The differential pair is the best, and will remain the best, since an improved constant current source for the μ-follower could be adapted to become an improved constant current sink for the differential pair.

Knowing the PSRR enables us to design power supplies correctly because it gives an indication of the allowable hum on the HT supply.

As an example, the second stage of the balanced pre-amplifier (see Chapter 7) needs the 100 Hz power supply hum to be 100 dB quieter than the maximum expected audio signal. At this point, the signal has not received RIAA 3180 μs/318 μs correction, so the level at 100 Hz is 13 dB lower than at 1 kHz. However, peak levels from LP are +12 dB compared to the 5 cms^{-1} line-up level, so the maximum audio signal at 100 Hz is 1 dB lower than the 1 kHz calculated signal level at the anode ($2.2\,\text{V}_{\text{RMS}}$) = 2 V. We want 100 dB signal/hum, but because 62 dB of this will be provided by PSRR, we only need the hum on the power supply to be 38 dB quieter than 2 V, so we could tolerate 25 mV of hum on the power supply – which is easily achievable.

Semiconductor constant current sinks

The differential pair demonstrated the need for constant current sinks, but the pentode constant current sink is profligate with HT voltage (although it is a very good sink), and a differential pair with grids at ground potential would require a subsidiary negative supply for the sink of −100 V. This is often undesirable, so a solution is needed.

Unlike the original valve designers, we are in the fortunate position of being able to use transistors, and even op-amps, if we consider them to be necessary. This is a perfect example of where a transistor or two can be very helpful.

The simplest form of a transistor constant current sink is very similar to our triode version. The red LED sets a constant potential of ≈1.7 V on the base of the transistor. V_{be} is ≈0.7 V, so the emitter resistor has 1 V held across it. If we need to sink 5 mA, we would use a 200 Ω sense resistor. The AC resistance looking into the collector is:

$$r_{\text{out}} = R_{\text{E}} \cdot h_{\text{fe}} + 1/h_{\text{oe}}$$

In this instance, a BC549 ($h_{\text{fe}} \approx 400$, $1/h_{\text{oe}} \approx 12\,\text{k}\Omega$) gives $r_{\text{out}} \approx 92\,\text{k}\Omega$. Note that an expensive 2 W resistor is required to bias the LED. See Fig. 2.48a.

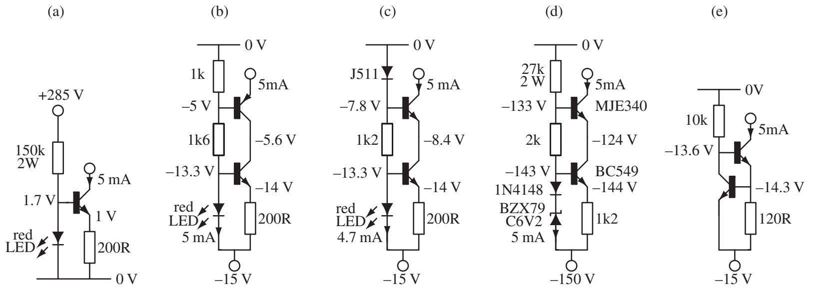

Fig. 2.48 *Semiconductor constant current sources*

The simple circuit can easily be improved upon, and since silicon is cheap, it seems worthwhile to do so. There are two problems to be addressed. First, the transistor needs $V_{CE} > 0.5\,V$ for it to operate as a constant current sink, which is uncomfortably close to typical bias voltages for high μ valves such as the ECC83. Second, 92 kΩ output resistance is not especially high, and we can do much better.

A transistor cascode is broadly similar to a pentode, but a practical circuit requires a negative supply. However, this may not be a problem in a power amplifier, because there is often a negative bias supply for the output valves that we can use. (Even though the bias winding normally supplies <1 mA, wire rated for 1 mA is very fragile, so transformer manufacturers typically use thicker wire, allowing us to draw 10 mA from this winding, and the increase in total transformer VA loading is usually negligible.)

The cascode constant current sink has much higher output resistance than a single transistor constant current sink:

$$r_{\mathrm{out}} = R_{\mathrm{E}} \cdot h_{\mathrm{fe(upper)}} \cdot h_{\mathrm{fe(lower)}} + 1/h_{\mathrm{oe(upper)}}$$

The AC output resistance of the initial design has been multiplied by the h_{fe} of the second transistor which improves it from ≈92 kΩ to ≈32 MΩ, so the value of $1/h_{oe}$ is now negligible. However, a more practical advantage is that the negative supply allows the output port to be taken down to 0 V without linearity problems. High frequency stability is excellent. See Fig. 2.48b.

As shown, the cascode current source is relatively sensitive to hum and noise on the negative supply because of current changes through the voltage reference. This sensitivity can be greatly reduced by modifying the circuit to include a current regulator diode in the chain that feeds the voltage reference. See Fig. 2.48c.

The cascode constant current sink can be adapted to withstand a larger voltage simply by substituting the transistor that feeds the load for a higher voltage type. This slightly lowers r_{out}, because the higher voltage transistor inevitably has a lower h_{fe}, but because we now have volts to spare, most of this loss can be recovered by setting a higher reference voltage, allowing a higher value of R_E. Unfortunately, if a power transistor is required, its higher output capacitance degrades performance at high frequencies. The 1N4148 diode compensates for variation of the lower transistor's V_{be} due to temperature, but requires all component values to be recalculated. See Fig. 2.48d.

The 'ring of two' circuit works by holding 0.7 V across the 120 Ω sense resistor. If that voltage rises, due to increased current through the resistor, T_1 turns on harder, which causes the base voltage of T_2 to fall. T_2 begins to turn off and so the current through the 120 Ω resistor, and therefore the sink current, is held constant. Because this circuit uses feedback applied over two transistors, there is a possibility of oscillation at high frequencies due to stray capacitances. See Fig. 2.48e.

Using transistors as active loads for valves

All the previous sink circuits can be mirrored about 0 V and PNP transistors substituted for NPN. If the circuit is then connected to the HT supply, they become constant current sources allowing a triode to achieve $A_v = \mu$. More significantly, they permit a valve to achieve low distortion from a low HT voltage.

As an example, in common with all high μ valves, the ECC83 needs considerable V_a before it can be biased out of grid current, 150 V is typical. As a general rule of thumb, $R_L > 2r_a$, and as $r_a \approx 75\,k\Omega$ for the ECC83, we might use $R_L = 150\,k\Omega$. If $I_a = 0.7\,mA$, we would drop 105 V across R_L, so we would need 255 V of HT. But we might only require the stage to produce an output swing of $5\,V_{pk-pk}$, so most of the HT is wasted. If we replace the 150 kΩ resistor with a constant current source the valve sees a much higher value of R_L, and we can set the HT voltage independently to accommodate the maximum required output swing. See Fig. 2.49.

In Fig. 2.49, the concept of operating a high μ valve from a low HT was taken to the extreme because the author needed a high gain differential pair stage (ECC83: $\mu = 100$), but only had 150 V of positive HT available. Note that high voltage transistors are required to withstand either anode swinging towards 0 V.

Although Zener diodes are normally bypassed to reduce noise, the noise generated by both Zener diodes is common mode, and is therefore rejected by