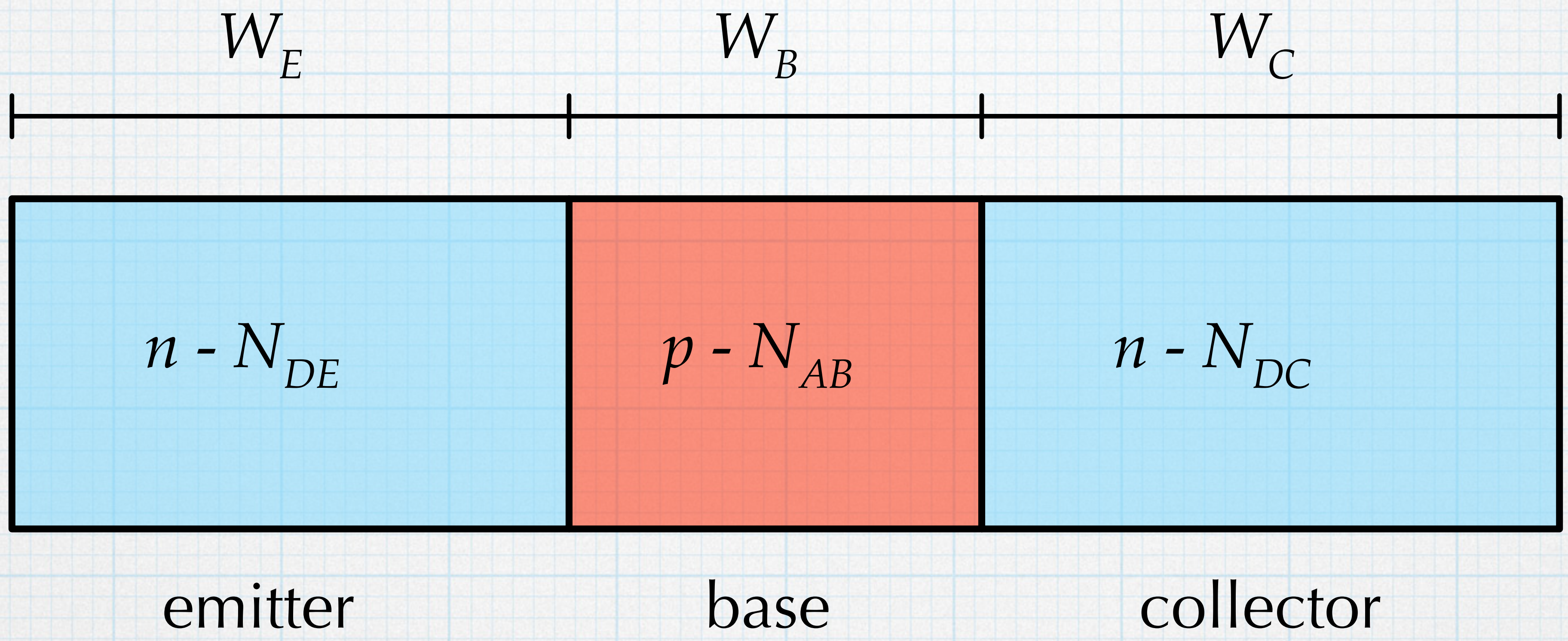
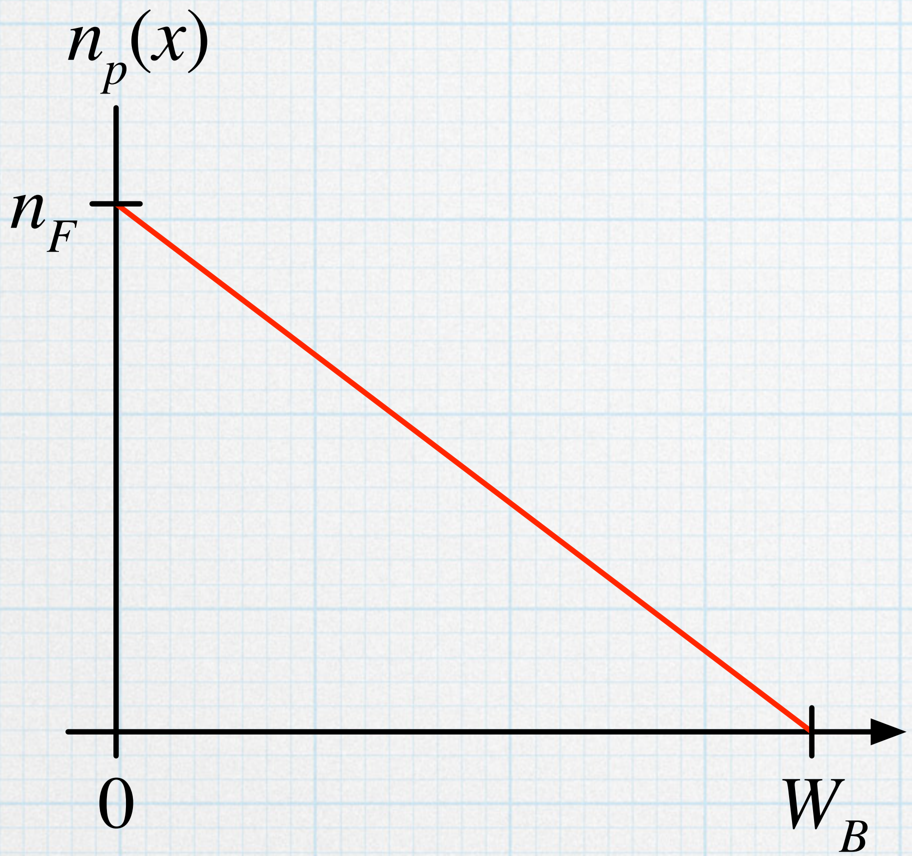
BJT — Early effect (base-width modulation)



