For all parts of this problem, your answers should be expressed in terms of the parameters shown in the figures as well as physical constants. Parts a) and b) refer to the pn junction diode structure shown below, operated at room temperature and without light. Note that the n-side (left) is composed of a material with parameters denoted with subscript “1” and the p-side (right) is composed of a material with parameters denoted with subscript “2”. For convenience, x=0 is chosen as the right side of the depletion region (normally denoted as “x_p”).

a) (25 points) Consider the excess minority carrier distribution in the p-bulk region (right side), \( \Delta n_p(x) = n_p(x) - n_{p0} \), where \( n_p(x) \) is the minority carrier concentration at position \( x \) and \( n_{p0} \) is the equilibrium minority carrier concentration. There is an applied forward bias that induces low-level injection of excess minority carriers with concentration at \( x=0 \) of \( \Delta n_p(0) = N_2 \). Assume that \( N_2 >> n_{p0} \).

For this heterojunction diode, derive expressions for:

i) the \( \Delta n_p(0) \) as a function of the applied forward bias, \( V_A \)

ii) the ratio \( \Delta n_p(0)/\Delta n_p(-W) \) as a function of forward bias, where \( W \) is the width of the depletion region.

It may be helpful to recall that the homojunction equivalent of part i) is typically called “the law of the junction.”
b) (25 points) Note that in this geometry, a contact is placed at $x = d_2$. This contact is characterized by a surface recombination velocity of $S_2$ (units: cm/sec). You may assume that $d_2 \ll$ minority carrier diffusion length, therefore recombination within the region $0 < x < d_2$ can be ignored. Find the excess electron concentration as a function of position ($\Delta n_e(x)$) in the p-bulk region ($0 < x < d_2$).

For parts c), d), and e), assume that the diode from parts a) and b) is integrated into a bipolar junction transistor, as shown below. The regions occupied by materials 1 and 2 refer to the emitter and base regions, respectively. The emitter length ($d_1$) is $>>$ minority carrier diffusion length in emitter. The C-B junction is reverse biased in order to maintain the same boundary condition at $x = d_2$, so the minority carrier distribution in the region $0 < x < d_2$ is the same as that found in part b). (Note: there is no contact at $x = d_2$ in parts c), d) or e).) The current is continuous across $x = d_2$. There is no collector-to-base injection. The E-B and B-C junctions both have cross-sectional area $A$. If you have not yet solved part b), you may express your answer in terms of $\Delta n_e(x)$.

c) (20 points) Find the magnitude and sign of the collector current (for sign, consider a current flowing in $+x$ direction to be positive).

d) (20 points) Find the emitter injection efficiency ($\gamma = I_{En} / (I_{En} + I_{Ep})$) for this transistor.

e) (10 points) Find the current gain ($I_C/I_B$) for this transistor.