Eqs. (20) and (21) apply whether the emitter is reverse biased or forward biased, and hence apply to both Regions I and II. Eqs. (20) and (21) can be simplified as follows:

$$I_B = -\frac{I_{EO}}{1-\alpha_N\alpha_I}e^{q\Phi_E/kT} + \frac{(1-\alpha_N)I_{EO}}{1-\alpha_N\alpha_I} \quad (22)$$

and

$$I_C = -\alpha_N I_E + I_{CO}. \quad (23)$$

Eqs. (22) and (23) lead to the equivalent circuit shown at the top of Fig. 5. In this circuit base resistance, r_B, and collector and emitter junction leakage resistances, r_{CL} and r_{EL}, have been added to account for the finite resistivity of the semi-conductor and the finite

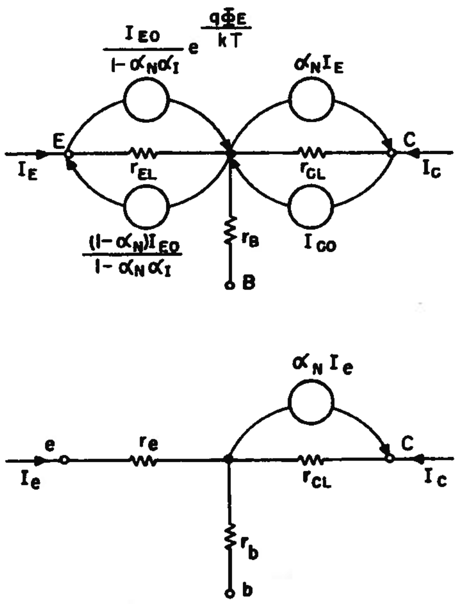

Fig. 5—Equivalent circuit of junction transistor valid in Regions I and II, and the small-signal equivalent circuit.

junction conductances. For small, low-frequency, ac signals, this reduces to the equivalent circuit shown at the bottom of Fig. 5 where

$$r_e \cong \frac{\frac{kT}{q}}{I_E - \frac{I_{EO}}{1-\alpha_N\alpha_I}} = \frac{0.026}{I_E - \frac{I_{EO}(1-\alpha_N)}{1-\alpha_N\alpha_I}}. \quad (24)$$

The boundaries of the three large signal regions are of particular interest since the transistor properties change very rapidly when the operating point approaches a boundary. There exists some choice as to which characteristic is used to define the large signal regions. Since the grounded base collector characteristic is the most widely published, it will be used for this purpose. It is convenient to define the boundary between Regions I and II as the curve for $I_E=0$. However, it is true that the transfer characteristic is relatively constant even for reverse values of emitter current. The "low current" boundary of Region I is of course a limit to possible quiescent operating points for the transistor. Mathematically, this boundary is obtained by assuming a large reverse bias on the emitter, and is realized practically by application of a few tenths of a volt reverse bias. The transistor has its smallest conductance in the collector circuit when the emitter has at least a few tenths of a volt reverse bias. The currents under this condition are

$$I_E = +\frac{I_{EO}(1-\alpha_N)}{1-\alpha_N\alpha_I} \quad (25)$$

$$I_C = +\frac{I_{CO}(1-\alpha_I)}{1-\alpha_N\alpha_I}. \quad (26)$$

As a typical example, assume that for a given transistor $\alpha_N=0.9$, $\alpha_I=0.45$, $I_{CO}=2$ μa and $I_{EO}=1$ μa (actually only three of these quantities need be specified). Provided the leakage resistances are negligible, the currents that will flow then under the condition of both junctions being reverse biased are, $I_C=1.85$ μa and $I_E=0.17$ μa. In this case it is seen that the sum of the two currents is approximately I_{CO}.

In terms of the grounded base collector characteristics, the boundary between Regions II and III is at $V_C=0$.

In Region III both emitter and collector junctions are forward biased. The collector and emitter are such low impedances that the currents are determined by the external circuit and it is most convenient to consider the currents as independent variables. By this same argument the voltages across the two junctions are seen to be the unknown quantities. These voltages can be obtained from (18) and (19)

$$\Phi_E = \frac{kT}{q}\ln\left[-\frac{I_E+\alpha_I I_C}{I_{EO}}+1\right], \quad (27)$$

and

$$\Phi_C = \frac{kT}{q}\ln\left[-\frac{I_C+\alpha_N I_E}{I_{CO}}+1\right]. \quad (28)$$

It should be recalled from the definitions of Φ_E and Φ_C that they are the voltage of the p material relative to the n material. Hence these equations apply for both n-p-n and p-n-p transistors. For any reasonable values of I_E and I_C in Region III, these equations become

$$\Phi_E = \frac{kT}{q}\ln\left[-\frac{I_E+\alpha_I I_C}{I_{EO}}\right] \quad (29)$$

and

$$\Phi_C = \frac{kT}{q}\ln\left[-\frac{I_C+\alpha_N I_E}{I_{CO}}\right]. \quad (30)$$

Eqs. (27) and (28) lead to the equivalent circuit shown at the top of Fig. 6 (next page). Base spreading resistance r_{BIII} has been added in this circuit. This resistance is the base resistance as measured in the current saturation region. For nonsymmetric transistors this resist-