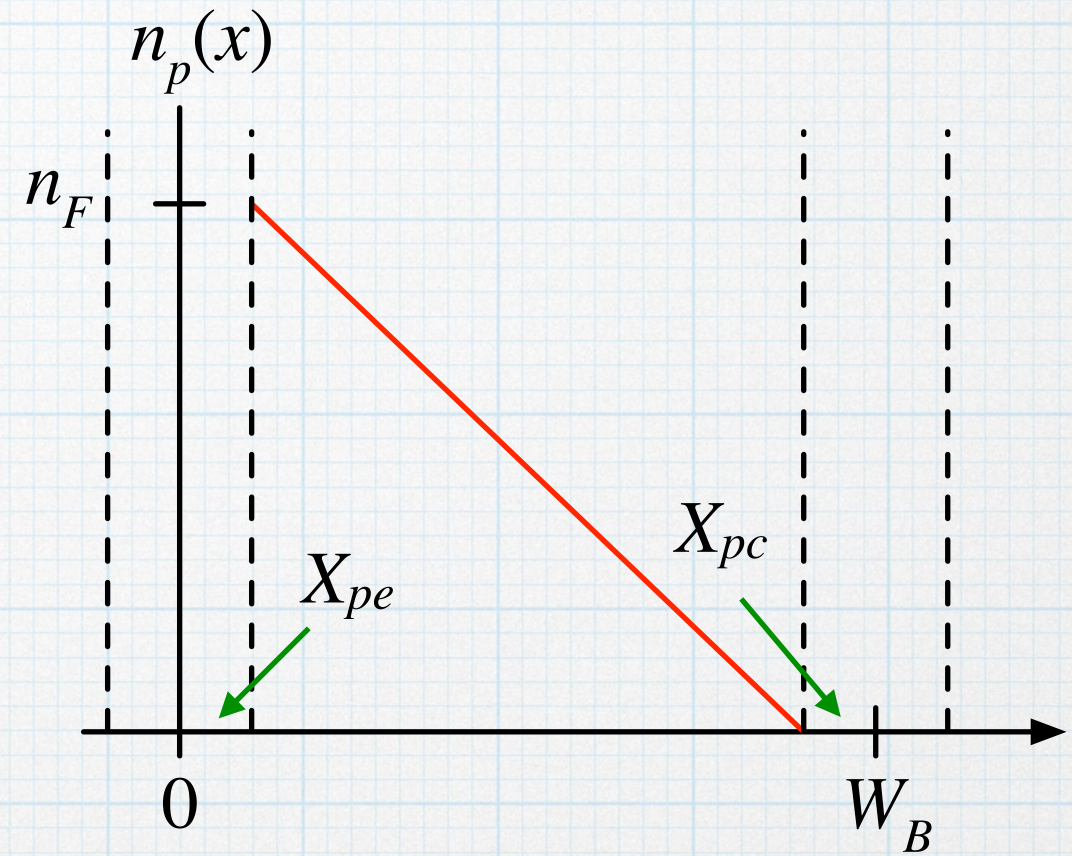
N_{DE}, N_{AB}, N_{DC} — uniform doping levels in emitter, base, and collector.

