Homework 3

February 20, 2022

GaAs HBT, surface recombination, base resistance and performance over time.

1. (a) Resistivity is given as:

$$R = \rho \frac{L}{A}$$

where:

$$\rho = \frac{1}{nq\mu_n + pq\mu_p}$$

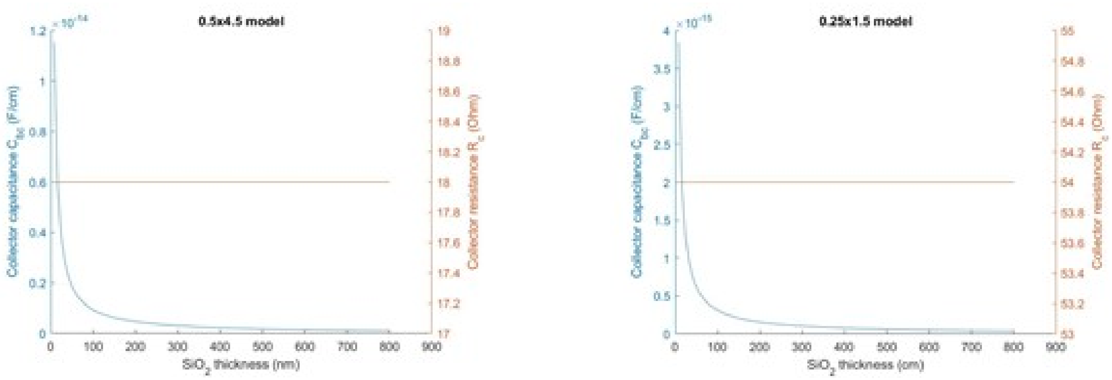
Assuming GaAs' intrinsic carrier concentration n_i is 2.1E+6 cm^{-3}, the collector width W_c is 1.5 µm, and the subcollector length L_s is 2 µm, the resistivity can be calculated.
From the graph given, the electron and hole mobilities can be obtained, resulting in $\mu_n = 6000 \frac{\mathrm{cm}^2}{\mathrm{V\,s}}$ for the collector, and $\mu_n = 1700 \frac{\mathrm{cm}^2}{\mathrm{V\,s}}$ for the subcollector.
This leads to a resistance of 18 Ωfor the 0.5×4.5 model, and 54 Ωfor the 0.25×1.5 model.

(b) For this model, we take the same assumptions as above, but using a base width W_b of 0.25 µm. This leads to a resistance of 5.56 Ωfor the 0.5×4.5 model, and 16.7 Ωfor the 0.25×1.5 model.

(c) Capacitance is given as:

$$C = \frac{\epsilon A}{d}$$

The permittivity of SiO_2 is 3.4515E-13 $\frac{\mathrm{F}}{\mathrm{cm}}$, and the oxide width W_O is 0.6 µm. By sweeping the oxide depth from 0 to 800 cm, the graphs in figures 1a and 1b are generated.



(a) 0.5×4.5 model (b) 0.25×1.5 model

Figure 1: Thickness vs capacitance for both models.

2. The steady state diffusion equation is given as:

$$\frac{d^2\delta p}{dx^2} = \frac{\delta p}{D_p \tau_p} - \frac{G_{op}}{D_P} \equiv \frac{\delta p}{L_p^2} - \frac{G_{op}}{D_p}$$

with a general solution of:

$$\delta p(x) = G_{op}\tau \left(1 - \frac{\cosh \frac{x}{L}}{\cosh \frac{a}{2L}}\right)$$

However, this does not include the effects of an arbitrary surface recombination velocity, as discussed in slide 43 of Lectures 11 and 12. Skipping the derivation, the diffusion equation with the included surface recombination velocity is given as:

$$\delta p(x) = G_{op}\tau \left(1 - \frac{s\cosh \frac{x}{L}}{s\cosh \frac{a}{2L} + \frac{D}{L}\sinh \frac{a}{2L}}\right)$$

where G_{op} and τ are constants in this case, D is the diffusion coefficient, and L is the length of the semiconductor. This is to be solved for all combinations of $s = \{$1E+3, 1E+4, 1E+5, 1E+6$\}$ $\frac{cm}{s}$, and $a = \{\frac{L_n}{5}, L_n, 5L_n\}$, leading to 12 cases to solve for.

