okano 1963) which find applications in many areas. Forward biased p–n junction diodes are often used as a log element. The lower limit of current measurement is decided by the reverse saturation current of the diode. The reverse saturation current  $I_0$  (McKelvey 1966 p 266) is given by the equation

$$I_0 = KT^3 \exp(-E_g/kT) \quad (1)$$

where  $K$  is a constant,  $T$  is the absolute temperature in K,  $E_g$  is the band gap of the material and  $k$  is Boltzmann's constant.

The exponential relation between  $I_0$  and  $E_g$  indicates that the reverse saturation current in diodes made of wide band gap material must be considerably lower than that of silicon. From the band gap difference between silicon and GaAs devices, the  $I_0$  of GaAs devices should be 6–7 orders of magnitude lower than that of silicon. Damljanovic and Arandjelovic (1981) have shown that  $I_0$  is of the order of  $10^{-20}$  A for some LEDs. This significant property of the material of LED makes it suitable as a nonlinear element of log amplifier for low current applications. The advantage of these devices is that they are commercially available at very low cost compared with low leakage diodes or transistors. Table 1 shows some interesting properties of several types of LEDs and of one silicon device for comparison in terms of colour, spectral dependence and band gap (Neuse *et al* 1972, Bhargava 1975).

The  $I$ – $V$  characteristics of a p–n junction are given by the classical diode equation in which forward current  $I$  is

**Table 1.** Material and spectral properties of LEDs.

Sr. no.	Material	Colour	Peak wavelength (nm)	Band gap (approx.) (eV)
(i)	(a) GaAs <sub>0.6</sub> P <sub>0.4</sub>	Red	650	1.91
	(b) GaP:Zn,O	Red	691	1.76
(ii)	(a) InGa AlP	Orange	620	1.86–2.03
	(b) GaAs <sub>0.35</sub> P <sub>0.65</sub> : N	Orange	632	2.01
(iii)	(a) Ga P:NN	Yellow	590	2.10
	(b) SiC	Yellow	590	1.970
(iv)	(a) Ga As <sub>0</sub> P <sub>100</sub> : N	Green	560	2.23
	(b) Ga P:N	Green	565	2.18
(v)	(a) Ga N	Blue	440	2.8–3.2
	(b) SiC	Blue	470	2.8–3.2
(vi)	(a) Ga As:Zn	Infrared	910	1.43
	(b) Ga As:Si	Infrared	950	1.40
(vii)	Silicon	Infrared	1140	1.2

**Table 2.** Estimated device constant ( $n$ ) and reverse saturation current ( $I_0$ ) from  $I$ – $V$  characteristics obtained experimentally.

LED	$n$	$I_0$ (approx.) (A)
Red 1	1.918	$10^{-17}$
Red 2	2.35	$10^{-16}$
Orange	1.854	$10^{-19}$
Yellow	1.981	$10^{-19}$
Green	1.866	$10^{-21}$
Blue	2.02	$10^{-26}$
IR (880)	2.00	$10^{-13}$
IR (950)	2.35	$10^{-12}$
Silicon diode FJT 1000	1.03	$10^{-16}$

given by

$$I = I_0[\exp(qV/nkT) - 1] \quad (2)$$

where  $q$  is the electronic charge,  $n$  is an empirical factor (device constant) between 1 and 3, and  $V$  is the junction voltage.

The current voltage characteristics deviate at low current due to  $I_0$  term on the RHS of equation (2). The equation can be rewritten as

$$I + I_0 = I_0 \exp(qV/nkT). \quad (3)$$

If a current equal to  $I_0$  could be drained out from the amplifier input away from log diode, the deviation can be corrected to some extent. This is possible by connecting a diode of opposite polarity across the log diode. This configuration not only helps in correcting the deviation, but also enables the measurement of both polarities of the signal. One of the two diodes is always reverse biased due to voltage developing across the forward biased diode. Higher output can be obtained by having a string of diodes in series which also improves the signal-to-noise ratio (Sheingold 1974).

The measured  $I$ – $V$  characteristics of a typical diode exhibit noticeable deviations from the ideal theory of diffusion for two reasons. One is the effect of ohmic resistance of diodes which becomes appreciable at high currents ( $> 10^{-3}$  A), and the other is the recombination

generation current which becomes dominant at lower currents (Sah *et al* 1957).

