SEPTEMBER 1959

APPLICATION NOTES

TRANSISTOR CHOPPERS

The designer of a chopper amplifier should consider the advantages of transistors over mechanical switches. In addition to being small, transistors have low driving power requirements, a drive frequency that can be varied widely, and long life expectancy.

Most limitations of transistor choppers arise because the transistor is not a perfect switch; during the ON period the resistance between the switch terminals is not zero, and during the OFF period it is not infinite. These resistances vary with temperature and with the current flow through the device. Also, the back bias that turns the transistor OFF creates temperature-dependent leakage currents, while the ON base current produces stray voltages at the switch terminals.

EQUIVALENT CIRCUITS

For the OFF condition, the equivalent circuit of a low-level PNP transistor chopper is*:

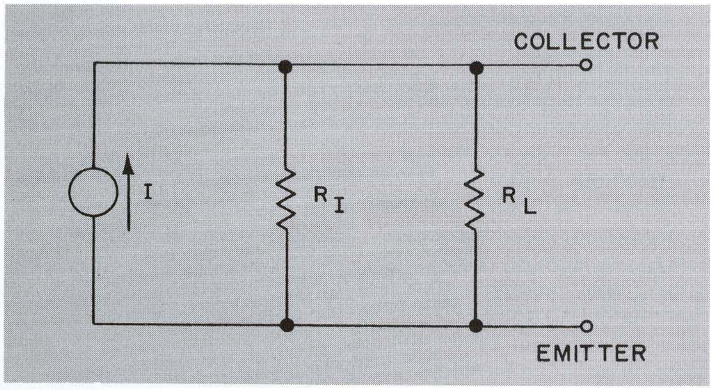

Figure 1

* R. B. Hurley, "Transistorized Low-Level Chopper Circuits," Electronic Industries and Tele-Tech, Dec. 1956

where $I = \dfrac{I_S(1-\alpha_i)(1-e^{V_B\delta/T})}{1-\alpha_i\alpha_n}$

$$R_I = \frac{T(1-\alpha_i\alpha_n)e^{-V_B\delta/T}}{I_S}$$

R_L = ohmic leakage resistance (usually a function of the surface condition of the semiconductor crystal)

I_S = true reverse-biased collector-base diode saturation current at T°K when $I_E = 0$ (does not include ohmic leakage currents)

α_n = common-base emitter-to-collector current transfer function, or normal alpha

α_i = common-base collector-to-emitter current transfer function, or inverted alpha

V_B = switching drive voltage between base and emitter, (assuming a positive voltage for the forward-biased direction)

T = temperature in degrees Kelvin

$\delta = 8.616 \times 10^{-5}$ joule/coulomb °K

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Figures 5 and 6 present test results for the particular germanium and silicon transistor types that were selected. Of the twenty 2N338 transistors tested, seven had I_{OFF} values too low to be accurately measured, and were omitted from Fig. 6.

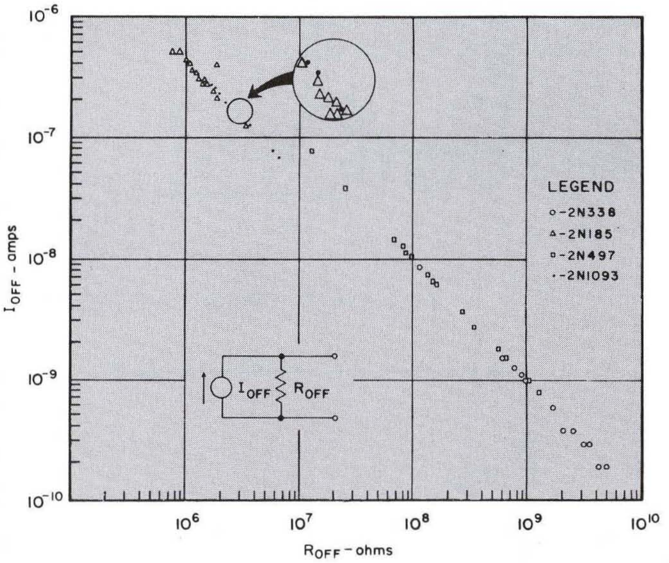

Figure 5

Table I gives the optimum impedance range into which each type will work and the noise level that may be expected, based on the test conditions. Four conclusions may be drawn from these tests:

1. For the silicon transistors tested,

$$I_{OFF}R_{OFF} = V_B$$

2. For the germanium transistors tested,

$$I_{OFF}R_{OFF} \cong \text{constant} \leqq V_B$$

3. The grown-junction silicon (2N338) and the alloy germanium transistors have about 16-db lower noise power output than the 2N497 transistors at the specified operating conditions.

