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A HIGH IMPEDANCE INPUT CIRCUIT USING GERMANIUM TRANSISTORS

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Abstract

A bootstrapped-emitter-follower circuit that achieves an input impedance greater than 10^7 ohms with germanium transistors is described. The circuit is analyzed and compared with a single emitter follower and a super-alpha-connected emitter follower for input impedance characteristics.

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Introduction

Several important applications exist for low-level, high-input-impedance amplifiers, particularly in the field of nuclear instrumentation. The development of an alternating-current ionization chamber, for example, required a 500-cycle amplifier with a noise level below 10^{-17} watts and an input impedance of at least a few megohms. In this particular application the smaller size, weight, and power requirements, and negligible microphonics of a transistorized circuit seemed to indicate the use of transistors.

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Input Circuit

Of the three transistor configurations that can be used to provide a power gain in excess of unity, the common-collector (emitter follower) connection gives the highest input impedance for any given load. This circuit, shown in Figure 1, has an input resistance:

$$R_i = \frac{h_i + \Delta^h R_L}{1 + h_o R_L} \quad (1)$$

where the h's are the common-collector hybrid parameters, and $\Delta^h = h_i h_o - h_r h_f$. In the case of the 2N369, a typical good germanium transistor,

$$\begin{aligned} h_i &= 1670 \text{ ohms} \\ h_o &= 28 \times 10^{-6} \text{ mho} \\ h_r &= 1 - 3.33 \times 10^{-6} \\ h_f &= -56 \end{aligned}$$

and the maximum value of input impedance obtainable, even with very large load resistance, is about 2 megohms. Furthermore, since a bias resistor of about the same order of magnitude appears essentially in shunt with this impedance, it is not surprising that transistor amplifiers with input impedances greater than 1 megohm are uncommon.

Although a single transistor stage is thus limited in its input impedance, it is possible to arrange two or more transistors into a composite device, the characteristics of which are superior to those of the individual components. One such circuit, called a super-alpha connection, is shown in Figure 2.

Analysis of this configuration shows that the super-alpha-connected pair can be represented as a single composite transistor with greatly improved characteristics. Such a connection using two of the 2N369 germanium transistors described would have the following common-collector parameters:

$$\begin{aligned} h_i &= 97000 \text{ ohms} \\ h_f &= -3250 \\ h_r &= 1 \\ h_o &= 1.62 \times 10^{-3} \text{ mho} \end{aligned}$$

These values, when inserted in equation(1), show that although the upper limit of input impedance is still about 2 megohms, it is not as strong a function of load resistance as in the case of the single emitter follower. The input impedance for the super-alpha connection exceeds 100,000 ohms even for very small load resistances. Figure 3 shows this result graphically and compares it with the input impedance of a single emitter follower. It must be remembered, of course, that these impedances are in practice shunted by a base-to-collector bias resistor that reduces the actual impedances to still lower values.

Fig. 1—Common-collector connection

Fig. 2—A super-alpha connection

Fig. 3 - Comparison of super-alpha connection and single emitter follower

A qualitative examination of the emitter follower of Figure 1 indicates that the input impedance can be increased if both the emitter signal current and the signal current flowing through the bias resistor can be reduced. Since the emitter voltage follows the base voltage closely, the common terminal (collector) must also be forced to follow the variations in base voltage. Circuits to achieve this result have been developed and are known as bootstrapped emitter followers, an example of which is shown in Figure 4.

Other arrangements are possible, including the use of more than two transistors in order to supply more power to the bootstrap voltage. Input impedances as high as 1000 megohms have been obtained using three silicon transistors in a circuit employing bootstrapped operation of an emitter follower. Since the requirements were more modest, two 2N369 germanium transistors were used in the circuit of Figure 4 with:

$$\begin{aligned} R_1 &= 47 \text{ K} \\ R_2 &= 14 \text{ K} \\ R_3 &= 5 \text{ meg} \end{aligned}$$

Fig. 4 — Bootstrapped-emitter-follower circuit

Circuit Analysis

The common-collector-equivalent circuit of Figure 5 can be used to build up the composite equivalent circuit of Figure 6 that represents the electrical characteristics of the bootstrapped-emitter-follower circuit of Figure 4 in the low and middle frequencies.