### 2.1. Temperature dependence of the idealized diode equation

The diode equation contains two terms which are dependent on temperature. One is explicit in the exponent ( $qV/nkT$ ) and the other results from the implicit temperature dependence of the reverse saturation current  $I_0$ . The temperature dependence of the reverse saturation current  $I_0$  is given by equation (1). However at small forward bias, recombination dominates rather than diffusion current (Grove 1967) and considering the dominance of exponential term (Gray *et al* 1964),  $I_0$  can be approximated as

$$I_0 = K \exp(-E_g/nkT) \quad (4)$$

where  $K$  is a constant which is nearly independent of temperature. Substituting the value of  $I_0$  in the diode equation (2) and differentiating for  $m$  diodes in series, we obtain

$$\left. \frac{\partial V_m}{\partial T} \right|_I = \frac{1}{T} [V_m - mE_g/q] \quad (5)$$

where  $V_m$  is the sum of voltages of all the  $m$  diodes. This coefficient usually lies in the range  $-1$  to  $-3$  mV K<sup>-1</sup> for one silicon diode and it increases with the number of diodes.

## 3. Experiment

### 3.1. $I$ – $V$ characteristics of LEDs

As predicted by equation (1), which states that the reverse saturation current is exponentially related to the band gap of the material, the reverse current should be substantially lower for devices having higher band gap.  $I$ – $V$  measurements have been made for blue, green, yellow, orange, red and IR LEDs by connecting a diode (LED) as a feedback element of the operational amplifier. LEDs were painted dull black and sealed to avoid any photo electric effect. The output voltage is measured by feeding an input current from a current source (Model 261 Keithley). The

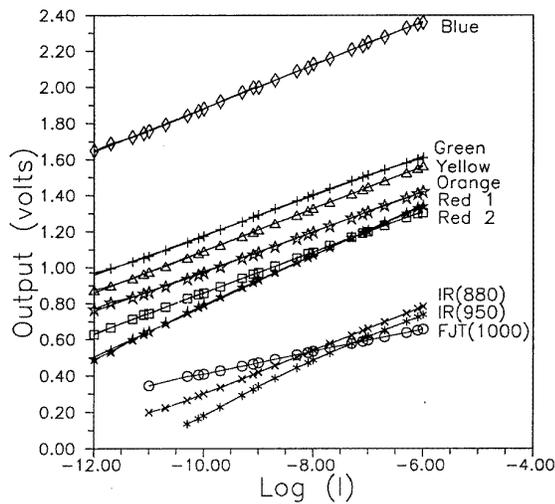


Figure 1.  $I$ - $V$  characteristics of different LEDs.

output voltage is plotted (figure 1) against  $\log I$  and the device constant  $n$  is derived from the slope  $nkT/q$  and  $I_0$  is derived from the intercept of the fitted line. Table 2 shows derived values of  $n$  and  $I_0$  for various LEDs.

It is clear from table 2 that the value of  $n$  is experimentally found to lie around 2 for all LEDs in the current range  $10^{-12}$ - $10^{-6}$  A and is around 1 for a silicon diode.  $I_0$  also reduces as the band gap increases from the red LED to the blue LED.  $I_0$  of blue LED is the lowest because it has the highest energy gap. A silicon low leakage planar diode is also used in order to show the difference between devices made of silicon and LEDs. It has also been observed that LEDs of the same colour also differ in terms of  $n$  and  $I_0$ . This could be due to difference of the device material as shown in table 1. The  $I_0$  of the silicon diode as estimated by fitting the line is found to be much lower than the value of  $10^{-13}$  A as reported by the manufacturer. This could be due to nonlinearities in the  $I$ - $V$  characteristics which have been reported by Sah *et al* (1957). It may be noted that  $I_0$  of general silicon diodes is of the order of nano amperes and the measured  $I_0$  of GaAs devices is 5-6 orders lower than the silicon diode (Damljanovic and Arandjelovic 1981).

### 3.2. Effect of temperature on the $I$ - $V$ characteristics

The temperature coefficient of voltage for one diode is approximately  $-1$  to  $-3$  mV  $K^{-1}$  for silicon diodes and will increase as a number of diodes are stacked together. The  $I$ - $V$  characteristics of a log amplifier having 5 log elements and 5 other diodes connected in anti-parallel configuration is measured for three temperatures (room temperature 30, 5 and 60 °C). This temperature range in general satisfies the requirement of most of the users. Expected outputs are calculated using equation (5) at two other temperatures, 5 and 60 °C, by taking the reference at room temperature (30 °C). It is seen that the percentage change in output (figure 2) between expected to measured value at 5 and 60 °C is within 4% for 5 °C and within 10% for 60 °C. The

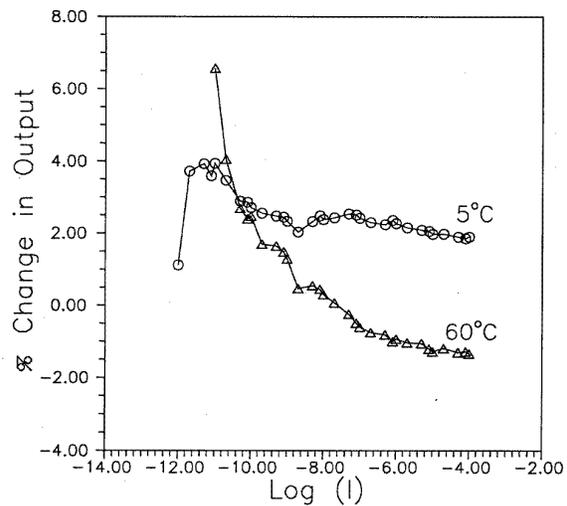


Figure 2. Temperature dependence of  $I$ - $V$  characteristics. Percentage change in output (theoretical to measured) at two different temperatures 5 and 60 °C with respect to output at room temperature.

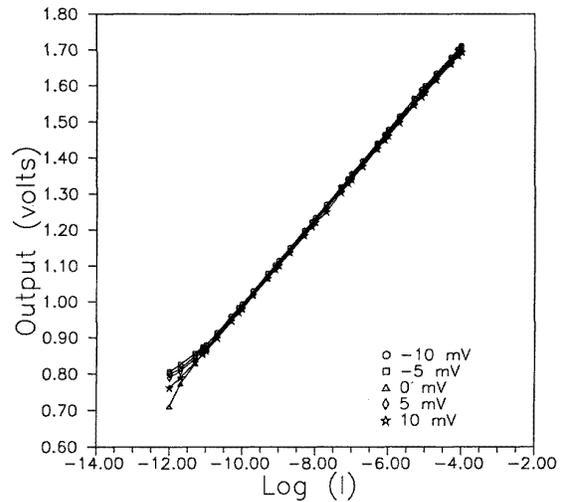


Figure 3. Effect of offset adjustment on the linearity at five different values of offset voltages  $-10$ ,  $-5$ ,  $0$ ,  $5$  and  $10$  mV.

error may be due to variations from diode to diode and other approximations involved.

### 3.3. Effect of offset adjustment on the linearity at low level

The zero setting of the amplifier is required for adjusting the initial potentials so that good linearity is attained at low input. Figure 3 shows the effect of the initial diode current on the linearity of the characteristics at the lower end. Offset voltage is changed from  $-10$  mV to  $+10$  mV in steps of 5 mV and the  $I$ - $V$  characteristics are plotted. Offset voltage is measured at the voltage output by connecting a short across LED and removing the input current. Figure 3 shows that the linearity at lower end of the current is dependent on the offset voltage and hence care must be