W_E, W_B, W_C — physical widths of emitter, base, and collector.

electron base charge profile
— ignoring depletion layers



electron base charge profile
— with depletion layers



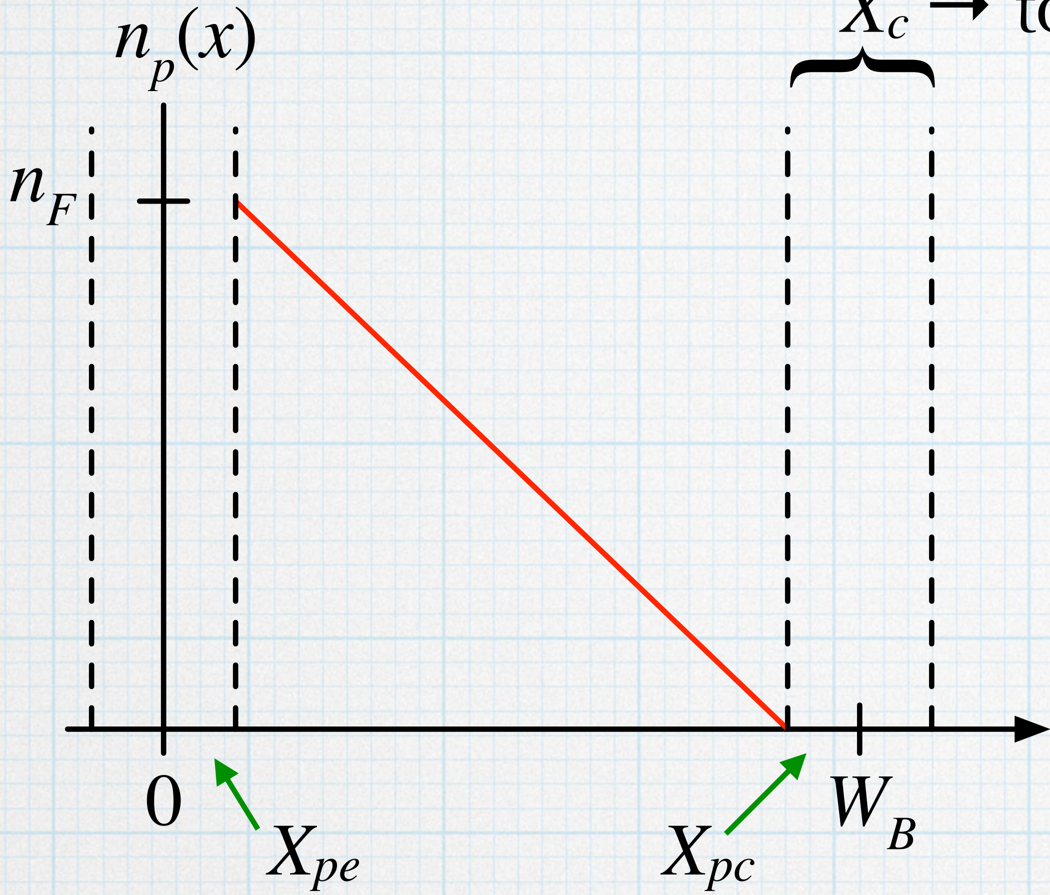
$$J_n = \frac{qD_n n_i^2}{N_{AB} W_B} \exp\left(\frac{qV_{BE}}{kT}\right)$$

$$J_n = \frac{qD_n n_i^2}{N_{AB}\left(W_B - X_{pc} - X_{pe}\right)} \exp\left(\frac{qV_{BE}}{kT}\right)$$

bigger!!

The base-collector depletion layer is more important in this case.

$X_{pc} \propto \sqrt{V_{CB}}$ $\qquad$ $V_{CB} = V_{CE} - V_{BE}$



X_c → total depletion layer width

$$X_c = \sqrt{\frac{2\epsilon\left(N_{AB} + N_{DC}\right)}{qN_{AB}N_{DC}}\left(\phi_{bi} + V_{CB}\right)}$$

$$= \sqrt{\frac{2\epsilon\left(N_{AB} + N_{DC}\right)}{qN_{AB}N_{DC}}\phi_{bi}} \cdot \sqrt{1 + \frac{V_{CB}}{\phi_{bi}}}$$

$$= X_{co}\sqrt{1 + \frac{V_{CB}}{\phi_{bi}}}$$

X_{co} → total depletion layer width when $V_{CB} = 0$.

We will ignore X_{pe} and focus on X_{pc}.

$$X_{pc} = \frac{N_{DC}}{N_{DC} + N_{AB}}X_c$$

$$= \sqrt{\frac{2\epsilon N_{DC}}{qN_{AB}\left(N_{AB} + N_{DC}\right)}\phi_{bi}} \cdot \sqrt{1 + \frac{V_{BC}}{\phi_{bi}}}$$

$$= X_{pco}\sqrt{1 + \frac{V_{CB}}{\phi_{bi}}}$$

Xp_{co} → depletion layer width on base side of BC when $V_{CB} = 0$.

$$J_n = \frac{qD_n n_i^2}{N_{AB}\left(W_B - X_{pc}\right)} \exp\left(\frac{qV_{BE}}{kT}\right)$$

$$= \frac{qD_n n_i^2}{N_{AB}\left(W_B - X_{pco}\sqrt{1 + \frac{V_{CB}}{\phi_{bi}}}\right)} \exp\left(\frac{qV_{BE}}{kT}\right)$$

$$= \frac{qD_n n_i^2}{N_{AB} W_B} \cdot \frac{1}{\left(1 - \frac{X_{pco}}{W_B}\sqrt{1 + \frac{V_{CB}}{\phi_{bi}}}\right)} \exp\left(\frac{qV_{BE}}{kT}\right)$$

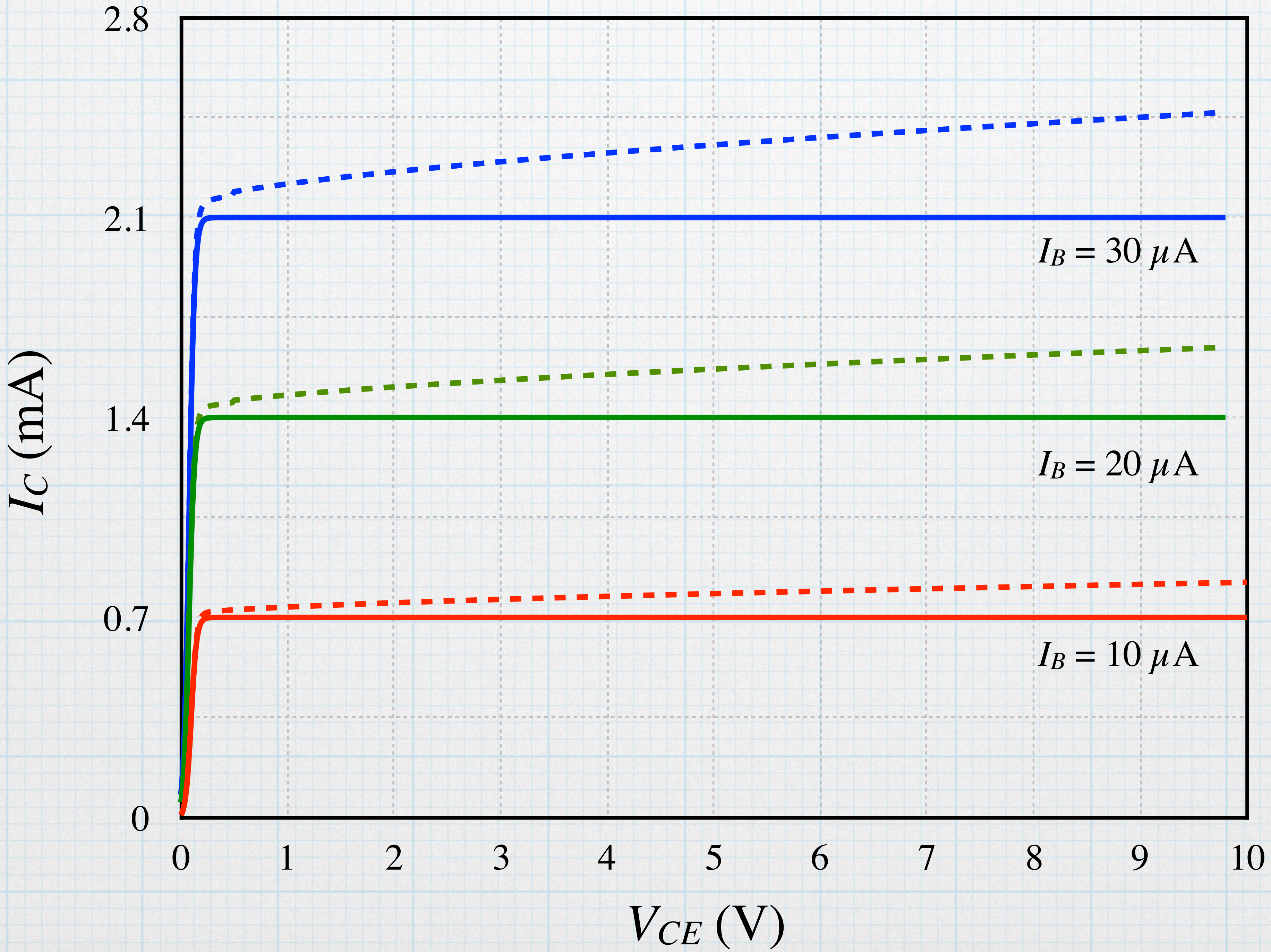
$$= \left[J_{Sn} \exp\left(\frac{qV_{BE}}{kT}\right)\right]\left(1 - \frac{X_{pco}}{W_B}\sqrt{1 + \frac{V_{CB}}{\phi_{bi}}}\right)^{-1}$$

The term in brackets on the left is the electron current if there were no base-width effects. The right-hand factor is the current enhancement due to base-width modulation at the collector end.

Effect of base-width modulation

Silicon BJT with uniform doping: $N_{DE} = 10^{18}$ cm^{-3}, $N_{AB} = 5\text{x}10^{16}$ cm^{-3}, $N_{DC} = 5\text{x}10^{15}$ cm^{-3}, $W_E = 1$ μm, $W_B = 1$ μm, $W_C = 5$ μm.