Summing the currents at the output terminal node, we obtain:

$$0 = V_o \left(\frac{1}{R_L} + \frac{1}{R_2} + h_o \right) + h_f i_{i2} - \left[v_{01} \left(\frac{1}{R_1} + h_o \right) + h_f i_i \right] + (V_o - V_i) \frac{1}{R_3} + (V_o + h_r v_{01} - V_i) \frac{1}{h_i} \quad (2)$$

and since

$$i_{i2} = - \left[v_{01} \left(\frac{1}{R_1} + h_o \right) + h_f i_i \right], \quad (3)$$

equation (2) can be rewritten:

$$V_o \left(\frac{1}{R_L} + \frac{1}{R_2} + h_o + \frac{1}{R_3} + \frac{1}{h_i} \right) - V_i \left(\frac{1}{R_3} + \frac{1}{h_i} \right) + v_{01} \left(\frac{h_o}{h_i} - \frac{1}{R_1} - h_o - \frac{h_f}{R_1} - h_f h_o \right) - i_i (h_f^2 - h_f) = 0 \quad (4)$$

Summing currents at the input terminal node results in:

$$i_i = I_i + (V_o - V_i) \frac{1}{R_3}, \quad (5)$$

so that

$$V_o \left[\frac{1}{R_L} + \frac{1}{R_2} + h_o + \frac{1}{R_3} + \frac{1}{h_i} - \frac{1}{R_3} (h_f^2 + h_f) \right] + V_i \left[\frac{1}{R_3} (h_f^2 + h_f) - \frac{1}{R_3} - \frac{1}{h_i} \right] + v_{01} \left[\frac{h_o}{h_i} - \frac{1}{R_1} - h_o - \frac{h_f}{R_1} - h_f h_o \right] - I_i (h_f^2 + h_f) = 0 \quad (6)$$

From the loop containing the current generator $h_f h_{i2}$ and the voltage generator $h_r V_o$,

$$V_o + v_{01} = h_r V_o + i_{i2} \frac{1}{h_i} \quad (7)$$

can be obtained, which, combined with equations (3) and (5), yields:

Fig. 5 – Common-collector equivalent circuit

Fig. 6 – Composite circuit that represents the electrical characteristics of the bootstrapped-emitter-follower circuit

$$v_{01} = \frac{-V_o(h_i + h_i h_r + \frac{h_f}{R_3}) - V_i \frac{h_f}{R_3} - I_i h_f}{h_i + \frac{1}{R_1} + h_o} \quad (8)$$

Substituting equation (8) for v_{01} in equation (6), and letting:

$$A = \frac{1}{R_L} + \frac{1}{R_2} + h_o + \frac{1}{R_3} + \frac{1}{h_i} - \frac{D}{R_3} \quad (9)$$

$$B = \frac{D}{R_3} - \frac{1}{R_3} - \frac{1}{h_i} \quad (10)$$

$$C = \frac{h_o}{h_i} - \frac{1}{R_1} - h_o - \frac{h_f}{R_1} - h_f h_o \quad (11)$$

$$D = h_f(h_f + 1) \quad (12)$$

we find that:

$$0 = V_o \left[A - \frac{(h_i - h_r h_i + \frac{h_f}{R_3})}{(h_i + \frac{1}{R_1} + h_o)} C \right] + V_i \left[B - \frac{h_f C}{R_3(h_i + \frac{1}{R_1} + h_o)} \right] - I_i \left[D + \frac{h_f C}{h_i + \frac{1}{R_1} + h_o} \right] \quad (13)$$

A summation of voltages about the loop containing the input voltage and the two voltage generators yields:

$$V_i = i_1 h_i + h_r v_{01} - v_{01} + i_2 2h_i + h_r V_o \quad (14)$$

which, by application of equations (3), (5), and (8) and the following definitions:

$$E = h_r - 1 - \frac{h_i}{R_1} - h_o h_i \quad (15)$$

$$F = h_i - h_f h_i \quad (16)$$

$$G = h_i - h_i h_r + \frac{h_f}{R_3} \quad (17)$$

$$H = h_i + \frac{1}{R_1} + h_o \quad (18)$$

becomes:

$$V_o \left[\frac{F}{R_3} + h_r - \frac{GE}{H} \right] - V_i \left(1 + \frac{F}{R_3} + \frac{h_f E}{R_3 H} \right) + I_i \left(F - \frac{h_f E}{H} \right) = 0 \quad (19)$$

Application of equations (15), (16), (17), and (18) to equation (13) yields:

$$V_o \left(A - \frac{GC}{H} \right) + V_i \left(B - \frac{h_f C}{R_3 H} \right) - I_i \left(D + \frac{h_f C}{H} \right) = 0 \quad (20)$$

Fig. 7 - Input resistance versus load - bootstrapped emitter follower

It is now possible to eliminate V_O from equations (19) and (20) to obtain:

$$0 = I_i \left[\frac{(D + \frac{h_f C}{H})}{(A - \frac{GC}{H})} (\frac{F}{R_3} + h_r - \frac{GE}{H}) + (F - \frac{h_f E}{H}) \right] - V_i \left[\frac{(B - \frac{h_f C}{R_3 H})}{(A - \frac{GC}{H})} (\frac{F}{R_3} + h_r - \frac{GE}{H}) + (1 + \frac{F}{R_3} + \frac{h_f E}{H R_3}) \right] \quad (21)$$

from which one can obtain the input impedance Z_i :

$$Z_i = \frac{V_i}{I_i} = \frac{(D + \frac{h_f C}{H}) (\frac{F}{R_3} + h_r - \frac{GE}{H}) + (F - \frac{h_f E}{H}) (A - \frac{GC}{H})}{(B - \frac{h_f C}{R_3 H}) (\frac{F}{R_3} + h_r - \frac{GE}{H}) + (1 + \frac{F}{R_3} + \frac{h_f E}{H R_3}) (A - \frac{GC}{H})} \quad (22)$$

It would be possible at this point to replace the symbols A, B, C, ..., H by their defined equivalents, and a cumbersome expression that might then simplify or at least be subject to simplifying assumptions would result. The primary concern, however, is the input impedance of the circuit of Figure 4 using two 2N369 transistors and the experimentally adjusted values of the various circuit elements. The input impedance as a function only of load resistance R_L is found by substituting these values in equation (22):

$$\begin{aligned} h_i &= 1670 \text{ ohms} \\ h_r &= 1 - 3.33 \times 10^{-6} \\ h_f &= -56 \\ h_o &= 28 \times 10^{-6} \text{ mho} \\ R_1 &= 47 \text{ K} \\ R_2 &= 14 \text{ K} \\ R_3 &= 5 \text{ meg} \end{aligned}$$

The evaluation of equation (22) then yields

$$Z_i = \frac{95,200 + 3460 R_L}{1.02 + 92 \times 10^{-6} R_L} \quad (23)$$

It is interesting to note that this equation is of the same form as the expression for the input impedance of a simple emitter follower as defined in equation (1). Effectively, what has been obtained is a transistor with the following common-collector parameters:

$$\begin{aligned} h_i &= 95200 \\ h_r &= 1 \\ h_f &= -3460 \\ h_o &= 92 \times 10^{-6} \end{aligned}$$

Figure 7 is a graphical presentation of equation (23) and shows that an input impedance of 34 megohms should be obtainable in this circuit with a load of 0.1 megohm such as can be obtained with a simple emitter follower in the succeeding stage.

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Laboratory Performance

The bootstrapped emitter follower was built in breadboard form and connected into the test circuit of Figure 8.

With $R_L = 14000$ ohms, the input impedance of the bootstrapped circuit was measured and found to be 18 megohms, in close agreement with the calculated curve of Figure 7. The voltage gain was 0.98 from 20 to 20,000 cycles, falling off above this frequency to a 3-decibel point somewhat in excess of 200 kilocycles. The output impedance was 1100 ohms. With the circuit suitably shielded and the input shunted by a 0.5 megohm resistor, the narrow band (480 to 520 cycles) noise level was reduced to as low as 2 microvolts by the selection of the two least noisy transistors from the twelve on hand. This indicates a transistor noise figure of 12 decibels compared to the 7 decibels claimed by the manufacturer, but some increase is to be expected in view of the high value of input resistance and the frequency (500 cycles) used.

Fig. 8 – Test circuit using bootstrapped emitter follower

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Conclusions

The bootstrapped emitter follower performed essentially as expected from the results of the analysis and shows that transistors can be used to achieve high input impedances usually obtained with vacuum tubes. The circuit is presently being used as the input stage in a low-level preamplifier that is used with an alternating-current ionization chamber, presently being developed. The complete amplifier, shown schematically in Figure 9, has a stable voltage gain of 1000 at 500 cycles and is filtered to give a 40-decibel-per-octave drop on either side of this frequency.

Fig. 9—500-cycle amplifier using the bootstrapped emitter follower as the input stage