Question 1 [25 marks]:

a) Using Athena approximate the thickness of a SiO$_2$ layer grown using a wet process for 2 hours at 1000°C? The wafer should be 111-terminated, boron-doped silicon, with a resistivity of 10 Ωcm. Please include code and an image from TonyPlot in your answer. [5 marks]

This is just a case of following the steps described in Lecture 17 and 18. Your code will hopefully look something like this:

```go
# Define the mesh
line x loc=0 spac=50
line x loc=100 spac=3
line x loc=200 spac=3
line x loc=250 spac=3

line y loc=0 spac=0.025
line y loc=2.5 spac=0.0625
line y loc=6.75 spac=0.0625
line y loc=10 spac=1.875

# Define substrate (resistivity is in Ohm cm)
init silicon boron resistivity=10 orientation=111

# Thermally grow the oxide
diffus time=120 minutes temp=1000 weto2 press=1

# Save and plot the data
structure outf=SA1_la.str
tonyplot SA1_la.str
```

The output in TonyPlot should look something like the below. We are not interested in doping concentration for this question, just the oxide thickness, so you can turn it off in the options if you think it would make the images clearer.

Recall that the original surface of the wafer was defined at $x = 0$, and the oxidation process will make the whole wafer slightly thicker (you can think of it like a sponge absorbing water). From the image on the right we can approximate the oxide thickness as:

$$x_{ox} = 0.325 - (−0.4)$$
Any reasonable approach will be accepted.

b) Use Athina to determine a set of steps one can take to generate a vertical \textit{npn}-structure from an intrinsic (undoped) wafer. I.e. generate a wafer that is n-doped at the surface of the wafer, p-doped below that, and n-doped below that. You just need to generate the vertical doping profile; you do not need to worry about making electrical contact etc. Note: there will be some overlap between n- and p-regions, you just need to make sure each region has the expected majority carrier. The thickness of the respective layers does not matter as long as they are distinct. Please include code and an image from TonyPlot in your answer. [10 marks]

There are a number of ways of doing this, and much of this will be via trial-and-error. In the below example I have not annealed with wafer at all; I have simply used 3 different ion-implantation commands. Phosphorus is a n-type dopant and boron is a p-type dopant, so these are the elements used in this example. An alternative would be to use a doped wafer initially.

\texttt{go athena}

\begin{verbatim}
#Define the mesh
line x loc=0 spac=50
line x loc=100 spac=3
line x loc=200 spac=3
line x loc=250 spac=3

line y loc=0 spac=0.005
line y loc=2.5 spac=0.005
line y loc=6.75 spac=0.005
line y loc=10 spac=0.05

#Define substrate (resistivity is in Ohm cm)
init silicon resistivity=10 orientation=111

#n-dope the surface with low energy
implant phosphorus dose=1.0e14 energy=50 tilt=0 rotation=0 crystal

#p-dope below that with higher energy
implant boron dose=1.0e14 energy=150 tilt=0 rotation=0 crystal

#n-dope even deeper
implant phosphorus dose=1.0e14 energy=500 tilt=0 rotation=0 crystal

#Save and plot the data
structure outf= SA1_1b.str
tonyplot SA1_1b.str
\end{verbatim}

This code should give rise to the following doping profile:
Any solution that gives rise to distinct n-type regions and p-type regions in the correct order will be accepted.

c) We wish to dope a region of a wafer with phosphorus. Use Athena to simulate local doping of a 10 μm wide region in the center of a wafer. The doping concentration is not important, but there should be no residual oxide / masking material left on the wafer. A small amount of unintentional doping is acceptable in adjacent regions. Please include code and an image from TonyPlot showing concentration as a function of position in your answer [10 marks]

Again, there are a number of different ways one can achieve this. However the way we approach it, we do need to define a mask. In the below example a thick oxide is grown globally, before it is etched in the center of the wafer. We here use ion implantation to dope the wafer, but diffusion could equivalently be used. Because the peak in dopant concentration is quite deep with ion implantation, we have to ensure that oxide is thick enough to adequately mask the wafer.

```
go athena

#Define the Mesh
line x loc=0 spac=50
line x loc=100 spac=3
line x loc=200 spac=3
line x loc=250 spac=5

line y loc=0 spac=0.025
line y loc=2.5 spac=0.0625
line y loc=6.75 spac=0.0625
line y loc=10 spac=1.875

#Define substrate (resistivity is in Ohm cm)
init silicon boron resistivity=10 orientation=111

#Thermally grow the oxide
diffus time=600 minutes temp=1100 dryo2 press=1

#Etch oxide to leave mask for wells
etch oxide start x=120.00 y=-0.50
etch cont x=120.00 y=0.50
etch cont x=130.00 y=0.50
etch done x=130.00 y=-0.50

#Use ion implantation to dope the wafer
```
implant phosphorus dose=1.0e14 energy=150 tilt=0 rotation=0 crystal

#Remove all of the oxide
etch oxide all

#Save and plot the data
structure outf= SA1lc.str
tonyplot SA1lc.str
quit

This should produce an output like the following: