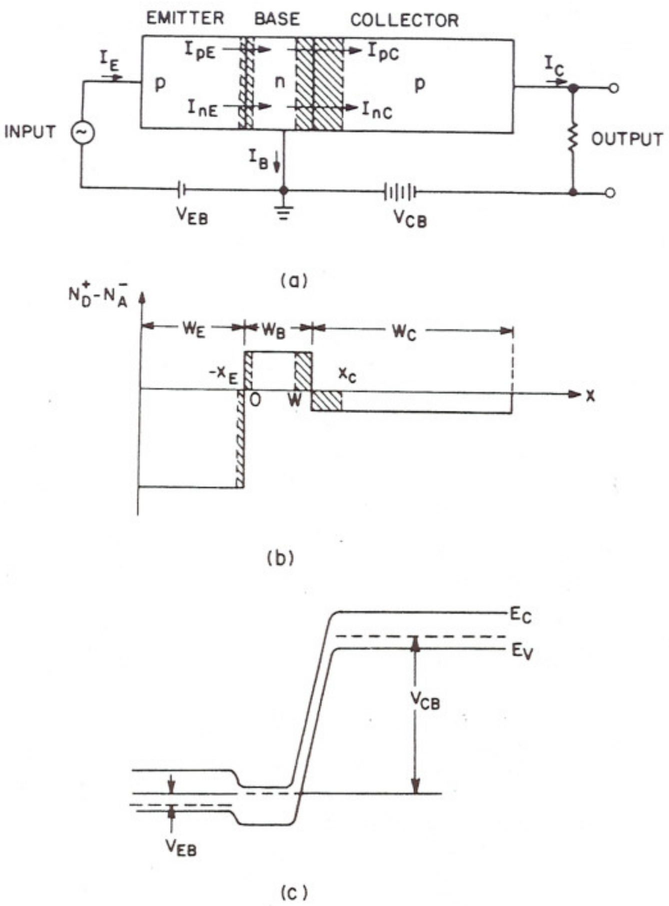

Fig. 3 (*a*) A *p-n-p* transistor connected in common-base configuration for amplifier application. (*b*) Doping profiles of a transistor with abrupt impurity distributions. (*c*) Energy-band diagram under normal operating conditions.

where n_E is the equilibrium minority-carrier density (electrons) in the emitter. A similar set of equations can be written for the collector junction:

$$p'(W) = p(W) - p_B = p_B\left[\exp\left(\frac{qV_{CB}}{kT}\right) - 1\right]$$
$$n'(x_C) = n(x_C) - n_C = n_C\left[\exp\left(\frac{qV_{CB}}{kT}\right) - 1\right]. \tag{4}$$

The solutions for the minority-carrier distributions, that is, the hole distribution in the base from Eq. 1 and electron distributions in the emitter

S. M. Sze, Phys. of Semi Dev. 2nd ed

and collector, are given by

$$p(x) = p_B + \left[\frac{p'(W) - p'(0)e^{-W/L_B}}{2\sinh(W/L_B)}\right]e^{x/L_B} - \left[\frac{p'(W) - p'(0)e^{W/L_B}}{2\sinh(W/L_B)}\right]e^{-x/L_B} \tag{5}$$

$$n(x) = n_E + n'(-x_E)\exp\left[\frac{(x + x_E)}{L_E}\right], \qquad x < -x_E \tag{6}$$

$$n(x) = n_C + n'(x_C)\exp\left[-\frac{(x - x_C)}{L_C}\right], \qquad x > x_C \tag{7}$$

where $L_B = \sqrt{\tau_B D_B}$ is the diffusion length of holes in the base, and L_E and L_C are the diffusion lengths in the emitter and collector, respectively. Equation 5 is important because it correlates the base width W to the minority-carrier distribution. If $W \to \infty$ or $W/L_B \gg 1$, Eq. 5 reduces to

$$p(x) = p_B + p(0)e^{-x/L_B} \tag{8}$$

which is identical to the case of a *p-n* junction. In this case, there is no communication between the emitter and collector currents, which are determined by the density gradient at $x = 0$ and $x = W$, respectively. The "transistor" action is thus lost. From Eqs. 2 and 3 we can obtain the total dc emitter current as a function of the applied voltages:

$$\begin{aligned} I_E &= AJ_p(x = 0) + AJ_n(x = -x_E) \\ &= A\left(-qD_B \left.\frac{\partial p}{\partial x}\right|_{x=0}\right) + A\left(-qD_E \left.\frac{\partial n}{\partial x}\right|_{x=-x_E}\right) \\ &= Aq\frac{D_B p_B}{L_B}\coth\left(\frac{W}{L_B}\right)\left[(e^{qV_{EB}/kT} - 1) - \frac{1}{\cosh(W/L_B)}(e^{qV_{CB}/kT} - 1)\right] \\ &\quad + Aq\frac{D_E n_E}{L_E}(e^{qV_{EB}/kT} - 1) \end{aligned} \tag{9}$$

and for the total dc collector current

$$\begin{aligned} I_C &= AJ_p(x = W) + AJ_n(x = x_C) \\ &= A\left(-qD_B \left.\frac{\partial p}{\partial x}\right|_{x=W}\right) + A\left(-qD_C \left.\frac{\partial n}{\partial x}\right|_{x=x_C}\right) \\ &= Aq\frac{D_B p_B}{L_B}\frac{1}{\sinh(W/L_B)}\left[(e^{qV_{EB}/kT} - 1) - \coth\left(\frac{W}{L_B}\right)(e^{qV_{CB}/kT} - 1)\right] \\ &\quad - Aq\frac{D_C n_C}{L_C}(e^{qV_{CB}/kT} - 1) \end{aligned} \tag{10}$$

where A is the cross-sectional area of the transistor. The difference between these two currents is small and appears as the base current:

$$I_B = I_E - I_C. \tag{11}$$

We shall now modify the doping distribution in the base layer of Fig. 3*b*

1255