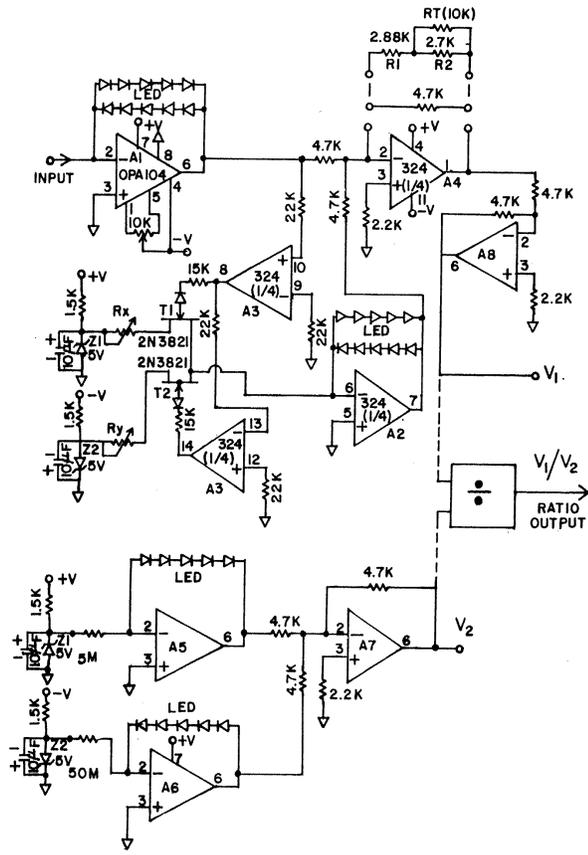


Figure 4. Circuit diagram of a bipolar log ratio amplifier.

taken for proper adjustment of offset to ensure linearity at the lower end.

### 3.4. Temperature compensated bipolar log ratio amplifier

The  $I-V$  characteristics of a diode are dependent on temperature and a temperature compensation technique is needed to obtain reliable data. A new technique for temperature compensation has been used by Ericson *et al* (1992) which uses a quad matched transistor array. A circuit (figure 4) using LEDs has been developed on similar lines. Part of the circuit is similar to the circuit using thermistor technique and is explained in detail by Acharya and Tikekar (1993). The circuit can basically be divided into two parts. One is the bipolar log ratio amplifier with a provision for automatic switching of polarity of the reference current, and a summing amplifier (A4) whose gain is controlled thermally such that it cancels the effect of the  $kT$  term and the other is another log ratio amplifier for two known currents (0.1 and 1  $\mu A$ ). In one configuration the  $R_1$ ,  $R_2$ ,  $R_T$  combination is connected as a feedback resistance of the operational amplifier (A4) shown in figure 4. The values of  $R_1$ ,  $R_2$ ,  $R_T$  are found from the measured  $I-V$  characteristics of the uncompensated log ratio amplifier. This is referred to as the ‘compensated’ technique using a thermistor. In the case of the new ‘ratio’ technique, the feedback containing  $R_1$ ,  $R_2$  and  $R_T$