4. Although the noise levels of the 2N185 and of the 2N338 are comparable, the ON voltages and OFF currents differ by 1.5 to 2 orders of magnitude. Thus for high-impedance sources, the silicon type 2N338 may provide a better signal-to-noise ratio, while for low-impedance sources the germanium type 2N185 may give better performance.

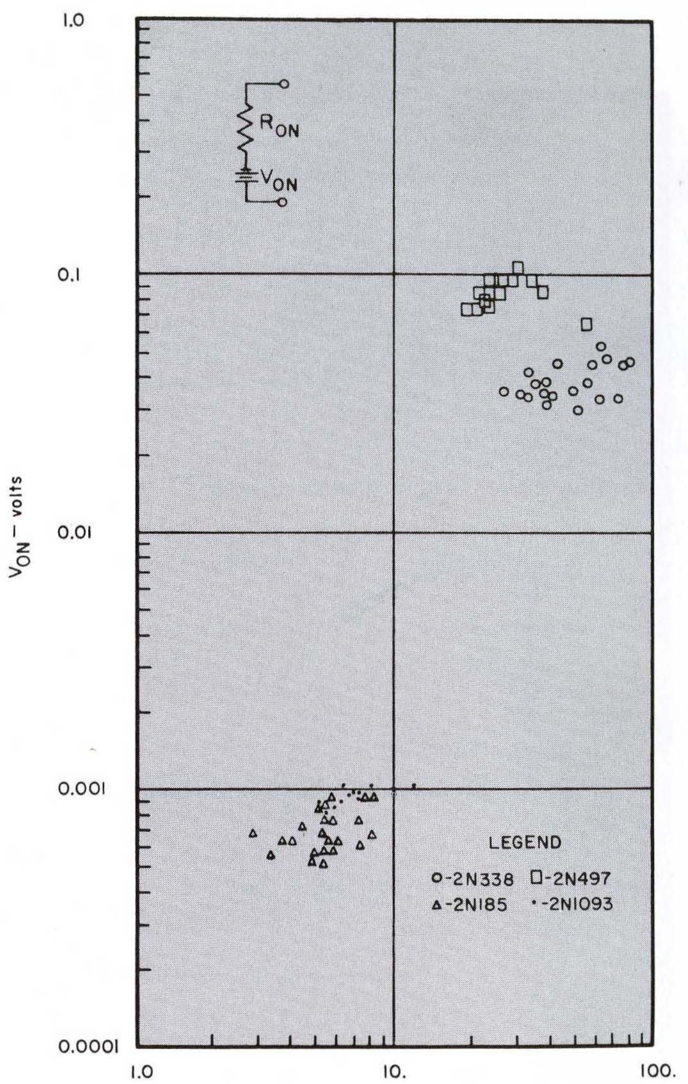

Figure 6

TABLE I

		2N185(Ge)	2N1093(Ge)	2N338(Si)	2N497(Si)
Optimum impedance range (in ohms)					
$Z_{(opt)} = \frac{V_{ON}}{I_{OFF}}$	max	7.4×10^3	6.3×10^3	2.7×10^8	1.3×10^8
	min	1.1×10^3	1.3×10^3	3.4×10^6	5.1×10^5
Maximum noise power (in watts) introduced by a pair of transistors into an optimum load Noise $Power_{(max)} = V_{ON}I_{OFF}$		4.8×10^{-10}	6.8×10^{-10}	4.7×10^{-10}	8.2×10^{-9}

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Note that the germanium transistors were operated in the inverted position.

The 2N338 and 2N497 silicon types were tested in the following circuits:

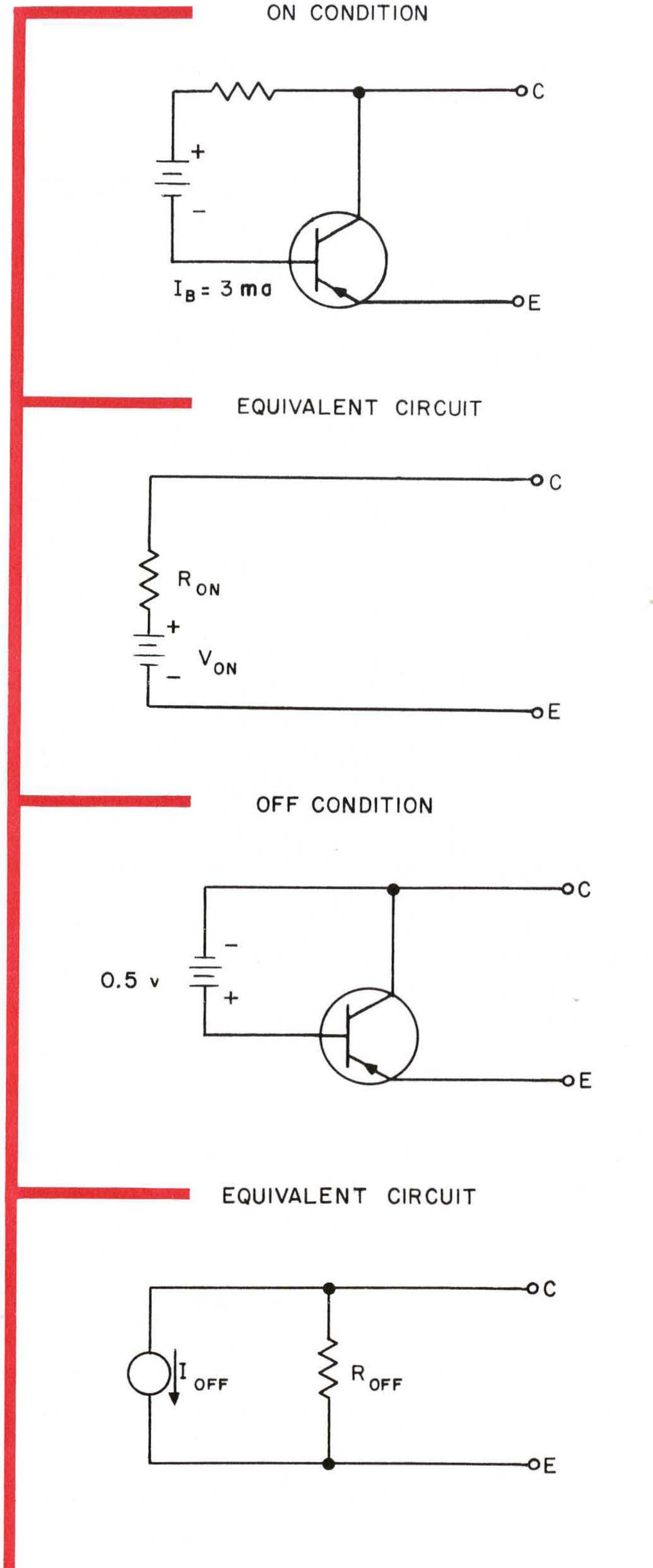


Figure 3

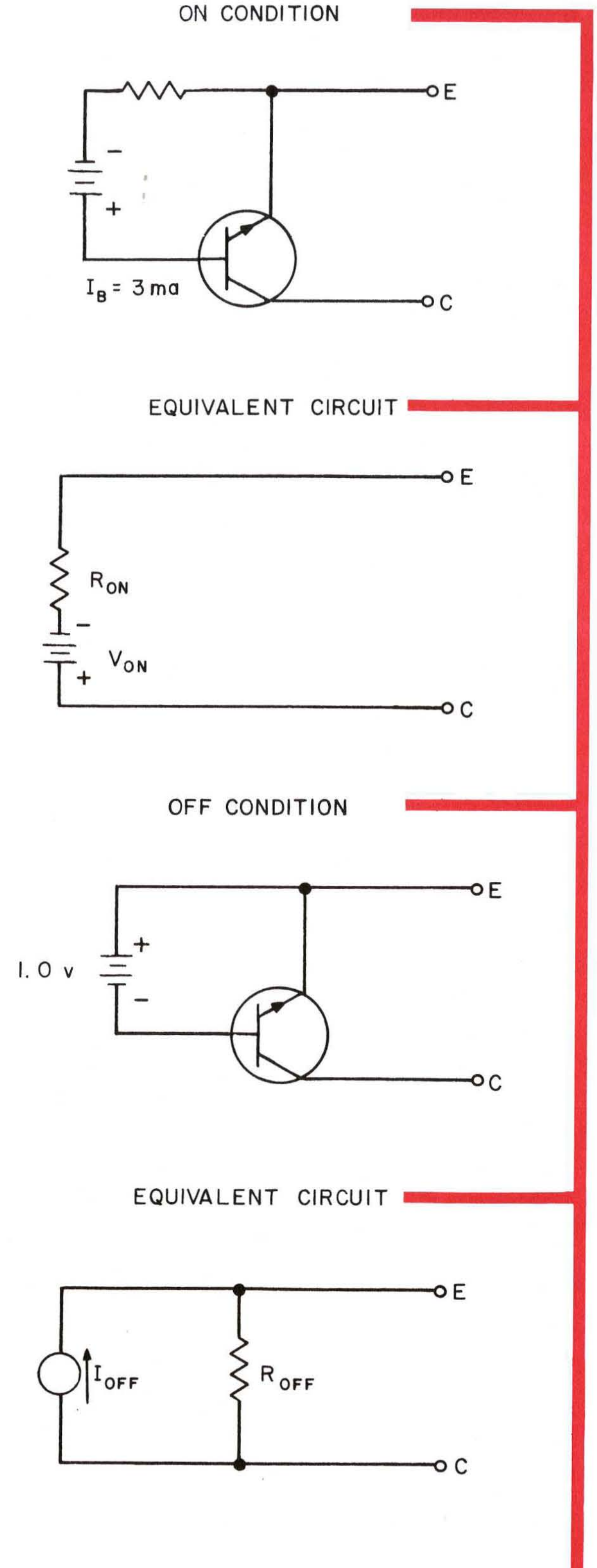
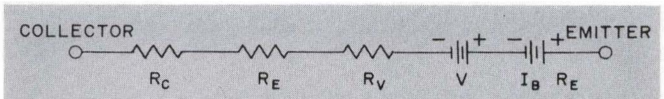