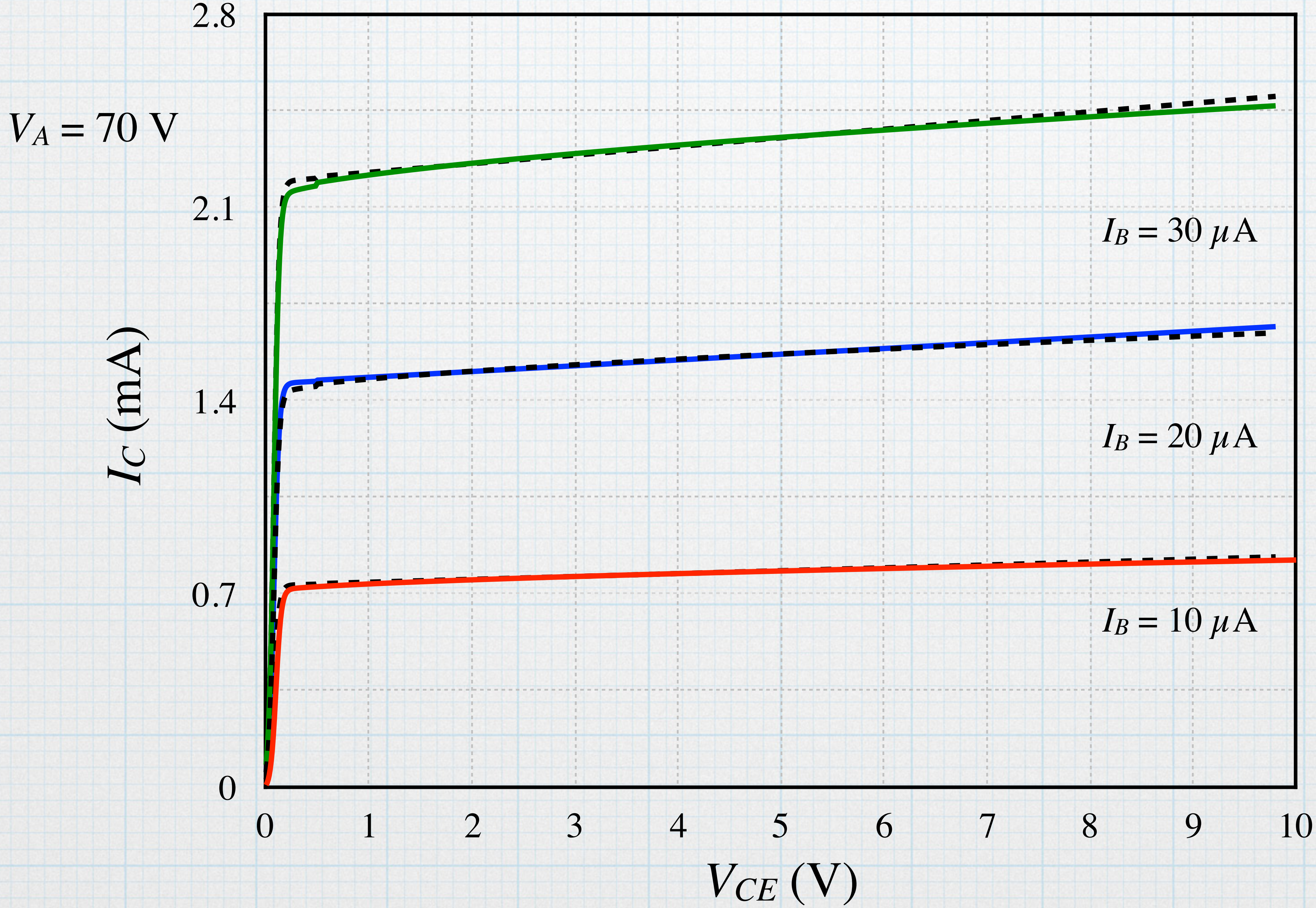
$\beta_F = 70$, $X_{pco} = 0.041\ \mu$m.



Model the current enhancement using a simple correction:

$$i_C \rightarrow i_C \cdot \left(1 + \frac{V_{CE}}{V_A}\right)$$

V_A is the Early voltage, chosen to best fit the current enhancement.



To reduce the base-width modulation effect, we need to have most of the base-collector depletion width occurring on the collector side of the junction. In order to do that, we need $N_{DC} < N_{AB}$.

In a typical BJT, the "doping rank" is: $N_{DE} > N_{AB} > N_{DC}$.

Even though the BJT appears to be a symmetric sandwich, the need to have high current gain and low base-width modulation makes any practical BJT very asymmetric — there is a correct direction for proper use. The low doping in the collector, needed to minimize the Early effect, leads to the very poor reverse current gain of typical BJTs.

The base-width effects are easily incorporated into the Gummel number view of BJT current. The physical narrowing of the base can be expressed as a reduction in the base Gummel number, leading to an increase in the current.

$$\Gamma_B = \int_0^{W_B} \frac{p(x)}{qD_n n_i^2} dx$$