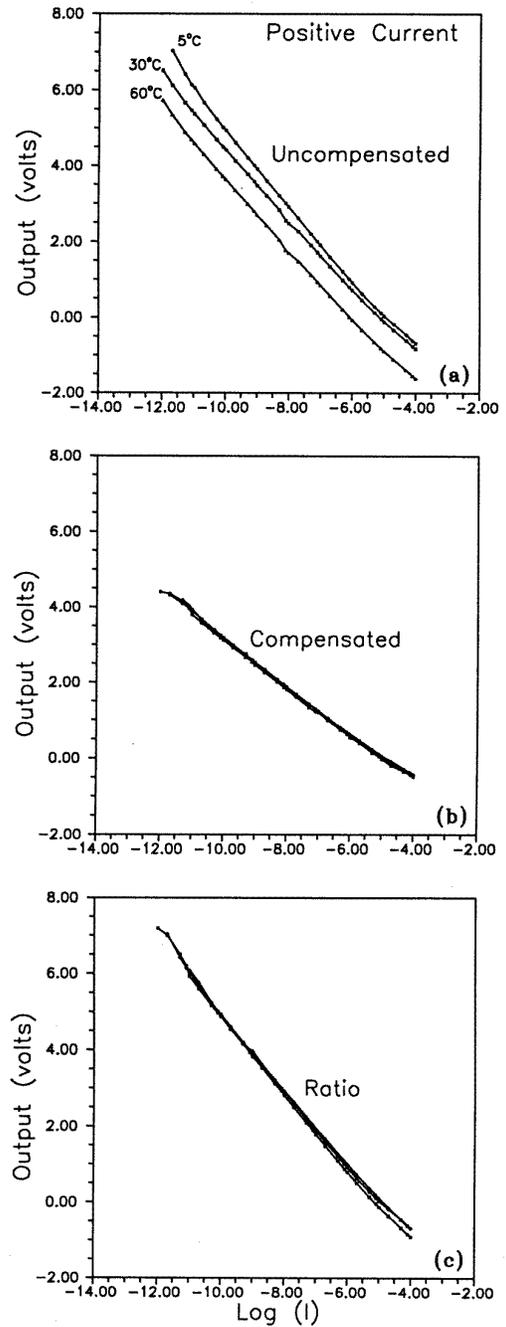
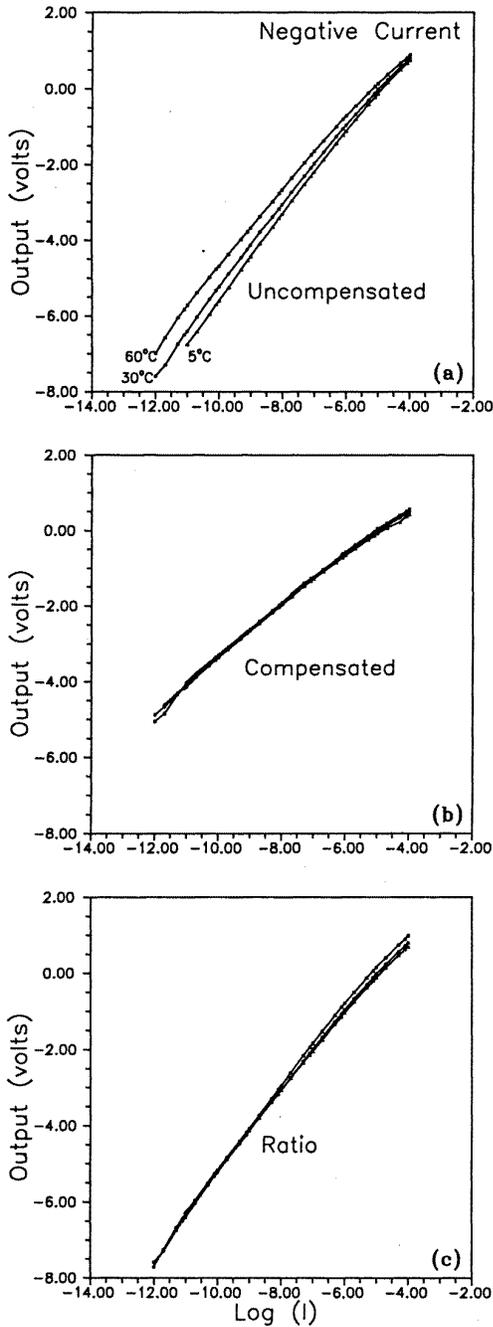


Figure 5.  $I-V$  characteristics of a bipolar log ratio amplifier for (a) uncompensated, (b) compensated using thermistor technique and (c) ratio (compensated by taking ratio of two outputs) at three different temperatures (5, 30 and 60 °C) for positive currents. Different symbols have been used for three temperatures in (b) and (c) also, but are not visible in the graphs.

is replaced by a 4.7 k $\Omega$  resistance. A log ratio amplifier consisting of amplifiers A5, A6 and A7 for two known current values having a ratio of 10 is also used.

Output  $V_1$  which is the ratio of logarithmic of input current by reference current is expressed as

$$V_1 = -\frac{5nkT}{q} \ln(I_{in}/I_{ref}) \quad (6)$$

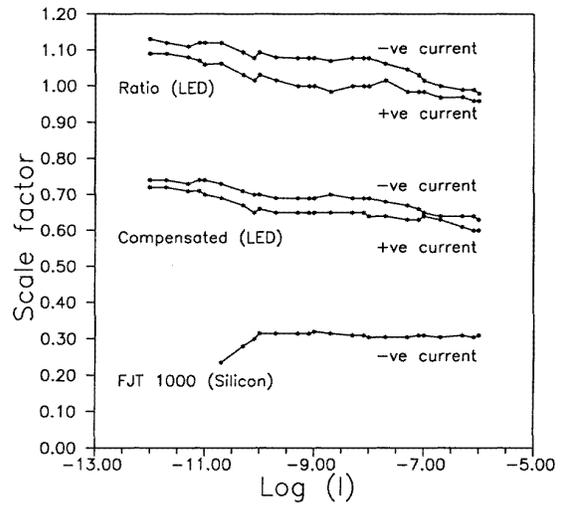


**Figure 6.**  $I$ - $V$  characteristics of a bipolar log ratio amplifier for (a) uncompensated, (b) compensated using thermistor technique and (c) ratio (compensated by taking ratio of outputs) at three different temperatures (5, 30 and 60 °C) for negative currents. Different symbols have been used for three temperatures in (b) and (c) also, but are not visible in the graphs.