To graph this, the vertical axis can be modified by $y' = \frac{\delta p(x)}{G_{op}\tau}$, and the horizontal axis can be normalized by $x' = \frac{x}{a}$. This leads to the formula:

$$y' = 1 - \frac{s\cosh \frac{x'a}{L}}{s\cosh \frac{a}{2L} + \frac{D}{L}\sinh \frac{a}{2L}}$$

As an example of the mathematics, the first combination of a surface recombination rate of 1E+3 $\frac{cm}{s}$ and a thickness of $\frac{L_n}{5}$, the problem would simplify to:

$$\begin{aligned} y' &= 1 - \frac{1000\cosh \frac{Lx'}{5L}}{s\cosh \frac{L}{10L} + \frac{D}{L}\sinh \frac{L}{10L}} \\ &= 1 - \frac{1000\cosh 0.2x'}{1000\cosh \frac{1}{10} + \frac{D}{L}\sinh \frac{1}{10}} \\ &\approx 1 - \frac{1000\cosh 0.2x'}{1005 + \frac{0.1002D}{L}} \end{aligned}$$

As diffusion coefficient D and diffusion length L are not given nor can they be omitted from the equation, I chose random numbers for them to accentuate the important curves.

All 12 combinations are graphed in figure 2. Since this graph is very cluttered, I have also provided graphs holding the surface recombination rates constant, at $s = \{1E+3, 1E+4, 1E+5, 1E+6\}$ in figures 3, 4, 5, and 6, respectively.

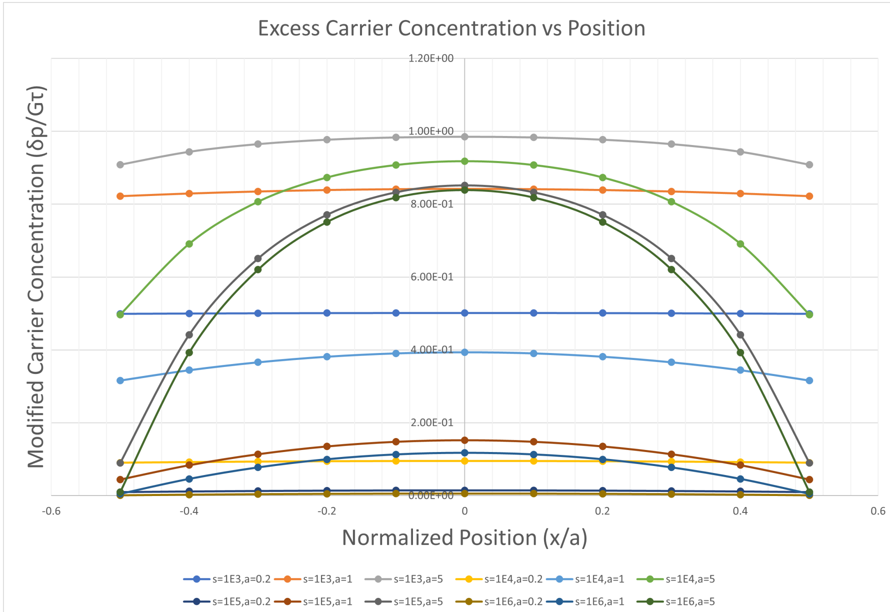


Figure 2: All twelve combinations of surface recombination rates and thicknesses.

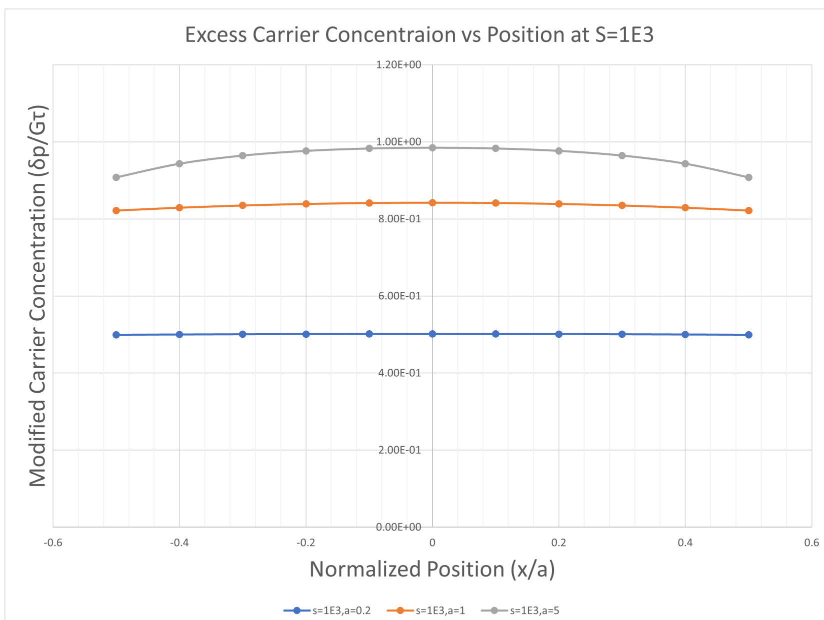


Figure 3: Graph for only s = 1E3.

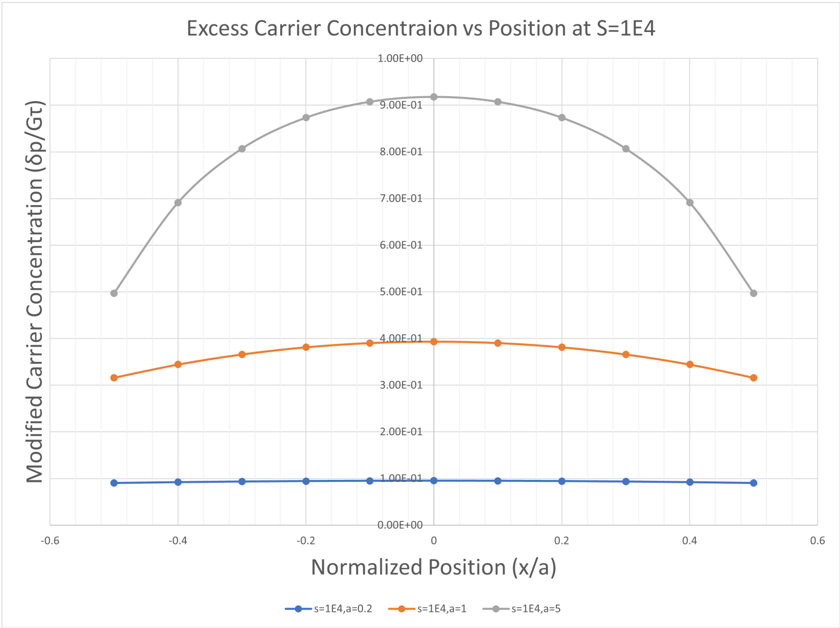


Figure 4: Graph for only s = 1E4.

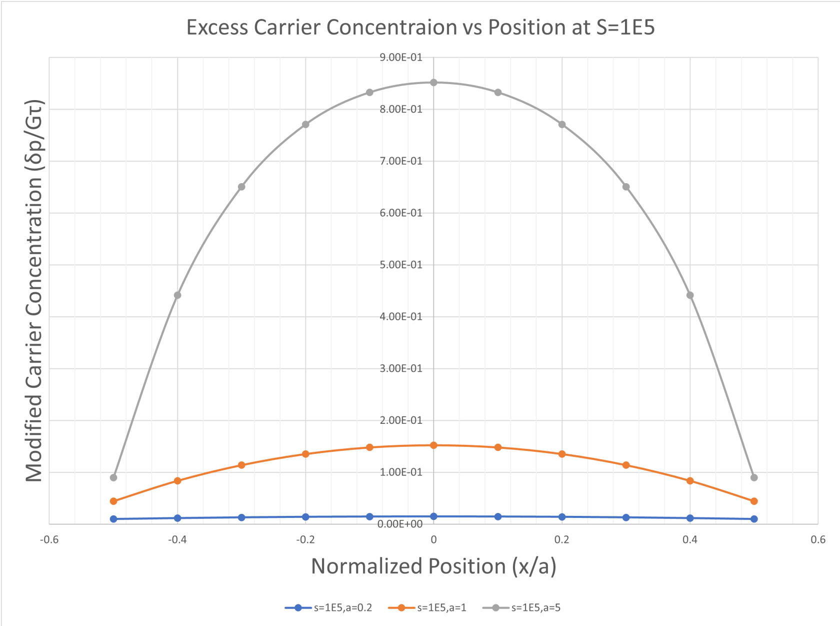


Figure 5: Graph for only s = 1E5.

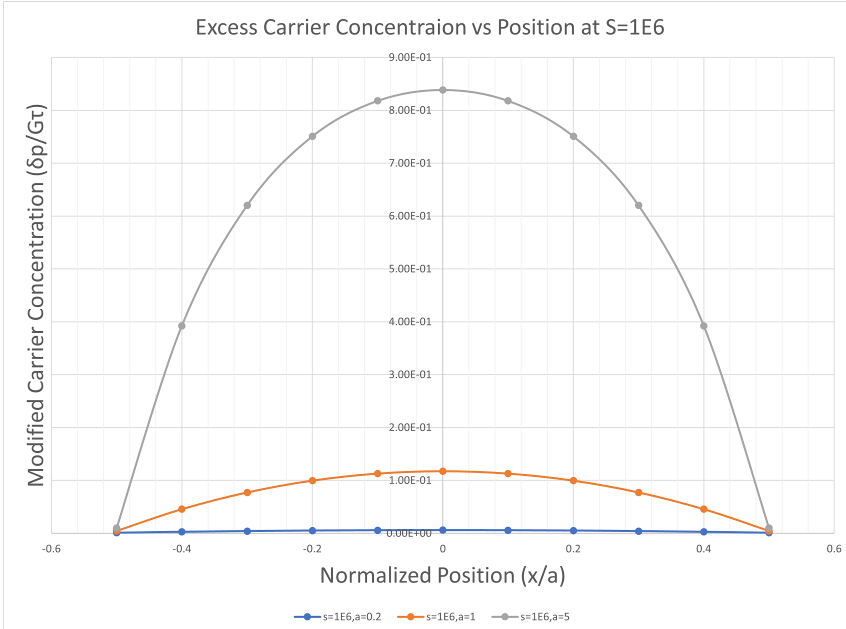


Figure 6: Graph for only s = 1E6.

3. (a) Base resistance is given as:

$$R_{sbi} = \frac{1}{q\int_0^{W_B} p_p(x)\mu_p(x)dx}$$

For constant base doping, we assume that $P_p(x) \approx N_{aB} = 1E + 20$, and the hole mobility is constant at 450. We also assume that the emitter and metal plugs are uniform in the same direction. This allows us to simplify the equation to:

$$R_{sbi} = \frac{1}{q\int_0^{W_B} N_{aB}\mu_p dx} = \frac{1}{qW_B N_{aB}\mu_p}$$

Because of the symmetry, we can divide by two for each side:

$$R_t = \frac{1}{2}R_{SiGe} + \frac{1}{2}R_{Si}$$
$$= \frac{1}{2}\frac{1}{1.609E - 19 * 0.025E + 18 * 450} + \frac{1}{2}\frac{1}{1.609E - 19 * 0.025E + 20 * 450}$$
$$= 0.279\ \Omega\mu\mathrm{m}$$

(b) In this case, simply take the resistance of the SiGe:

$$R_{SiGe} = \frac{1}{1.609E - 19 * 0.025E + 18 * 450} = 0.552\ \Omega\mu\mathrm{m}$$

(c) To find the percent improvement, use the formula for percentage increase:

$$\frac{0.552 - 0.279}{0.279} * 100\% = 97.84\%$$

(d) τ_B can be approximated as:

$$\tau_B \approx \frac{W_B^2}{2D_{nB}}$$

where

$$D_{nB} = \frac{kT}{q}\mu_{nB}$$

With the values as described in previous parts, this leads to $D_{nB} = 8.90\frac{\mathrm{cm}^2}{\mathrm{s}}$. Therefore:

$$\tau_B \approx \frac{(2.5E - 6)^2}{2 * 8.90} \approx 3.511E - 13\mathrm{s}$$

The frequency is simply the inverse of lifetime:

$$f = \frac{1}{\tau_B} \approx 284.8\mathrm{GHz}$$

The reported f_t is given to be about 320 GHz, which is greater than the found f_{SiGe} above.

(e) From the results above, by allowing epitaxial growth, the intrinsic resistance goes down, but the transit time goes up.

4.

Base Width	Device Size (L_E, W_E)	Unity current gain cutoff frequency, f_t	Base transit time (ps)	Base collector capacitance (C_{bc})	Base Resistance ($R_b b$)	Reference
0.1µm	0.12*2.5µm	350 GHz				1.
0.1µm	0.12*1.0µm	352 GHz	0.36		304	2.
0.1µm	0.12*0.96µm	300 GHz		13.9		3.
0.1µm	10*3µm	32 GHz				4.
0.14µm	3*10µm	40 GHz	6			5.
0.055µm	1*1µm	20 GHz				6.

References:

1: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1175952 (SiGe)

2: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1644829 (SiGe)

3: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6082749 (IHP2 SiGe)

4: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=108180 (Table IV, Device A)

5: https://ieeexplore.ieee.org/document/32211 (GaAs)

6: https://aip.scitation.org/doi/10.1063/1.5058717 (GaAs)

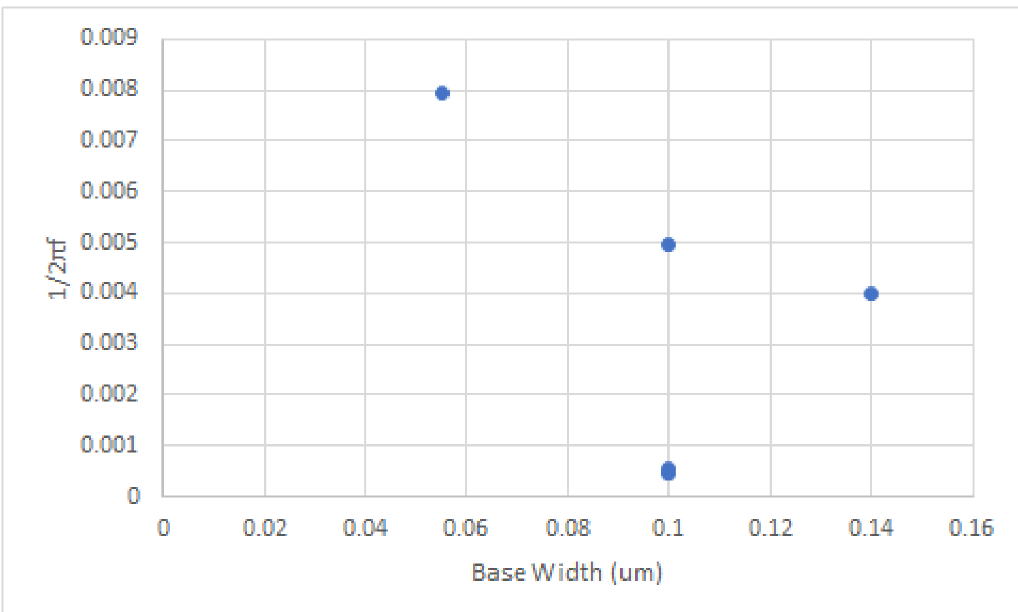


Figure 7: $\frac{1}{2\pi f_t}$ as a function of W_b.