NAME:

1. Design an MIS Capacitor on a p-type <100> silicon substrate to have a VT of 0.7 V if the fixed oxide charge is $5x10^{10}q/cm^2$, $NA=1x10^{16}cm^{-3}$, and the permittivity of the oxide layer is $3.9x8.85x10^{-14}F/cm$. The gate material is heavily doped n-poly-silicon. (Room temperature conditions apply.)

Looking at equation 1 and the EGB on page 171 of the text we can find a relation for the metal semiconductor work function. Given that the poly gate is heavily doped its Fermi level will be equal to the conduction band. The electron affinities cancel out and the phims is equal to Eg/2+phiB.

$T := 300 \qquad k := 1.38 \cdot 10^{-23} \qquad q := 1.6 \cdot 10^{-19}$

$U_T := \frac{k \cdot T}{q} \qquad V_T := 0.7$

$\chi := 4.05 \qquad \phi_n := 0 \qquad E_g := 1.12 \qquad n_i := 9.65 \cdot 10^9$

$\phi_m := \chi + \phi_n \qquad N_A := 10^{16}$

$\psi_B := U_T \cdot \ln\left(\frac{N_A}{n_i}\right) \qquad \psi_B = 0.358 \qquad \varepsilon_{SiO2} := 3.9 \cdot 8.85 \cdot 10^{-14}$

$\phi_{ms} := \frac{-E_g}{2} - \psi_B \qquad \phi_{ms} = -0.918 \qquad \varepsilon_{Si} := 11.8 \cdot 8.85 \cdot 10^{-14}$

$$\phi_F := \psi_B$$

$$Q_i := 5\cdot 10^{10}\cdot q \qquad Q_D := -2\cdot\left(\varepsilon_{Si}\cdot q\cdot N_A\cdot\phi_F\right)^{\frac{1}{2}}$$

+

$$V_T = \phi_{ms} - \frac{Q_i}{C_{ox}} - \frac{Q_D}{C_{ox}} + 2\cdot\phi_F$$

$$\frac{Q_i + Q_D}{C_{ox}} = -V_T + \phi_{ms} + 2\cdot\phi_F$$

$$\frac{1}{C_{ox}} = \frac{-V_T + \phi_{ms} + 2\cdot\phi_F}{Q_i + Q_D}$$

$$\frac{1}{\frac{\varepsilon_{Si02}}{d}} = \frac{-V_T + \phi_{ms} + 2\cdot\phi_F}{Q_i + Q_D}$$

$$d := \varepsilon_{SiO2}\cdot\left(\frac{-V_T + \phi_{ms} + 2\cdot\phi_F}{Q_i + Q_D}\right)$$

$d = 7.601 \times 10^{-6}$ This is in cm!

2. Calculate the maximum depletion width of the MOS diode in question 1.

$$W_m := 2\cdot\sqrt{\frac{\varepsilon_{Si}\cdot U_T\cdot\phi_F}{q\cdot N_A}} \qquad W_m = 4.92\times 10^{-6}$$

This is in cm!

3. Design an MIS Capacitor on a n-type <100> silicon substrate to have a VT of -1.0V if the fixed oxide charge is $5\text{x}10^{10}$q/cm^2, tox=d=600Å, and the permittivity of the oxide layer is $3.9\text{x}8.85\text{x}10^{-14}$F/cm. The gate material is heavily doped n-poly-silicon. (Room temperature conditions apply.)

The metal semiconductor work function changes as we move to an n-type substrate. The only parameter we have to change is the substrate doping. I used a solver in Mathcad. The doping I calculated is a little low on the "reasonable" scale, but it is much greater than ni.

$$\Psi_B := U_T \cdot \ln\left(\frac{N_D}{n_i}\right)$$

$$\phi_{ms} := \frac{-E_g}{2} + \Psi_B$$

$$C_{ox} := \frac{\varepsilon_{SiO2}}{.06 \cdot 10^{-4}} \qquad C_{ox} = 5.752 \times 10^{-8}$$

$$Q_i = 8 \times 10^{-9}$$

$$\phi_F = U_T \cdot \ln\left(\frac{N_D}{N_i}\right) \qquad Q_D := 2 \cdot \left(\varepsilon_{Si} \cdot q \cdot N_D \cdot \phi_F\right)^{\frac{1}{2}}$$

$$V_T = \phi_{ms} - \frac{Q_i}{C_{ox}} - \frac{Q_D}{C_{ox}} - 2 \cdot \phi_F$$

$$V_T := -1 \qquad N_D := 10^{15}$$

Given

$$V_T = \frac{-E_g}{2} + U_T \cdot \ln\left(\frac{N_D}{n_i}\right) - \frac{Q_i}{C_{ox}} - \frac{2 \cdot \left(\varepsilon_{Si} \cdot q \cdot N_D \cdot \phi_F\right)^{\frac{1}{2}}}{C_{ox}} - 2 \cdot \left(U_T \cdot \ln\left(\frac{N_D}{n_i}\right)\right)$$

$$N_D := \text{Find}(N_D) \qquad N_D = 6.97 \times 10^{13}$$

4. Design an MIS Capacitor on a p-type <100> silicon substrate to have a VT of .6V if the fixed oxide charge is 3×10^{10} q/cm^2, and the permittivity of the oxide layer is $3.9 \times 8.85 \times 10^{-14}$ F/cm. The gate material is heavily doped n-poly-silicon.

In this problem we have one equation and two unknowns. It worked in problem #1 to have an NA of 10^{16}cm^{-3}, so I will try that first.

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$U_T := \frac{k \cdot T}{q}$ $V_T := 0.6$

$\chi := 4.05$ $\phi_n := 0$ $E_g := 1.12$ $n_i := 9.65 \cdot 10^{9}$

$\phi_m := \chi + \phi_n$ $N_A := 10^{16}$

$\psi_B := U_T \cdot \ln\left(\frac{N_A}{n_i}\right)$ $\psi_B = 0.358$ $\varepsilon_{SiO2} := 3.9 \cdot 8.85 \cdot 10^{-14}$

$\phi_{ms} := \frac{-E_g}{2} - \psi_B$ $\phi_{ms} = -0.918$ $\varepsilon_{Si} := 11.8 \cdot 8.85 \cdot 10^{-14}$

$$\phi_F := \Psi_B$$

$$Q_i := 5 \cdot 10^{10} \cdot q \qquad Q_D := -2 \cdot \left(\varepsilon_{Si} \cdot q \cdot N_A \cdot \phi_F\right)^{\frac{1}{2}}$$

$$V_T = \phi_{ms} - \frac{Q_i}{C_{ox}} - \frac{Q_D}{C_{ox}} + 2 \cdot \phi_F$$

$$\frac{Q_i + Q_D}{C_{ox}} = -V_T + \phi_{ms} + 2 \cdot \phi_F$$

$$\frac{1}{C_{ox}} = \frac{-V_T + \phi_{ms} + 2 \cdot \phi_F}{Q_i + Q_D}$$

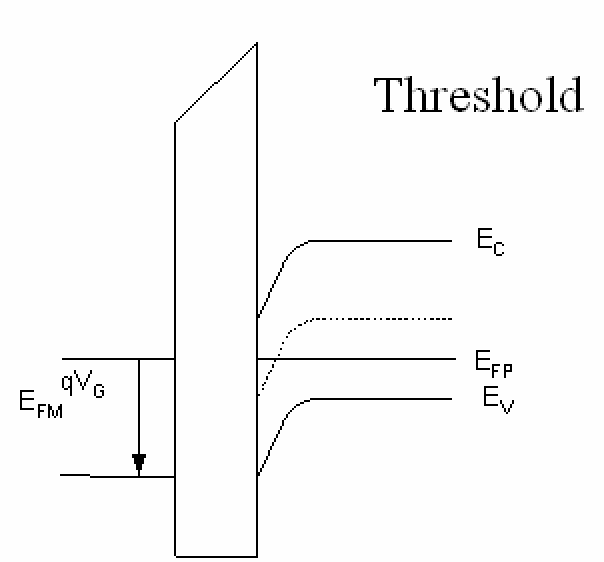
$$\frac{1}{\frac{\varepsilon_{Si02}}{d}} = \frac{-V_T + \phi_{ms} + 2 \cdot \phi_F}{Q_i + Q_D}$$

$$d := \varepsilon_{SiO2} \cdot \left(\frac{-V_T + \phi_{ms} + 2 \cdot \phi_F}{Q_i + Q_D}\right)$$

$d = 6.758 \times 10^{-6}$ This is in cm!

5. Draw the EGB of an MIS Capacitor on a p-type <100> silicon substrate where VG=VT. (Room temperature conditions apply.)

It would be fig six on page 177 with the surface potential pushed down twice the bulk Fermi level.



6. As you remember, the number of grid points affects the time a TCAD simulation has to run, and the accuracy of the simulation. In the case of the MIS diode from question #1, up to what point would you need a fine grid to accurately simulate the MIS diode?

You would need a fine grid up to WMAX plus the width of the inversion region, because at this point the bands stop bending, as can be seen from question six. Fig 6 on page 177

7. The figure below shows the measured CV data of a MIS capacitor on p-type <100> silicon substrate with an aluminum gate (ϕ_{ms}=-.6ev-UTxln(NA/ni)) (The Insulator is Si02.) Extract d, (tox) NA, VT, and fixed oxide charge. (Room temperature conditions apply.) Hint, you do not have to scale the measured data by the area.

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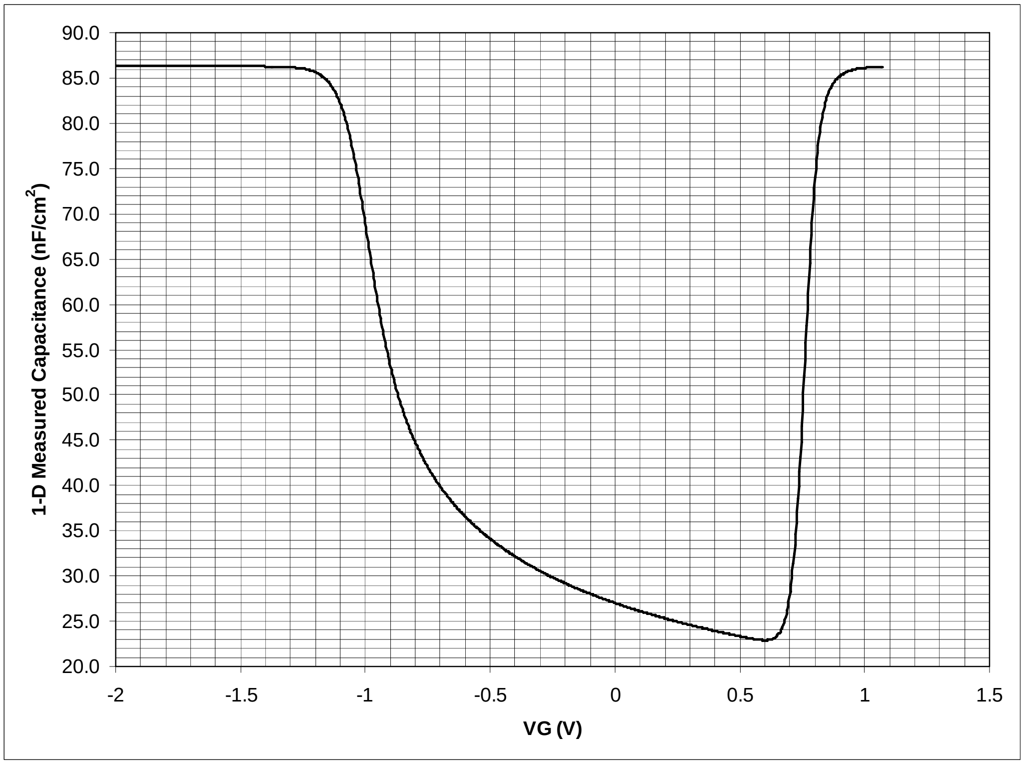


Figure 1: Measured 1-D CV plot of MIS capacitor.

From the Graph

$$C_{g\_max} := 86 \cdot 10^{-9} \frac{F}{cm^2}$$

$$C_{g\_min} := 23 \cdot 10^{-9} \frac{F}{cm^2}$$

$$C_{g\_min} = \frac{C_{si\_min} \cdot C_{g\_max}}{C_{si\_min} + C_{g\_max}}$$

$$C_{si\_min} := \frac{C_{g\_max} \cdot C_{g\_min}}{C_{g\_max} - C_{g\_min}}$$

$$C_{si\_min} = 3.14 \times 10^{-8} \frac{F}{cm^2}$$

$$N_b := 10^{30.388+1.683\cdot\log(C_{si\_min})-0.03177\cdot\log(C_{si\_min})^2}$$

$$N_b = 9.369 \times 10^{15}$$

$$L_D := \sqrt{\frac{\varepsilon_{si}\cdot U_T}{q\cdot N_b}} \qquad L_D = 4.283 \times 10^{-6}$$

$$C_{Debye} := \frac{\varepsilon_{si}\cdot\sqrt{2}}{L_D} \qquad C_{Debye} = 3.506 \times 10^{-7}$$

$$C_{g\_max} := \frac{C_{g\_max}}{\frac{F}{cm^2}}$$

$$C_{FB} := \frac{C_{g\_max}\cdot C_{Debye}}{C_{g\_max} + C_{Debye}} \qquad C_{FB} = 6.906 \times 10^{-8}$$

VFB from the reverse look up of the chart is -1V

$$ni := 9.65 \cdot 10^{10}$$

$$V_{FB} := -1$$

$$Q_D := -2 \cdot \left(\varepsilon_{si} \cdot q \cdot N_b \cdot U_T \cdot \ln\left(\frac{N_b}{ni}\right)\right)^{\frac{1}{2}} \qquad Q_D = -4.352 \times 10^{-8}$$

$$V_T := V_{FB} - \frac{Q_D}{C_{ox}} + 2 \cdot 0.0259 \cdot \ln\left(\frac{N_b}{ni}\right) \qquad V_T = 0.101$$

$$V_{FB} = \phi_{ms} - \frac{Q_i}{C_{g\_max}} \qquad \phi_{ms} := -0.6 - U_T \cdot \ln\left(\frac{N_b}{ni}\right)$$

$$\phi_{ms} = -0.897$$

$$Q_i := \left(-V_{FB} + \phi_{ms}\right) \cdot C_{g\_max} \qquad V_{FB} = -1$$

$$Q_i = 8.822 \times 10^{-9}$$

8. What determines the MOS capacitance in accumulation mode? Does it depend on applied voltage?

MOS capacitance in accumulation mode depends on Oxide thickness and oxide dielectric constant for devices with out tunneling. It does not depend on applied voltage

9. What determines the MOS capacitance in depletion mode? Does it depend on the voltage applied?

MOS capacitance in accumulation mode depends on Oxide thickness and oxide dielectric constant, as well the doping and the dielectric constant of the substrate for devices with out tunneling. It does depend on applied voltage.

10. Draw a picture of the device you are going to simulate in TCAD. Describe what you are going to measure, and extract. Include any relationships you will find or confirm.

NA

11. Down load and run a few sample experiments from the TCAD file for your project. Some TCAD files exist for some projects. Others need to be created. You need to work with me on this.

NA

12. ** Derive the relationship for the temperature dependence of the threshold voltage of a MOS capacitor.

First let's rearrange the metal semiconductor work function:

$$\phi_{ms} = \frac{-E_g}{2} + \phi_p$$

$$\phi_{ms} = \frac{-E_g}{2} - \phi_F$$

$$\phi_F = U_T \cdot \ln\left(\frac{N_A}{n_i}\right)$$

Then let's expand this into the VT equation:

$$V_T = \frac{-E_g}{2} - \phi_F - \frac{Q_i}{C_{ox}} - \frac{-2\cdot\left(\varepsilon_{Si}\cdot q\cdot N_A\cdot\phi_F\right)^{\frac{1}{2}}}{C_{ox}} + 2\cdot\phi_F$$

$$V_T = \frac{-E_g}{2} - \frac{Q_i}{C_{ox}} - \frac{-2\cdot\left(\varepsilon_{Si}\cdot q\cdot N_A\cdot\phi_F\right)^{\frac{1}{2}}}{C_{ox}} + 1\cdot\phi_F$$

Use the chain Rule:

Equation 1:

$$\frac{d}{dT}V_T = \frac{d}{dT}\phi_F\cdot\left(1 + \frac{1}{C_{ox}}\cdot\sqrt{\frac{\varepsilon_{Si}\cdot q\cdot N_A}{\phi_F}}\right)$$

Now we need to find:

$$\frac{d}{dT}\phi_F$$

$$\phi_F = \frac{k \cdot T}{q} \cdot \ln\left(\frac{N_A}{3.16 \cdot 10^{16} \cdot T^{1.5} \cdot e^{\frac{-E_g \cdot q}{2k \cdot T}}}\right)$$

$$\phi_F = \frac{k \cdot T}{q} \cdot \left(\ln\left(\frac{N_A}{3.16 \cdot 10^{16}}\right) - 1.5 \cdot \ln(T) - \ln\left(e^{\frac{-E_g \cdot q}{2k \cdot T}}\right)\right)$$

$$\phi_F = \frac{k \cdot T}{q} \cdot \ln\left(\frac{N_A}{3.16 \cdot 10^{16}}\right) - 1.5 \cdot \frac{k \cdot T}{q} \cdot \ln(T) - \frac{k \cdot T}{q} \cdot \ln\left(e^{\frac{-E_g \cdot q}{2k \cdot T}}\right)$$

$$\frac{d}{dT}\phi_F = \frac{k}{q} \cdot \ln\left(\frac{N_A}{3.16 \cdot 10^{16}}\right) - 1.5 \cdot \frac{k}{T} \cdot \ln(T) - 1.5 \cdot \frac{k \cdot T}{q} \cdot \frac{1}{T} - \frac{k}{q} \cdot \ln\left(e^{\frac{-E_g \cdot q}{2k \cdot T}}\right) - \frac{k \cdot T}{q} \cdot \frac{-E_g \cdot q}{2k \cdot T^2}$$

$$\frac{d}{dT}\phi_F = \frac{k}{q} \cdot \ln\left(\frac{N_A}{3.16 \cdot 10^{16}}\right) - 1.5 \cdot \frac{k}{T} \cdot \ln(T) - 1.5 \cdot \frac{k \cdot T}{q} \cdot \frac{1}{T} - \frac{k}{q} \cdot \ln\left(e^{\frac{-E_g \cdot q}{2k \cdot T}}\right) + \frac{-E_g}{2 \cdot T}$$

$$\frac{d}{dT}\phi_F = \frac{k}{q} \cdot \ln\left(\frac{N_A}{3.16 \cdot 10^{16} \cdot T^{1.5} \cdot e^{\frac{-E_g \cdot q}{k \cdot T}}}\right) - 1.5 \cdot \frac{k}{q} + \frac{E_g}{2 \cdot T}$$

$$\frac{d}{dT}\phi_F = \frac{1}{T}\left(\frac{k \cdot T}{q} \cdot \ln\left(\frac{N_A}{3.16 \cdot 10^{16} \cdot T^{1.5} \cdot e^{\frac{-E_g \cdot q}{k \cdot T}}}\right) - 1.5 \cdot \frac{k \cdot T}{q} + \frac{E_g}{2}\right)$$

$$\frac{d}{dT}\phi_F = \frac{1}{T}\left(\phi_F - 1.5 \cdot \frac{k \cdot T}{q} + \frac{E_g}{2}\right)$$

+

Combine this last result with equation 1:

$$\frac{d}{dT}V_T = \frac{1}{T}\cdot\left(U_T\cdot\ln\left(\frac{N_A}{3.16\cdot10^{16}\cdot T^{1.5}\cdot e^{\frac{-E_g}{2U_T}}}\right) - \frac{E_g}{2} - 1.5\cdot U_T\right)\cdot\left(1 + \frac{1}{C_{ox}}\cdot\sqrt{\frac{q\cdot\varepsilon_{Si}\cdot N_A}{U_T\cdot\ln\left(\frac{N_A}{3.16\cdot10^{16}\cdot T^{1.5}\cdot e^{\frac{-E_g}{2\cdot U_T}}}\right)}}\right)$$

MathCad can calculate a numerical derivative. As can be seen below the analytical VT (T) is the same:

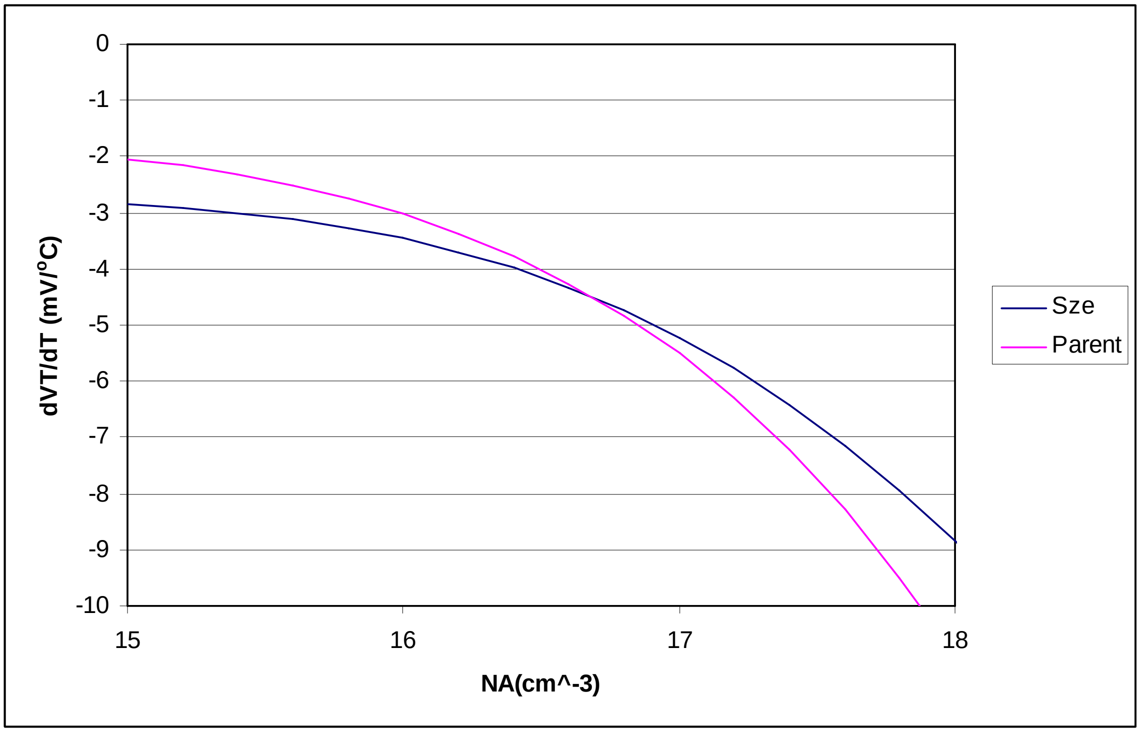
$$\frac{d}{dT}\left[\frac{-E_g}{2} - \frac{Q_i}{C_{ox}} - \frac{-2\cdot\left[\varepsilon_{Si}\cdot q\cdot N_A\cdot\left(k\cdot\frac{T}{q}\cdot\ln\left(\frac{N_A}{3.16\cdot10^{16}\cdot T^{1.5}\cdot e^{\frac{-E_g\cdot q}{2\cdot k\cdot T}}}\right)\right)\right]^{\frac{1}{2}}}{C_{ox}} + 1\cdot\left(k\cdot\frac{T}{q}\cdot\ln\left(\frac{N_A}{3.16\cdot10^{16}\cdot T^{1.5}\cdot e^{\frac{-E_g\cdot q}{2\cdot k\cdot T}}}\right)\right)\right] = -1.401\times10^{-3}$$

$$\frac{1}{T}\cdot\left(k\cdot\frac{T}{q}\cdot\ln\left(\frac{N_A}{3.16\cdot10^{16}\cdot T^{1.5}\cdot e^{\frac{-E_g\cdot q}{2\cdot k\cdot T}}}\right) - \frac{E_g}{2} - 1.5\cdot U_T\right)\cdot\left(1 + \frac{1}{C_{ox}}\cdot\sqrt{\frac{q\cdot\varepsilon_{Si}\cdot N_A}{k\cdot\frac{T}{q}\cdot\ln\left(\frac{N_A}{3.16\cdot10^{16}\cdot T^{1.5}\cdot e^{\frac{-E_g\cdot q}{2\cdot k\cdot T}}}\right)}}\right) = -1.401\times10^{-3}$$

Note: This is on page 319 of “Big Sze” with the following simplification:

$$\frac{d}{dT}V_T = \frac{1}{T}\cdot\left(U_T\cdot\ln\left(\frac{N_A}{3.16\cdot10^{16}\cdot T^{1.5}\cdot e^{\frac{-E_g}{2U_T}}}\right) - \frac{E_g}{2}\right)\cdot\left(2 + \frac{1}{C_{ox}}\cdot\sqrt{\frac{q\cdot\varepsilon_{Si}\cdot N_A}{U_T\cdot\ln\left(\frac{N_A}{3.16\cdot10^{16}\cdot T^{1.5}\cdot e^{\frac{-E_g}{2\cdot U_T}}}\right)}}\right)$$

If we plot the two equations we get:



Given the at most it is 1mV per degree C of error the simplification seems fine.