where  $I_{in}$  is the input current (A1),  $I_{ref}$  is the reference current fed to A2 and factor 5 is due to 5 diodes used as a log element. Output  $V_2$  can be written as

$$V_2 = \frac{5nkT}{q} \ln(I_1/I_2) = \frac{5nkT}{q} \ln(10) \quad (7)$$

where  $I_1$  and  $I_2$  are reference currents fed to the log



**Figure 7.** Scale factor- $I$  plot of a bipolar log ratio amplifier using ratio and compensated technique for both polarities of the input current and also for log amplifier using silicon diode.

amplifiers A5 and A6 respectively. The values of  $I_1$  and  $I_2$  are 1  $\mu$ A and 0.1  $\mu$ A respectively. Dividing  $V_1$  by  $V_2$ , the term  $T$  is cancelled out and a relationship is established which is independent of temperature. This is referred to as the ratio technique. Division can be implemented by software or a hardwired divider:

$$\frac{V_1}{V_2} = -\log(I_{in}/I_{ref}). \quad (8)$$

It can be seen from the above equation that the ratio output is independent of the number of diodes used. Moreover the scale factor (volts/decade) is unity if the divider gain is 1. The scale factor is directly proportional to the gain of the divider unlike in the thermistor technique where the scale factor is approximately 5 ( $2.3 nkT/q$ ) which is approximately 0.7 V at room temperature.  $I_{ref}$  is chosen to be 10  $\mu$ A and  $V_1/V_2$  division is performed by software.

Figure 5 shows the combined plot of the  $I$ - $V$  characteristics at three different temperatures (5, 30 and 60 °C) of a bipolar log ratio amplifier for uncompensated, compensated using the thermistor technique and compensated using the ratio technique for positive currents. Similarly figures 6 shows the combined plot for negative currents.

Figure 7 shows the plot of the scale factor versus the log of current for both the ratio technique as well as the compensated technique for LEDs. The experimental plot for the circuit with five silicon diodes in series is also shown in the same figure. Since different diodes are used for different polarities of the signal, change in scale factor is observed.

The output of the ratio technique is found to deviate for low temperatures (5 °C) at higher currents for both polarities of the signal ( $> 10^{-5}$  A). The reason could be the mismatch of diodes. Moreover at higher currents the  $I$ - $V$  characteristics also deviates due to ohmic resistance which becomes appreciable (Sah *et al* 1957). For this study, the

diodes have been chosen from at random. Although output of the ratio technique does not depend upon the number of diodes used, the signal-to-noise ratio is definitely better if a greater number of diodes is used. Accordingly an attempt has been made using 30 diodes having nearly similar  $I$ - $V$  characteristics for the complete log ratio amplifier. The performance can be improved further by the use of matched LEDs. In this study of the ratio technique, the behaviour of actual log element at different temperatures is not addressed, unlike in the thermistor technique. The behaviour of diodes at different temperatures should be the same so as to cancel out the effect of the temperature term. It would be therefore desirable to use matched diodes, or to choose the diodes carefully, not only in terms of  $I$ - $V$  characteristics at room temperature but also at different temperatures, so as to have good compensation. The study of the ratio method establishes the viability of the method, which is easier to use since in the old thermistor method,  $R_1$ ,  $R_2$  and  $R_T$  are decided on the basis of performance of uncompensated amplifier at different temperatures over a specific current range. The ratio method circuit remains unchanged over a wide temperature and current range. In addition, the performance is only marginally inferior when compared with the thermistor method, even when diodes have been selected from at random. If a matched set of 30 LEDs is used, the performance may also turn out to be better and there is also the advantage that they are easier to use.

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