Figure 4

For the ON condition, the equivalent circuit of a low-level PNP transistor chopper is*:



$$\text{where } V = \frac{T(1-\alpha_i)(1-e^{-V_B\delta/T})}{\delta}$$

$$R_V = \frac{T\alpha_i(1-\alpha_i\alpha_n)}{I_B\delta\alpha_n}$$

I_B = base current drive

R_E = emitter bulk resistance (ohmic)

R_C = collector bulk resistance (ohmic)

Figure 2

For NPN transistors, the direction of current flow I and the polarity of voltage sources V and $I_B R_E$ are reversed.

REDUCING NOISE

The leakage current I and offset voltage $(V + I_B R_E)$ are the sources of the noise signal introduced by the switch. Notice, however, that both V and I are proportional to $(1 - \alpha_i)$. If the two transistor diode junctions are used as marked by the manufacturer, that is, if the terminal marked "collector" is used in the circuit as collector, etc., then α_n will generally be larger than α_i. But if the terminal marked "collector" is used as the emitter, and vice versa, then the new α_i will be larger than the new α_n. This inverted operation substantially reduces the magnitudes of V and I. However, it has some disadvantages; it causes an increase in R_V and a possible increase in I_S. It should also be noted that the former BV_{EBO} becomes BV_{CBO} in inverted operation. Grown- and diffused-junction transistors may not respond well to this technique due to a large increase in R_E.

* R. B. Hurley, "Transistorized Low-Level Chopper Circuits," Electronic Industries and Tele-Tech, Dec. 1956

Many chopper circuits use pairs of transistors in such a way that the leakage currents and/or offset voltages either oppose one another or combine to produce a constant d-c signal into the amplifier. The success of this approach depends on how accurately these quantities can be matched over the operating temperature range. A match for $(V + I_B R_E)$ may be achieved by placing selected resistors in each emitter lead to produce an additional voltage drop. R_V and V_B may be further stabilized by resistors in the base leads which maintain constant base drive currents. Good temperature compensation can be provided by making one of the base resistors temperature-sensitive. The effect of the OFF currents may be minimized by selected resistors shunting the emitter-collector terminals. Germanium diodes shunting the emitter and base can reduce the reverse bias, V_B. However, perfect temperature compensation requires that the transistors be matched for I_S. Although the ON and OFF resistances of the switch are degraded by these additions, this loss is often outweighed by the decrease in noise level.

During the actual instant of switching, the transistors are not matched and a noise spike may be produced. Therefore it is important that the switching time of the transistors be very short. For the same reason, the square-wave switching drive must have a fast rise-time. If transformers are used in the circuit, care must be taken to reduce the effect of leakage inductance. Switching transient noise can often be reduced by careful attention to stray inductances and capacitances.

Although a blanket recommendation of transistor types cannot be made, an idea of the noise power which a transistor may introduce and the optimum impedance into which the device should operate may be obtained from $I(V + I_B R_E)$ and from $(V + I_B R_E)/I$, respectively.

TRANSISTORS FOR CHOPPERS

Four transistor types have recently been evaluated for chopper service: 2N185, 2N1093, 2N338, and 2N497. The 2N185 and 2N1093 germanium types were tested in the following circuits: