ELEC 5509 Fall 2013   Integrated Circuit Technology

Prof. N. Garry Tarr

Project “3-Week CMOS Process Flow”

Stage 2

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Overview

The project consists on the design of a process flow for building a CMOS using Silicon-on-Insulator with five photolithography steps and one ion implant.

The Second Stage of the project consists of the steps specification of the design process flow required for the SOI CMOS fabrication.

A Silicon-on-Insulator type wafer will be used, where the buried oxide thickness is 1µm and the p-type lightly doped Si film thickness is 240nm. The p-type doped silicon of the wafer has a resistivity of 10Ωcm. The Si film has a <100> crystal orientation.

Hand calculations like junction depth, dose and doping concentrations will mark a starting point, and TSuprem4 software will be used to simulate most of the process steps using the calculated values.

Cross-sections, threshold voltage graphs, doping concentration plots, and the thermal budget will be provided by TSuprem4.

Requirements for the CMOS design

The technology employed will be **Silicon-on-Insulator**.

The thickness of the **Gate Oxide** must be no less 25 nm. The thickness of the **Si film** must be no less than 100 nm. The values calculated on the Stage 1 of the project can be used instead of these references.

The Si film must have a **p-type** doping concentration of approximately $4\text{x}10^{16}$ atoms/cm^3 using Boron ion implantation, which is prior the formation of Source and Drain of NMOS and PMOS. With this, the gate-channels of NMOS and PMOS will be p-type doped.

The **threshold voltage** for the CMOS must be: $V_{TN} = -V_{TP}$.

The process flow must be completed with no more than **5 Photolithography-Exposure (PE) steps**.

The n+ doped **Source and Drain** of NMOS, and p+ doped Source and Drain of PMOS, must have a surface concentration close to solid solubility at 1000°C, and a **sheet resistance** less than 100Ω/□. The n+ and p+ regions must extend completely through the Si film.

Aluminum will be used for metallization of contacts.

Procedure

Calculation of NMOS and PMOS threshold voltages

Knowing that the silicon of the wafer has a resistivity of $\rho = 10\Omega\text{cm}$, we can calculate the acceptor-carrier concentration using the formula:

$$\rho = \frac{1}{q\,(\mu_p p + \mu_n n)}$$

Since there is only Boron available (*p* concentration), the *n* (donor) concentration is zero:

$$\rho = \frac{1}{q\,\mu_p p} \quad \rightarrow \quad p = N_A = \frac{1}{q\,\mu_p \rho} = \frac{1}{(1.6x10^{-19} A \cdot s)(\,\mu_p\,)(10\Omega\text{cm})}$$

Hole mobility μ_p	Doping concentration N_A
450 cm^2 /(V s)	$1.389x10^{15}$ atoms/cm^3
470 cm^2 /(V s)	$1.329x10^{15}$ atoms/cm^3

Table 1. μ_p value from two sources, and the corresponding N_A for a resistivity of 10Ωcm.

Normally, the PMOS has an n-type well, and p+ doped Source and Drain. For this project, the PMOS well will be p-type doped.

TSuprem4 calculation

For this step onward, we will use the Gate Oxide thickness and Si film thickness values calculated on Stage 1 of the project: t_{OX}=25nm and t_{Si}=150nm.

TSuprem4 cannot compute the threshold voltage for the PMOS while the PMOS has a p-type well. So, the way to compute the threshold voltages for NMOS and PMOS, where $V_{TN} = -\,V_{TP}$ is the following:

On the input file for the V_{TP}:

- Set the initial Si substrate layer to be lightly doped with a concentration of $1.3889x10^{15}$atoms/cm^3.
- Deposit the Bulk oxide layer of 1μm of thickness.
- Deposit a Phosphorus layer with t_{Si}=150nm, lightly doped around $1x10^{11}$ atoms/cm^3.
- Deposit the gate oxide, with a thickness t_{OX}= 25nm.
- Add 100nm polysilicon gate layer with a n+ doping concentration of $3x10^{20}$ atoms/cm^3.

Run TSuprem4 and calculate the threshold voltage V_{TP} for the PMOS: V_{TP} = -0.874 V

On the input file for the V_{TN}:

- Set the initial Si substrate layer to be lightly doped with a concentration of 1.3889×10^{15} atoms/cm^3.
- Deposit the Bulk oxide layer of 1µm of thickness.
- Deposit a Boron layer with t_{Si}=150nm, with a concentration of 1.3889×10^{15} atoms/cm^3.
- Deposit the gate oxide, with a thickness t_{OX}= 25nm.
- Add 100nm polysilicon gate layer with an n+ doping concentration of 3×10^{20} atoms/cm^3.

Run TSuprem4 and calculate the threshold voltage V_{TN} for the NMOS: V_{TN} = -0.188 V

Threshold Voltage Calculation

Calculate the difference between V_{TN} and V_{TP} as V_{diff}: $V_{diff} = |V_{TN} - V_{TP}|$

Setting the V_{TN} equal to half of the magnitude of V_{diff}, we have: $V_{TN} = \frac{V_{diff}}{2} = -V_{TP}$

Hole mobility	V_{diff}	$V_{diff}/2$
$\mu_p = 450\ \mathrm{cm^2/\ (V\ s)}$	0.686 V	0.343 V
$\mu_p = 470\ \mathrm{cm^2/\ (V\ s)}$	0.685 V	0.342 V

Table 2. Threshold voltage calculation using different values of hole mobility.

We will select **V_{TN} = 0.343V**, and **V_{TP} = -0.343V**.

Si film dose Q calculation for threshold voltage adjustment using Ion Implantation

Next, we need to find the **dose Q** for *Boron Ion Implantation* on the Si film layer so that the NMOS can have a threshold voltage of 0.343V.

$$\Delta V_T = \frac{qN_A t_{Si}}{C_{ox}} \quad \rightarrow \quad N_A \cdot t_{Si} = Q = \frac{\Delta V_T \cdot C_{ox}}{q}$$

$$\Delta V_T = V_{final} - V_{init} = 0.343V - (-0.188V) = 0.531V$$

$$C_{ox} = \frac{\epsilon_{ox}}{t_{ox}} = \frac{(3.9)(8.854 \times 10^{-14}\ F/cm)}{2.5 \times 10^{-6} cm} = 1.38122 \times 10^{-7}\ F/cm^2$$

$$Q = \frac{\Delta V_T \cdot C_{ox}}{q} = 4.57769 \times 10^{11}\ \mathrm{atoms/cm^2}$$

It is also possible to have the hole concentration calculated:

$$N_A = \frac{Q}{t_{Si}} = 4.57769 \times 10^{16}\ \mathrm{atoms/cm^3}$$

TSuprem4 NMOS Threshold Voltage and dose Q calculation

Ion Implantation is used for adjusting the threshold voltage of a transistor. Adding Boron gives a positive shift. Adding Phosphorus gives a negative voltage shift. Using TSuprem4, adjust the Boron ion implant dose so that the NMOS can have a threshold voltage equal to 0.343V. **Table 3** shows the computed V_{TN}'s with their respective dose, using energy implantation of 21KeV and a temperature of 1000°C.

Boron dose Q	NMOS V_{TN}
4.577769×10^{11} atoms/cm^2	0.156V
7.25×10^{11} atoms/cm^2	0.343V

Table 3. Threshold voltage calculation using hand calculated Q and TSuprem4 computed Q.

The Boron dose for threshold voltage adjustment using ion implantation will be **Q = 7.25 x10^{11} atoms/cm^2.**

See Figure A.1 for the NMOS threshold voltage plot.

Doping Profiles and Sheet Resistance of the Source and Drain regions of the CMOS

Part of the requirement of the project is that the n+ and p+ doped regions (Source and Drain) must each have a sheet resistance less than 100Ω/□. Another requirement is to make the Source/Drain regions extend completely through the Si film, while trying to have the least lateral diffusion as possible.

Sheet Resistance

The sheet resistance depends on the doping(s) available on a region. We can calculate the sheet resistance using the following formulas, but TSuprem4 can give more accurate results.

To calculate the sheet resistance, simply calculate the resistivity of the source and drain regions. Then find the sheet resistance with a thickness of 150nm.

$$\rho = \frac{1}{q\,(\mu_p p + \mu_n n)} \qquad R_{\square} = \frac{\rho}{t_{Si}}$$

With Q=7.25 x10^{11} atoms/cm^2 and t_{Si}=150nm, we have $N_A = p = \frac{Q}{t_{Si}} = 4.833 \times 10^{16}\ \text{atoms/cm}^3$

With $\mu_p = 450\ \text{cm}^2/\ (\text{V s}),\ \mu_n = 1500\ \text{cm}^2/\ (\text{V s}), p = 4.833 \times 10^{16}\ \text{atoms/cm}^3$,

$n = 3 \times 10^{20}\ \text{atoms/cm}^3$, and $q = 1.60218 \times 10^{-19}\ C$

$$\rho = 1.3869 \times 10^{-5}\ \Omega\text{cm} \qquad R_{\square} = \frac{\rho}{t_{Si}} = 0.9246\ \Omega/\square$$

Tsuprem4 CMOS Sheet resistance calculation

TSuprem4 can calculate the sheet resistance of a doped silicon layer using the proper commands. The sheet resistance will be calculated after all the design steps are done within the input files.

The NMOS Source and Drain have a sheet resistance of 110 Ω/□. (**See "nplus.inp output" on Appendix**)

The PMOS Source and Drain have a sheet resistance of 87 Ω/□. (**See "pplus.inp output" on Appendix**)

Doping profile plots

For the doping profile of predeposition, ion implant and annealing, the simplest type is a Gaussian shape profile. There are several types of profiles more sophisticated and precise. An example of an ion implant profile is shown in **Figure 1**.

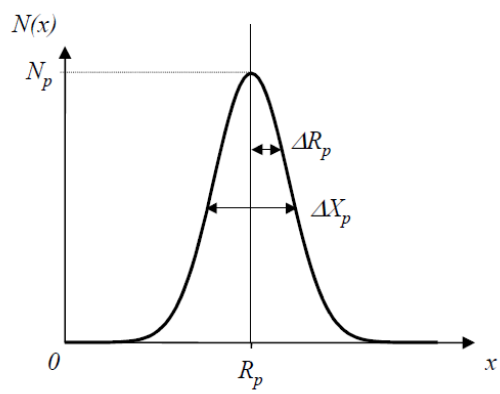


Figure 1. Gaussian distribution for the concentration profile of implanted ions. (Source: Technology of Quantum Devices, M. Razeghi). [4]

Predeposition

The NMOS source and drain regions are formed by doping the p-type Si film areas with Phosphorus using the **Predeposition** technique. Dopant in form of gas is supplied constantly and it diffuses into the silicon under **high temperature** during certain **amount of time**. There will be a limit on how much doping can dissolve at a given constant temperature. This is called solid solubility.

The **solid solubility** is the maximum concentration of doping that dissolves (moves through) in the silicon at a given temperature.

Solid Solubility	At 950°C	At 1000°C
Phosphorus	7.8×10^{20} atoms/cm^3	1.0×10^{21} atoms/cm^3
Boron	3.9×10^{20} atoms/cm^3	4.1×10^{20} atoms/cm^3

Table 4 . Solid Solubilty of Phosphorus and Boron at 950°C and 1000°C.

If the concentration supplied by a source is greater than the limit concentration related to a specific temperature, the “exceeding” doping that goes in the Silicon film will not dissolve or it will cluster with other atoms of the same element and will precipitate into a solid state.

A Gaussian profile under an Infinite medium is used to represent the predeposition doping. It is possible to calculate the junction depth too. Here are the equations:

Doping concentration at x distance after predeposition	$C_{(x,t)} = C_S\ [1 - \mathrm{erf}^{\left(\frac{x_j}{2\sqrt{Dt}}\right)}]$
Doping concentration at the surface	$C_S = \frac{Q\sqrt{\pi}}{2\sqrt{Dt}}$
Error function	$\mathrm{erf}(z) = \frac{2}{\pi}\int_0^z e^{-x} dx$
Junction depth	$x_j = z * 2\sqrt{Dt}$
Diffusivity	$D = D^o\ e^{(-\frac{E_A}{kT})}$

Table 5. Equations corresponding to the dopant predeposition.

For **Phosphorus**, the **diffusivity constant** is $D^o = 4.7\ cm^2 s^{-1}$, and the **activation energy** is $E_A = 3.68\ eV$.

Part of the process flow is that CMOS will go through a predeposition doping process. This not only will dope the source and drain of the NMOS, but also the gates and the source and drain of the PMOS too. The now n+ type source and drain of the PMOS will be doped again on a later step with Boron so they can be turned into p+type silicon.

For our purposes, the predeposition will take place for a period of time of 20 minutes, at a temperature of 1000°C, supplying a doping concentration of $C_S = 1 \times 10^{20} \mathrm{atoms/cm^3}$.

See Figure A.2 for the NMOS Doping Concentration plot after threshold voltage adjustment.

Ion Implantation

The Source and Drain of the PMOS will require a Boron Ion Implantation in order to make them p+ type doped silicon after they have been blank-doped with Phosphorus. **Table 5** shows the equations for calculating the doping concentration after an Ion Implantation. This does not take into account the doping already present in the Si film.

Doping concentration at distance x after Ion Implantation	$C_{(x)} = C_p\, e^{\left(-\frac{(x-R_p)^2}{2\,\Delta R_p{}^2}\right)}$
Peak doping concentration	$C_p = \dfrac{Q}{\sqrt{2\pi}\,\Delta R_p}$

Table 6. Equations corresponding to the dopant Ion Implantation.

Reviewing ion implantation tables, taking a Boron **ion implant energy** of **10 KeV**, the projected range is $\boldsymbol{R_p}$ **= 0.0333 µm** and the standard deviation is $\Delta\boldsymbol{R_p}$ **= 0.0171 µm**. The dose Q is calculated by multiplying the desired hole concentration N_A with the Si film thickness (or the junction depth).

Diffusion profile

The following formula we can calculate the final doping concentration, added from the ion implantation, on the Si film:

Doping concentration at distance x after diffusion	$C_{(x,t)} = C_o\, e^{\left(-\frac{x^2}{4Dt}\right)}$
Peak doping concentration	$C_o = \dfrac{Q}{2\sqrt{\pi D t}}$

Table 7. Equations corresponding to the diffusion or annealing of the dopant.

For Boron, the **diffusivity constant** is $D^o = 1.0\ cm^2 s^{-1}$ and the **activation energy** is $E_A = 3.5\ eV$.

Ion Implant + Anneal

There is a formula that combines both processes: $C_{(x,t)} = \dfrac{Q}{\sqrt{2\pi(\Delta R_p{}^2+2Dt)}}\ e^{\left(-\frac{(x-R_p)^2}{2\,\Delta R_p{}^2}\right)}$

With the following values we can calculate the doping concentration as a function of position and time of diffusion, $C_{(x,t)}$:

R_p = 0.0333 µm, ΔR_p = 0.0171 µm, $D^o = 1.0 \text{ cm}^2\text{s}^{-1}$, $E_A = 3.5 \text{ eV}$, and $Q = 7.25 \times 10^{11} \text{atoms/cm}^2$

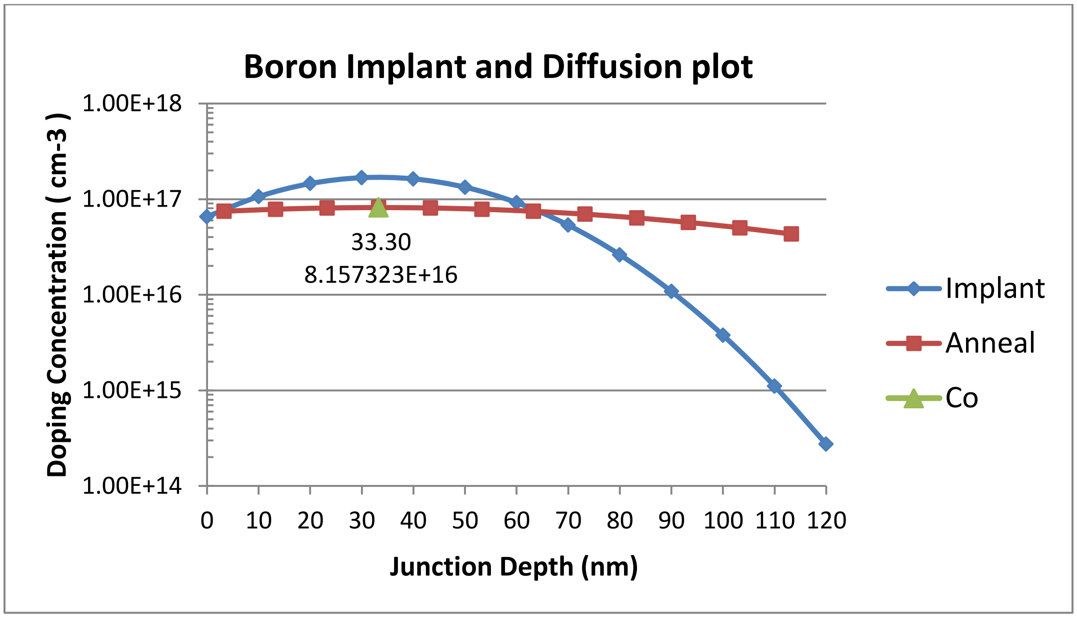


Figure 2. Plotting of doping concentration before anneal and after anneal.

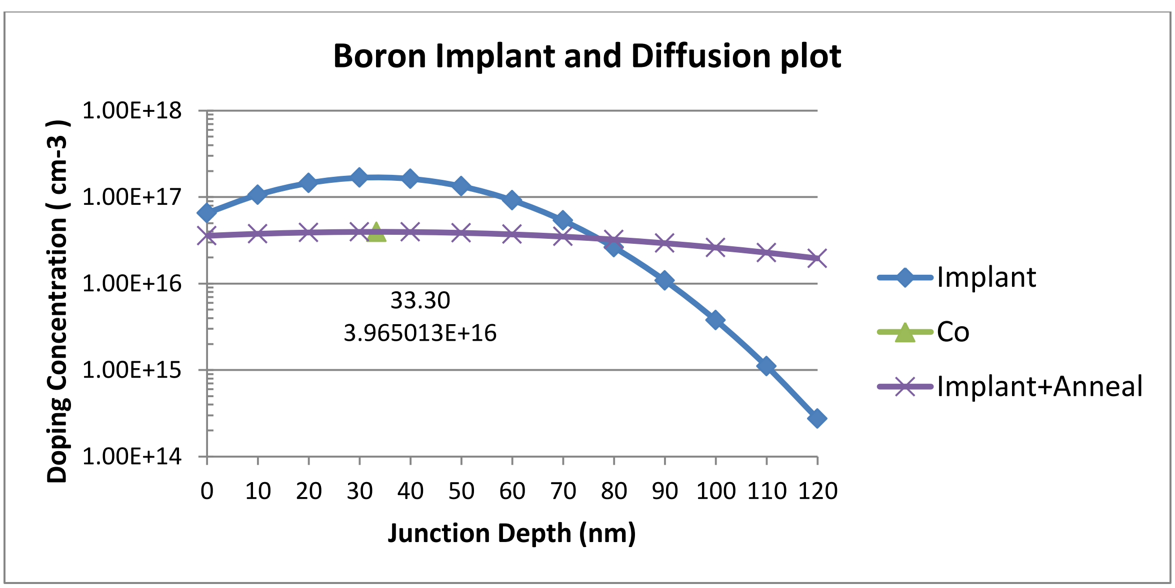


Figure 3. Plotting of doping concentration with the combined equation.

These plots are used as a reference. TSuprem4 computes and generates plots that are more accurate than what we can do by hand.

See Figure A.3 for the NMOS Source and Drain doping concentration plot after the predeposition.

See Figure A.4 for the PMOS Source and Drain doping concentration plot after the predeposition and ion implantation.

Lateral Diffusion

When there is a diffusion process of impurities, if a mask is employed for protecting a desired area, the impurities will diffuse downward on the unmasked area and sideways (i.e. laterally) at the edge of the mask window. [1]

TSuprem4 can compute the lateral diffusion plot of dopants, drawing contours for mapping different doping concentrations of a same element in a cross-section 2D plot.

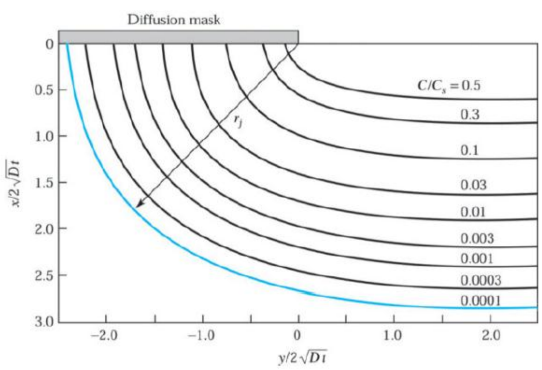


Figure 4. Diffusion contours at the edge of an oxide mask window.
(Source: Semiconductor Devices, Physics and Technology 3rd Ed, S.M.SZE). [5]

It has been determined that the lateral penetration is about 70%-80% of the vertical penetration for concentration three to more orders of magnitude below the surface concentration, depending on the type of diffusion process. This produces rounded junction interfaces, which makes breakdown voltages be lower due to the high electric-field activity on those areas. [5]

See Figures A.5 to A.7 for the NMOS and PMOS lateral diffusion plots, with contours of doping concentration plot at the end of the process.

Thermal Budget

Since there are often multiple diffusion steps in a semiconductor fabrication process, the sum of these individual diffusion steps is what is called the **thermal budget** or effective Dt product. [1]

If the diffusion steps occurred at a constant temperature where the diffusivity is the same, but at different rates, then the thermal budget is given by:

$$(Dt)_{eff} = D_1 t_1 + D_1 t_2 + D_1 t_3 \ldots$$

Because the diffusion coefficient D varies exponentially with T, the highest temperature steps in the process generally dominate the thermal budget. Some of the steps in the process may be negligible in determining the overall amount of diffusion.

For this project, here is the list of the steps that involve a significant Dt product:

Process Step	Temp. in °K	Duration t in seconds	Diffusivity D in cm^2/s	Dt product in cm^2
Anneal Boron Si film	1273.15	2400	1.396877E-14	3.352506E-11
Predep. Phosp CMOS	1273.15	1200	1.272686E-14	1.527224E-11
Anneal Boron PMOS	1273.15	1200	1.396877E-14	3.352506E-11

The thermal budget for the CMOS fabrication process is: $(Dt)_{eff} = 8.23134 \times 10^{-11}\ cm^2$

Note: the thermal budget doesn't include the oxide growth, since there was no need of "growing" the oxide during the TSuprem4 simulations.

Conclusion

Process flow key step

Normally for doping the NMOS and PMOS, each will require its own mask to prevent unwanted impurities on the sensitive areas while a doping process is in progress. The secret for the 5 PE steps is located on the PMOS Source and Drain doping. Phosphorus has a higher solid solubility than Boron at the same temperature, which means Phosphorus diffuses faster than Boron. Also, a layer will be n-type or p-type depending on which is carrier has the highest concentration at the same layer.

Removing the PE step that will normally protect the PMOS from the Phosphorus doping of the NMOS predeposition, essentially the PMOS will be doped with the same dopant given to the NMOS. But, it is possible to fix the PMOS so that the Source and Drain can be turned to p-type by using a Boron Ion Implantation, with a dose so that there are more hole carriers on the PMOS Source and Drain than electron carriers due to the Phosphorus. Finally, when they annealing process is been employed, boron will move slower than the Phosphorus, helping the Source and Drain to turn faster into p-type silicon.

By doing this, it is possible to reduce from 6 PE steps up to 5 PE steps.

References

1. James D. Plummer, “Silicon VLSI Technology: Fundamentals, Practice and Modeling”, Prentice Hall,2000.
2. Wiley-IEEE Press , “Complete Guide to Semiconductor Devices (Appendix)“, Source: http://ieeexplore.ieee.org/xpl/articleDetails.jsp?tp=&arnumber=5487785&queryText%3DRange+and+standard+deviation+ion+implantation
3. Ben G. Streetman, “Solid State Electronic Devices, 6th Edition”, Prentice Hall, 2006.
4. M. Razeghi, “Technology of Quantum Devices”, Springer, 2010.
5. Ed, S.M.SZE, “Semiconductor Devices, Physics and Technology 3rd Ed.”, John Wiley & Sons Inc.
6. ECE Illinois, “GT10 · Silicon Diffusivity Data”. Source: http://fabweb.ece.uiuc.edu/gt/gt/gt10.aspx

Appendix

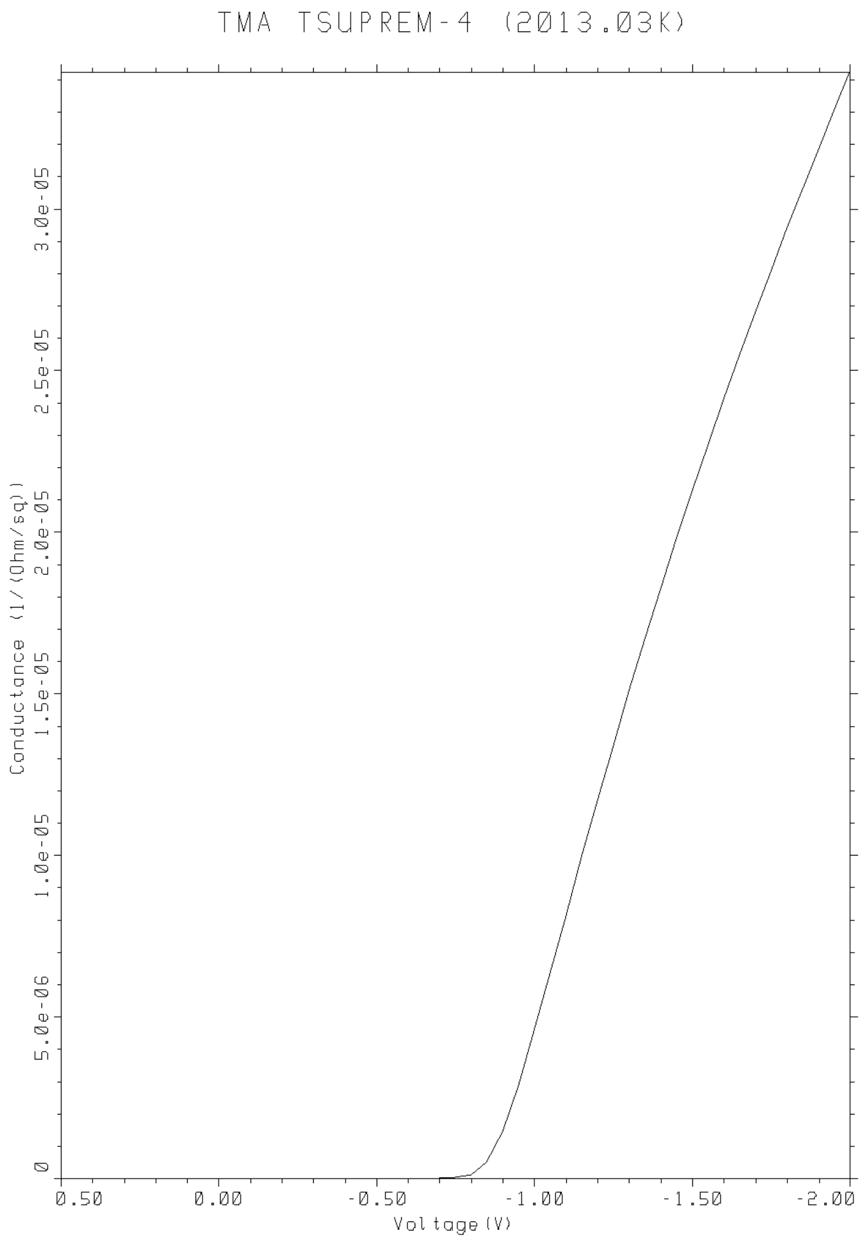


Figure A.1 **NMOS Threshold Voltage plot after the Ion Implantation for threshold voltage adjustment.**

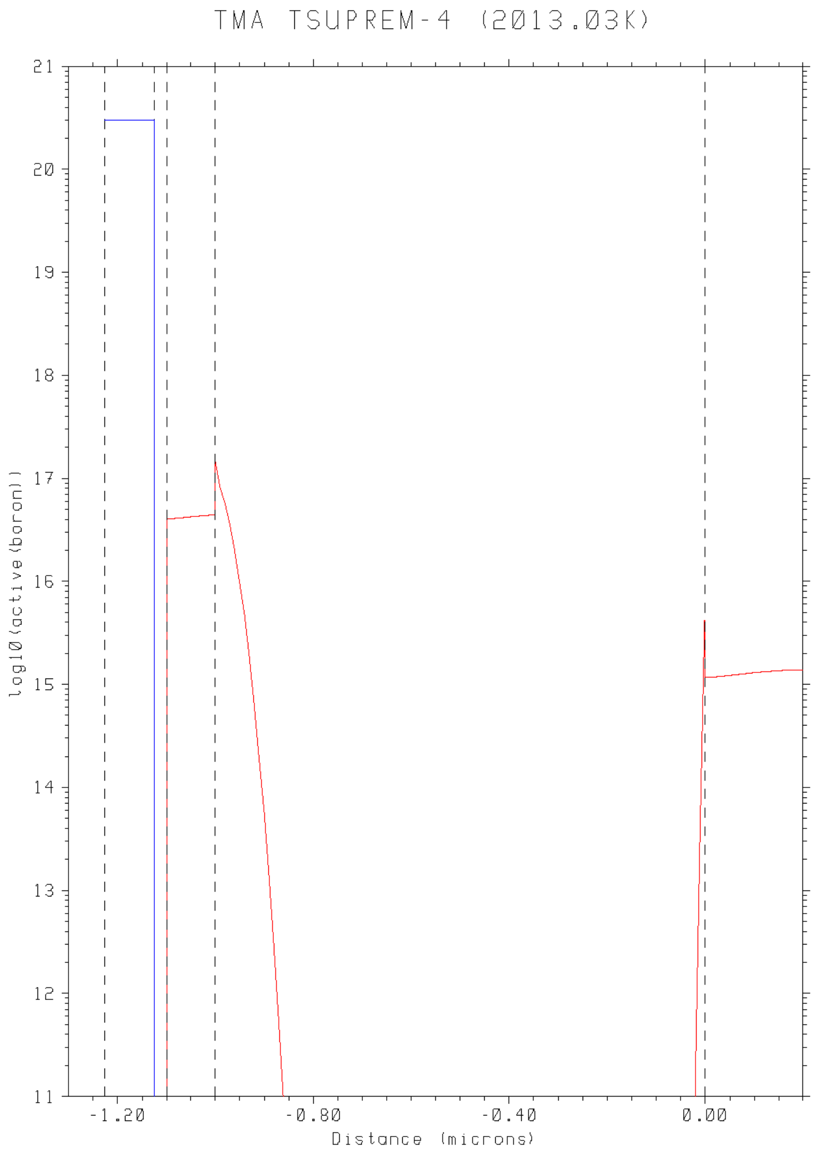


Figure A.2 Doping concentration plot of NMOS after Threshold Voltage adjustment. Blue line represents Phosphorus concentration, and red line represents Boron concentration.

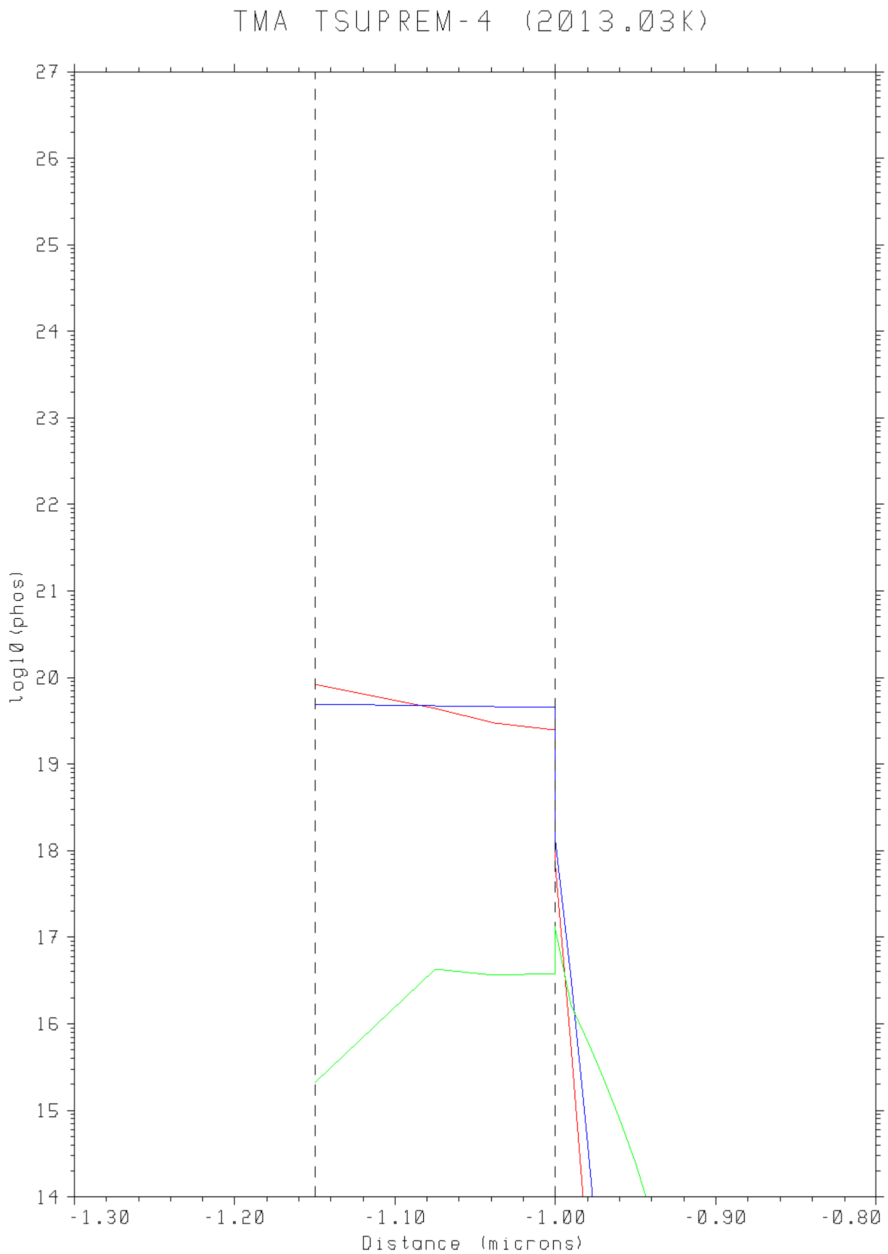


Figure A.3 Doping concentration of Source and Drain of NMOS after Phosphorus predeposition. Red color represents Phosphorus concentration distribution. Blue color represents electrically active Phosphorus concentration. Green color represents electrically active Boron concentration.

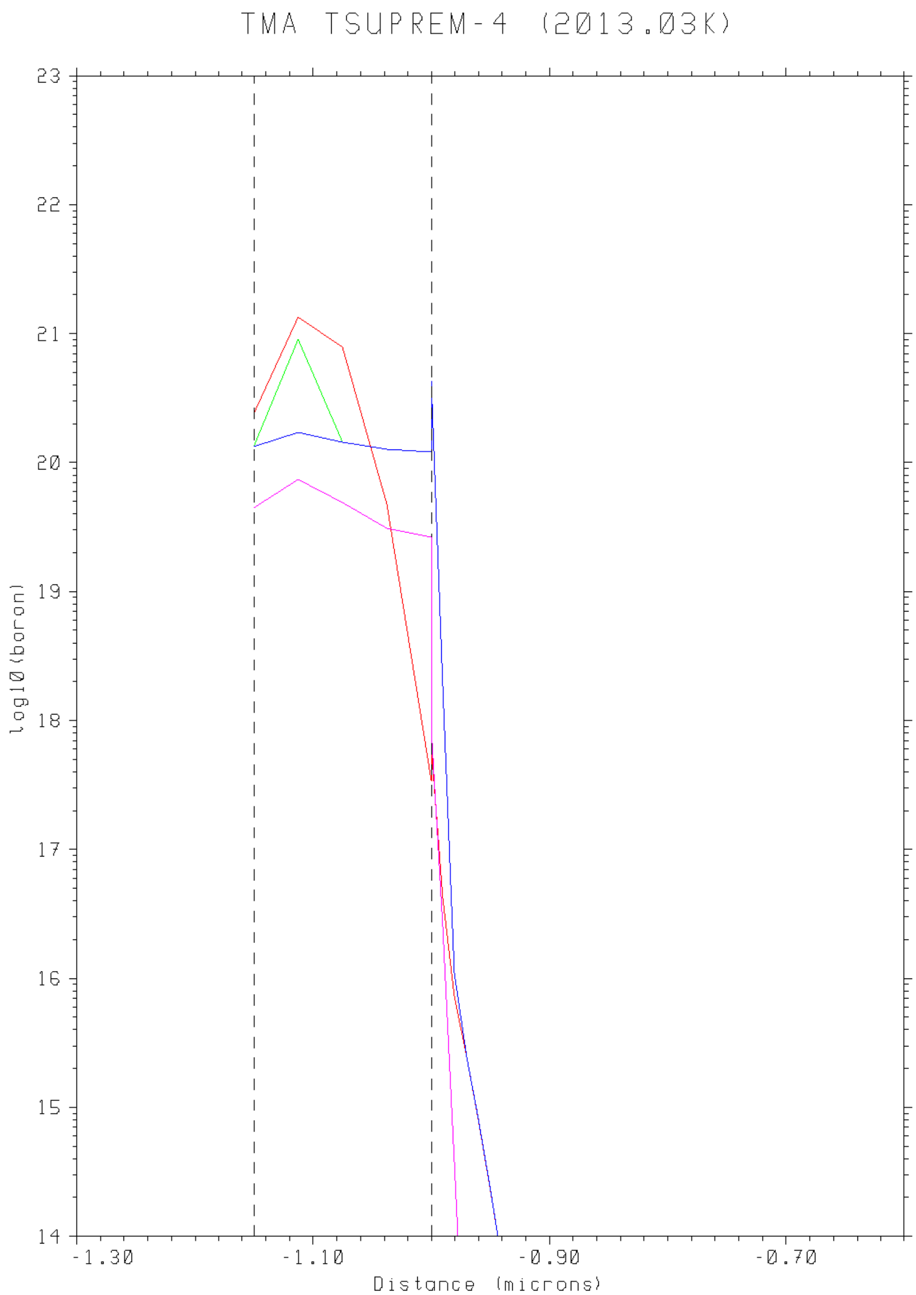
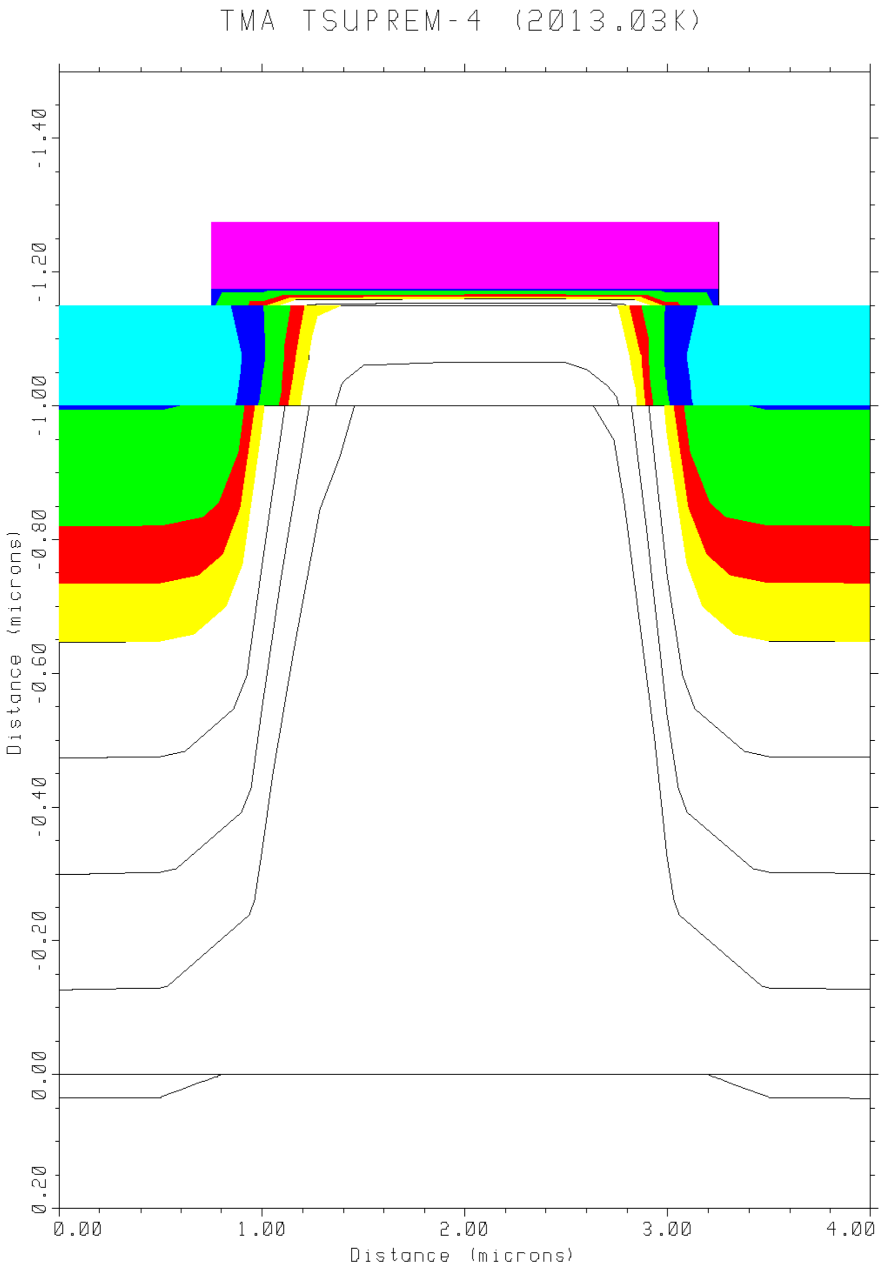


Figure A.4 Doping concentration of Source and Drain of PMOS after Phosphorus predeposition and Ion Implantation. Red color represents Phosphorus concentration distribution. Blue color represents electrically active Phosphorus concentration. Green color represents electrically active Boron concentration.

For the following lateral diffusion plots, the legend below provides the description of each color and the associated doping concentration.



Color	Range of doping concentration (atoms/cm^3)
Yellow	$1x10^{16}$ to $5x10^{16}$
Red	$5x10^{16}$ to $1x10^{17}$
Green	$1x10^{17}$ to $5x10^{18}$
Blue	$1x10^{18}$ to $5x10^{19}$
Cyan	$1x10^{19}$ to $5x10^{20}$
Magenta	$1x10^{20}$ to $1x10^{21}$

Figure A.5 Cross-section plot of NMOS representing lateral diffusion. The colors represent different Phosphorus doping concentrations.

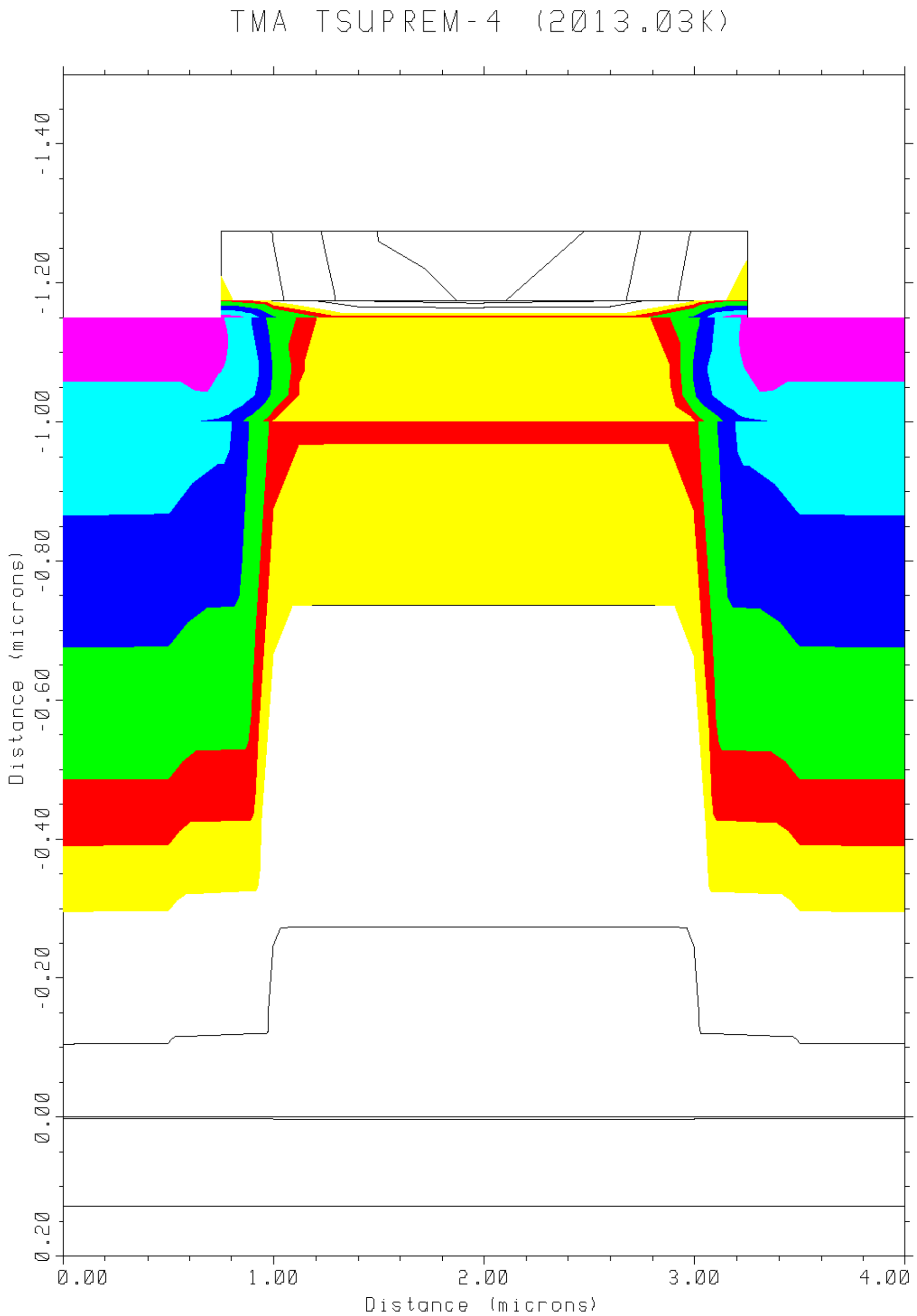


Figure A.6 Cross-section plot of PMOS representing lateral diffusion. The colors represent different Boron doping concentrations.

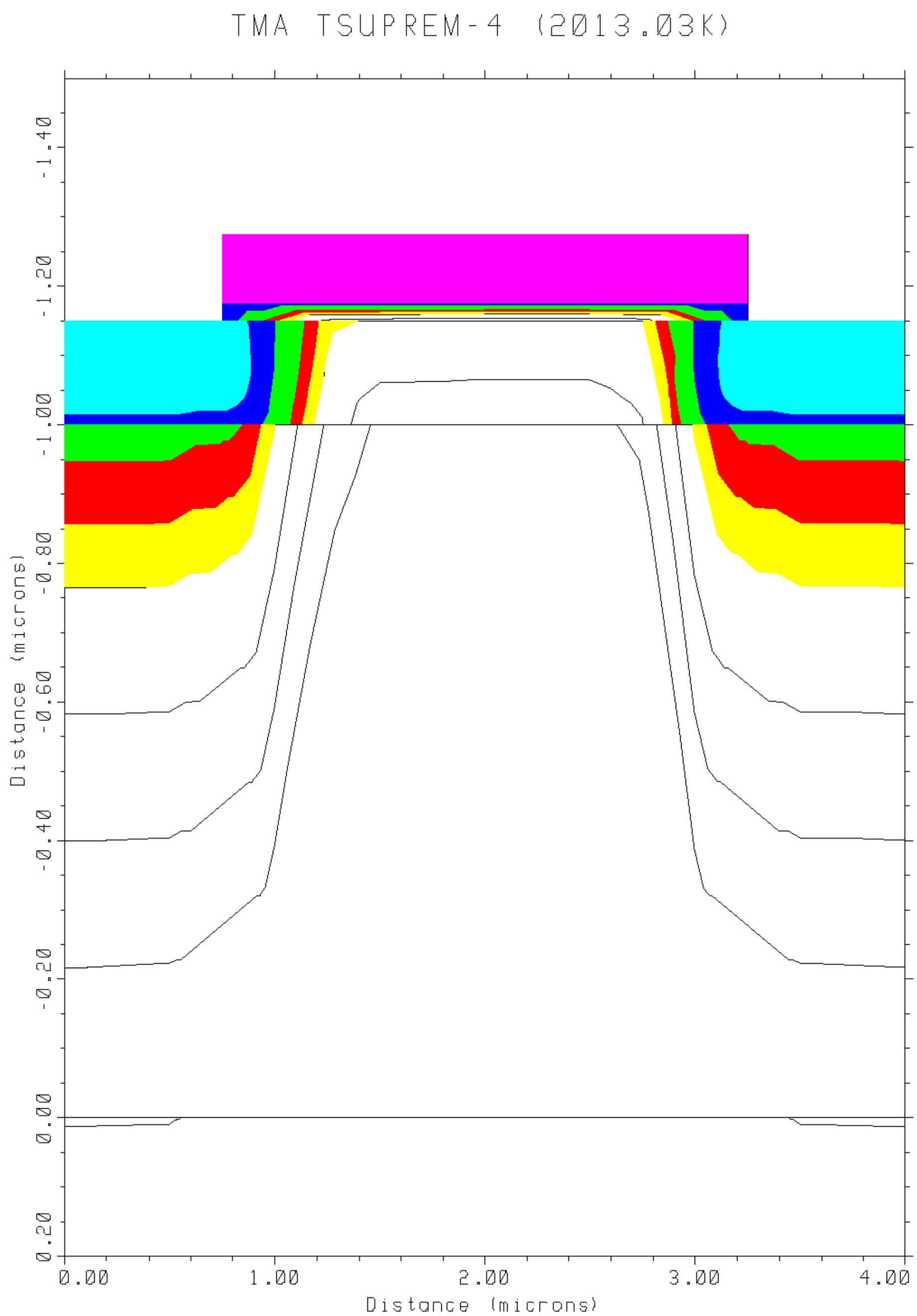


Figure A.7 **Cross-section plot of PMOS representing lateral diffusion. Colors represent different Phosphorus concentrations.**

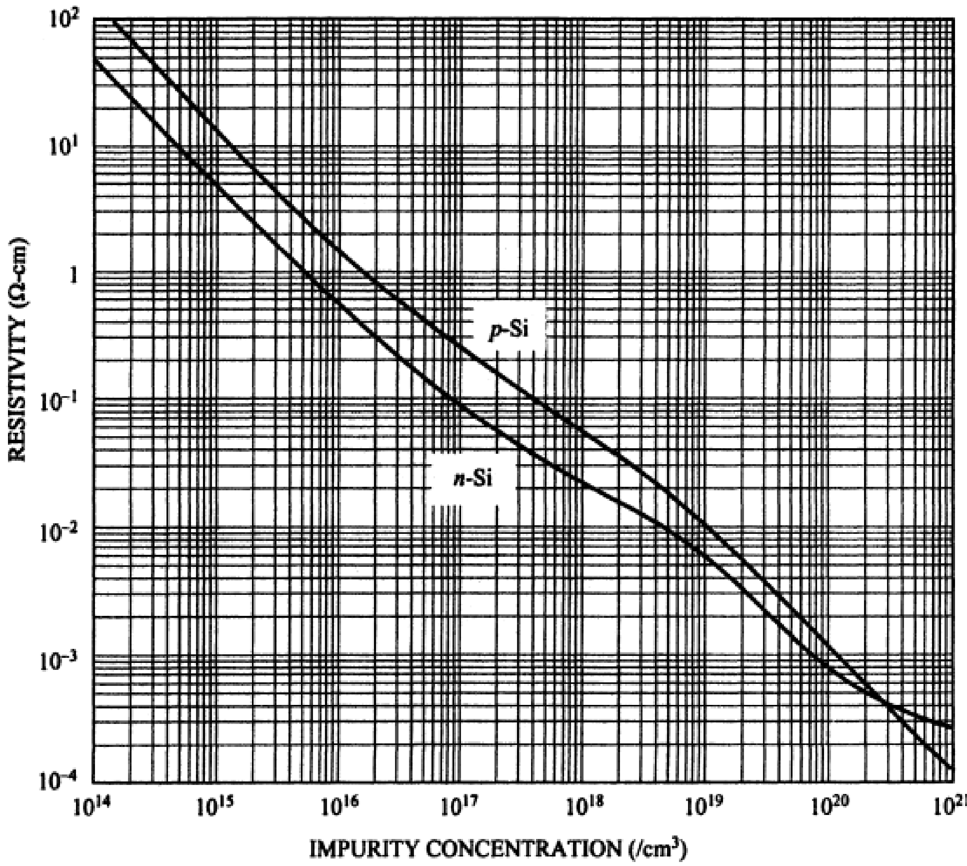


Figure A.8 Diagram of Impurity Concentration vs Resistivity of carriers in Silicon. [2]

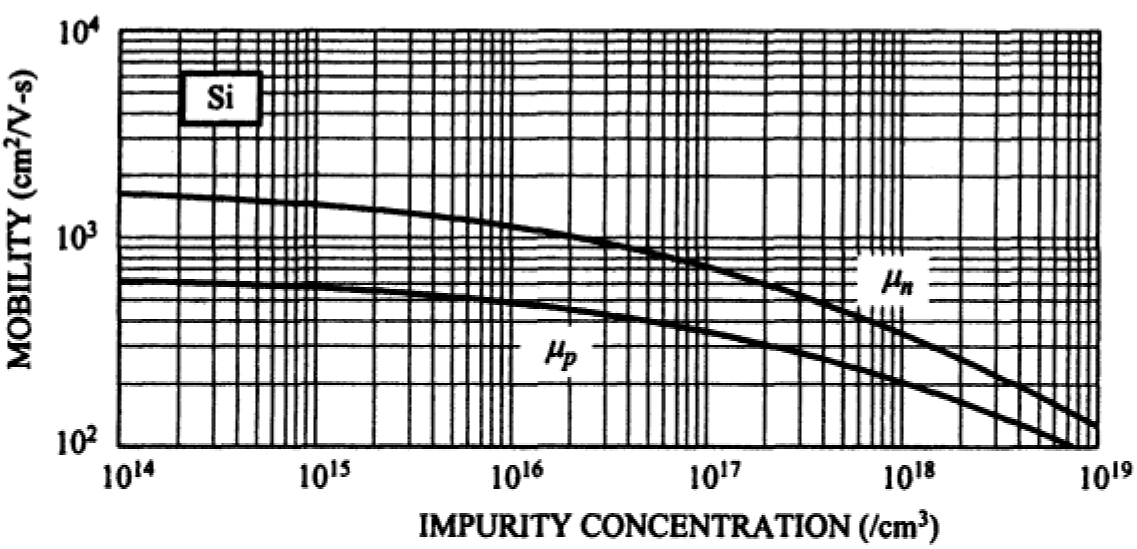


Figure A.9 Diagram of Impurity Concentration vs Mobility of carriers in Silicon. [2]

Ion-implantation projected range (R_p) and standard deviation (ΔR_p) into Si[1]

ENERGY (keV)	ANTIMONY R_p (μm)	ANTIMONY ΔR_p (μm)	ARSENIC R_p (μm)	ARSENIC ΔR_p (μm)	BORON R_p (μm)	BORON ΔR_p (μm)	PHOSPHORUS R_p (μm)	PHOSPHORUS ΔR_p (μm)
10	0.0088	0.0026	0.0097	0.0036	0.0333	0.0171	0.0139	0.0069
20	0.0141	0.0043	0.0159	0.0059	0.0662	0.0283	0.0253	0.0119
30	0.0187	0.0058	0.0215	0.0080	0.0987	0.0371	0.0368	0.0166
40	0.0230	0.0071	0.0269	0.0099	0.1302	0.0443	0.0486	0.0212
50	0.0271	0.0084	0.0322	0.0118	0.1608	0.0504	0.0607	0.0256
60	0.0310	0.0096	0.0374	0.0136	0.1903	0.0556	0.0730	0.0298
70	0.0347	0.0107	0.0426	0.0154	0.2188	0.0601	0.0855	0.0340
80	0.0385	0.0118	0.0478	0.0172	0.2465	0.0641	0.0981	0.0380
90	0.0421	0.0130	0.0530	0.0189	0.2733	0.0677	0.1109	0.0418
100	0.0457	0.0140	0.0582	0.0207	0.2994	0.0710	0.1238	0.0456
110	0.0493	0.0151	0.0634	0.0224	0.3248	0.0739	0.1367	0.0492
120	0.0529	0.0162	0.0686	0.0241	0.3496	0.0766	0.1497	0.0528
130	0.0564	0.0172	0.0739	0.0258	0.3737	0.0790	0.1627	0.0562
140	0.0599	0.0183	0.0791	0.0275	0.3974	0.0813	0.1757	0.0595
150	0.0634	0.0193	0.0845	0.0292	0.4205	0.0834	0.1888	0.0628
160	0.0669	0.0203	0.0898	0.0308	0.4432	0.0854	0.2019	0.0659
170	0.0704	0.0213	0.0952	0.0325	0.4654	0.0872	0.2149	0.0689
180	0.0739	0.0224	0.1005	0.0341	0.4872	0.0890	0.2279	0.0719
190	0.0773	0.0234	0.1060	0.0358	0.5086	0.0906	0.2409	0.0747
200	0.0808	0.0244	0.1114	0.0374	0.5297	0.0921	0.2539	0.0775
220	0.0878	0.0264	0.1223	0.0407	0.5708	0.0950	0.2798	0.0829
240	0.0947	0.0283	0.1334	0.0439	0.6108	0.0975	0.3054	0.0880
260	0.1017	0.0303	0.1445	0.0470	0.6496	0.0999	0.3309	0.0928
280	0.1086	0.0322	0.1558	0.0502	0.6875	0.1020	0.3562	0.0974
300	0.1156	0.0342	0.1671	0.0533	0.7245	0.1040	0.3812	0.1017

Table A.1 Table displaying the projected range and standard deviation of Ion Implantation into silicon. [2]

Ion-implantation projected range (R_p) and standard deviation (ΔR_p) into SiO_2[1]

	ANTIMONY		ARSENIC		BORON		PHOSPHORUS	
ENERGY (keV)	R_p (μm)	ΔR_p (μm)	R_p (μm)	ΔR_p (μm)	R_p (μm)	ΔR_p (μm)	R_p (μm)	ΔR_p (μm)
10	0.0071	0.0020	0.0077	0.0026	0.0298	0.0143	0.0108	0.0048
20	0.0115	0.0032	0.0127	0.0043	0.0622	0.0252	0.0199	0.0084
30	0.0153	0.0042	0.0173	0.0057	0.0954	0.0342	0.0292	0.0119
40	0.0188	0.0052	0.0217	0.0072	0.1283	0.0418	0.0388	0.0152
50	0.0222	0.0061	0.0260	0.0085	0.1606	0.0483	0.0486	0.0185
60	0.0254	0.0070	0.0303	0.0099	0.1921	0.0540	0.0586	0.0216
70	0.0286	0.0078	0.0346	0.0112	0.2228	0.0590	0.0688	0.0247
80	0.0316	0.0086	0.0388	0.0125	0.2528	0.0634	0.0792	0.0276
90	0.0347	0.0094	0.0431	0.0138	0.2819	0.0674	0.0896	0.0305
100	0.0377	0.0102	0.0473	0.0151	0.3104	0.0710	0.1002	0.0333
110	0.0406	0.0110	0.0516	0.0164	0.3382	0.0743	0.1108	0.0360
120	0.0436	0.0118	0.0559	0.0176	0.3653	0.0774	0.1215	0.0387
130	0.0465	0.0126	0.0603	0.0189	0.3919	0.0801	0.1322	0.0412
140	0.0494	0.0133	0.0646	0.0201	0.4179	0.0827	0.1429	0.0437
150	0.0523	0.0141	0.0690	0.0214	0.4434	0.0851	0.1537	0.0461
160	0.0552	0.0149	0.0734	0.0226	0.4685	0.0874	0.1644	0.0485
170	0.0581	0.0156	0.0778	0.0239	0.4930	0.0895	0.1752	0.0507
180	0.0610	0.0164	0.0823	0.0251	0.5172	0.0914	0.1859	0.0529
190	0.0639	0.0171	0.0868	0.0263	0.5409	0.0933	0.1966	0.0551
200	0.0668	0.0178	0.0913	0.0275	0.5643	0.0951	0.2073	0.0571
220	0.0726	0.0193	0.1003	0.0299	0.6100	0.0983	0.2286	0.0611
240	0.0784	0.0208	0.1095	0.0323	0.6544	0.1013	0.2498	0.0649
260	0.0842	0.0222	0.1187	0.0347	0.6977	0.1040	0.2709	0.0685
280	0.0900	0.0237	0.1280	0.0370	0.7399	0.1065	0.2918	0.0719
300	0.0958	0.0251	0.1374	0.0394	0.7812	0.1087	0.3125	0.0751

Table A.2 Table displaying the projected range and standard deviation of Ion Implantation into silicon dioxide. [2]

	B, P	B[1]	P[1]
T, °C	D (cm^2/s)	N_{sl} (cm^{-3})	N_{sl} (cm^{-3})
900	1.5×10^{-15}	3.7×10^{20}	6.0×10^{20}
950	6.6×10^{-15}	3.9×10^{20}	7.8×10^{20}
1000	2.6×10^{-14}	4.1×10^{20}	1.0×10^{21}
1050	9.3×10^{-14}	4.3×10^{20}	1.2×10^{21}
1100	3.0×10^{-13}	4.5×10^{20}	1.4×10^{21}
1150	9.1×10^{-13}	4.8×10^{20}	1.5×10^{21}
1200	2.5×10^{-12}	5.0×10^{20}	1.5×10^{21}
1250	6.5×10^{-12}	5.2×10^{20}	1.4×10^{21}
1300	1.6×10^{-11}	5.4×10^{20}	1.1×10^{21}
1350	3.7×10^{-11}	5.7×10^{20}	7.1×10^{20}

Table A.3 Silicon Diffusivity data [6]. ([1]F.A. Trumbore, "Solid Solubilities of Impurity Elements in Germanium and Silicon," Bell Syst. Tech. J., 19, 911), 38-43, Nov. 1976.)

TSuprem4 Input Files

"vtn.inp" file for calculating the threshold voltage on the NMOS

```
$ Suprem example: computing VTn on SOI wafer
$ deposited gate oxide, no thermal budget (to avoid boron outdiffusion)
$ undoped Si film

$ Graphics written as postscript file
option     device="c/postscript" plot.out="vtn.ps"

mesh      dy.surf=0.002

$ Set the substrate background doping
initialize boron=1.3889e15

$.......................................................
$ specify SOI structure

$ specify buried oxide    1um
deposit    oxide thick=1.0 dy=0.01

$specify Si film thickness and doping    150nm
deposit    silicon  boron=1.3889e15 thick=0.1 dy=0.001

$.............Threshold voltage Adjustment..........................
implant boron dose=7.25e11 energy=21 gaussian

$ Deposit a cap oxide to seal surface during anneal
deposit    oxide thick=0.1 dy=0.001

diffusion  temp=1000 time=40

etch oxide
$.......................................................
$ deposit gate oxide    25nm
deposit    oxide thick=0.025 dy=0.001

$ deposit poly gate    100nm
deposit    polysilicon thick=0.1 phosphorus=3e20

$.......................................................

$ Print oxide thickness
select      z=doping
print.1d    layers

$ Plot the electrically active boron distribution
select     z=log10(active(boron))
plot.1d    top=21 bottom=11 left=-1.3 right=0.2 color=2

$ add thephosphorus concentration to the plot
select     z=log10(phos)
plot.1d    ^ax ^cl color=4

$compute VT, looking at conductivity in the top Si layer (layer 3)
electric   x=0.0 threshold nmos v="0.0 1.5 0.05" gate.ele bulk.lay=3


$ output results of Vt calculation
plot.1d    electric

stop
end

$....................................................
```

“nplus.inp” file for calculating the Source and Drain sheet resistance on the NMOS

```
$ nmos source/drain diffusion

$ Full non-equilibrium point defect model
method     pd.full

$ Graphics written as postscript file
option     device="c/postscript" plot.out="nplus.ps"

$set the grid spacing to 2nm
mesh      dy.surf=0.002

$ Set the substrate background doping
initialize boron=1.3889e15

$........ specify SOI structure.....................
$ specify buried oxide
deposit    oxide thick=1.0 dy=0.01

$ Set the Si film doping
deposit  silicon boron=1.3889e15 thick=0.15

$.............Threshold voltage adjustment.............

implant boron dose=7.25e11 energy=21 gaussian

$ Deposit a cap oxide to seal surface during anneal
deposit    oxide thick=0.1 dy=0.001

diffusion  temp=1000 time=40
etch oxide

$............nmos phosphorus predeposition...........

$phosphorus diffusion- gas
diffuse    phos=1e20 time=20 temp=1000

$.....................................................

$ Plot the phosphorus distribution  RED
select     z=log10(phos)
plot.1d    top=27 bottom=14 left=-1.3 right=-0.8 color=2

$...................pplus part......................

$ Deposit a cap oxide to seal surface during anneal
Deposit    oxide thick=0.15

$ Furnace anneal to activate implant
diffusion  temp=1000 time=20

$ Remove oxide
etch       oxide

$.....................................................

$ Plot the active Phos distribution   BLUE
select     z=log10(active(phos))
plot.1d    ^ax ^cl color=4

$ Add the boron background concentration to the plot   Magenta
select     z=log10(boron)
plot.1d    ^ax ^cl color=6

$ Plot the active Boron  distribution     GREEN
select     z=log10(active(boron))
plot.1d    ^ax ^cl color=3

$.....................................................
```

```
$ Magic invocation to compute sheet resistance
electrical  x=0

$ Print junction depth information
select      z=doping
print.1d    layers

stop
end
$..................................................
```

[*“nplus.inp” file output plotting the sheet resistance of the source and drain of the NMOS*]()

```
************************ STRUCTURE INFORMATION ************************
LAYER    MATERIAL THICKNESS REGION DIFTYP THICKNESS       TOP    BOTTOM

    3     silicon    0.1500      1      n    0.1500   -1.1500   -1.0000
    2       oxide    1.0000                  1.0000   -1.0000    0.0000
    1     silicon  200.0000      1      p  200.0000    0.0000  200.0000

***********************************************************************


 Bias step   1:    0.00 (Volts)

     ********************************************************************
       Material    Thickness   Type   Junction Depth   Sheet Resistance
     --------------------------------------------------------------------

        silicon      1500 A      N           0.15 um       110   ohm/sq
          oxide      1.00 um
        silicon       200 um     P            200 um       460   ohm/sq

     ********************************************************************
```

[*“pplus.inp” file for calculating the Source and Drain sheet resistance on the PMOS*]()

```
$ pmos p+ source/drain

$ Full non-equilibrium point defect model
$(includes transient enhanced diffusion)
method     pd.full

$ Graphics written as postscript file for transfer to PC
option     device="c/postscript" plot.out="pplus.ps"

$set the grid spacing to 2nm
mesh      dy.surf=0.002

$ Set the well background doping
initialize boron=1.3889e15

$...........SOI structure.......................
$ specify buried oxide     1um
deposit    oxide thick=1.0 dy=0.01

$ Set the Si film doping          150nm
deposit  silicon boron=1.3889e15 thick=0.15

$.............Threshold voltage adjustment............

implant boron dose=7.25e11 energy=21 gaussian


$ Deposit a cap oxide to seal surface during anneal
deposit    oxide thick=0.1 dy=0.001
```

```
diffusion  temp=1000 time=40
etch oxide

$.........nmos phosphorus predep.........................

$phosphorus diffusion- gas
diffuse    phos=1e20 time=20 temp=1000

$............Source Drain Ion Implant.........................

implant    boron dose=9e15 energy=10 gaussian

$.....................................................

$ Plot the as-implanted boron distribution      RED
select     z=log10(boron)
plot.1d    top=23 bottom=14 left=-1.3 right=-0.6 color=2

$.....................................................

$ Deposit a cap oxide to seal surface during anneal
Deposit    oxide thick=0.15

$ Furnace anneal to activate implant
diffusion  temp=1000 time=20

$ Remove oxide
etch       oxide
$.....................................................

$ Plot the boron distribution after anneal on the same axes GREEN
select     z=log10(boron)
plot.1d    ^ax ^cl color=3

$ Check that all the boron is electrically active      BLUE
select     z=log10(active(boron))
plot.1d    ^ax ^cl color=4

$ Add the phosphorus background concentration to the plot    CYAN
$select     z=log10(phos)
$plot.1d    ^ax ^cl color=5

$ Add the electrically active phosphorus   PINK
select     z=log10(active(phos))
plot.1d    ^ax ^cl color=6

$.....................................................

$ Magic invocation to compute sheet resistance
electrical  x=0

$ Print junction depth information
select      z=doping
print.1d    layers

stop
end
$.....................................................
```

“pplus.inp” *file output plotting the sheet resistance of the source and drain of the PMOS*

```
************************ STRUCTURE INFORMATION ************************
LAYER    MATERIAL THICKNESS REGION DIFTYP THICKNESS       TOP    BOTTOM

    3     silicon    0.1500      1      p    0.1500   -1.1500   -1.0000
    2       oxide    1.0000                  1.0000   -1.0000    0.0000
    1     silicon  200.0000      1      p  200.0000    0.0000  200.0000

***********************************************************************


 Bias step   1:    0.00 (Volts)

     *********************************************************************
       Material    Thickness   Type   Junction Depth   Sheet Resistance
     ---------------------------------------------------------------------

        silicon      1500 A      P           0.15 um        87   ohm/sq
          oxide      1.00 um
        silicon       200 um     P            200 um       459   ohm/sq

     *********************************************************************
```

“nmos.inp” *file for lateral diffusion plot of the NMOS*

```
$ Lateral implant straggle example:  NMOS device

$ Full non-equilibrium point defect model
$(includes transient enhanced diffusion)
method     pd.full

$ Graphics written as postscript file
option     device="c/postscript" plot.out="nmos.ps"

$ Set the grid spacing, now a 2-dimensional grid, y is the depth co-ordinate
mesh      dy.surf=0.002

$ Set the structure width and background doping  10 ohm/cm
initialize width=4.0 boron=1.3889e15

$...............SOI structure......................

$ specify SOI structure

$ specify buried oxide      1um
deposit    oxide thick=1.0

$ Set the Si film doping       150nm
deposit  silicon boron=1.3889e15 thick=0.15

$.............Threshold voltage adjustment............

implant boron dose=7.25e11 energy=21 gaussian

$ Deposit a cap oxide to seal surface during anneal
deposit    oxide thick=0.1 dy=0.001

diffusion  temp=1000 time=40
etch oxide

$.....................................................

$ deposit gate oxide    25nm
deposit    oxide thick=0.025

$ deposit poly gate    100nm
deposit    polysilicon thick=0.1
```

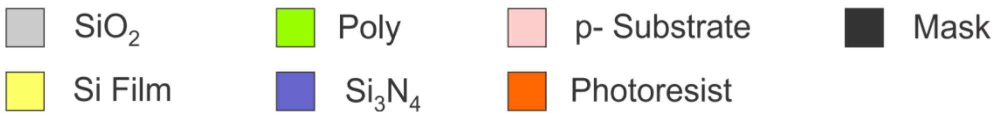
```
$.............................................

$etch polysilicon
etch polysilicon p1.x=.75 p1.y=-1.175 p2.x=0.75 p2.y=-1.275 left
etch polysilicon p1.x=3.25 p1.y=-1.175 p2.x=3.25 p2.y=-1.275 right

$etch oxide
etch oxide p1.x=0.75 p1.y=-1.15 p2.x=0.75 p2.y=-1.175 left
etch oxide p1.x=3.25 p1.y=-1.15 p2.x=3.25 p2.y=-1.175 right


$......................................................

$phosphorus diffusion- gas
diffuse    phos=1e20 time=20 temp=1000

$.................pplus annealing part .................

$ Deposit a cap oxide to seal surface during anneal
$ With cap is has a higher concentration, good diffusion
deposit oxide thick=0.15

$ Furnace anneal to activate implant
diffusion  temp=1000 time=20

$......................................................

$remove oxide
etch oxide p1.x=0.75 p1.y=-1.15 p2.x=0.75  p2.y=-1.425 left
etch oxide p1.x=3.25 p1.y=-1.15 p2.x=3.25  p2.y=-1.425 right
etch oxide p1.x=4.0 p1.y=-1.275 p2.x=4.0  p2.y=-1.425 left


$.................Plotting..........................

$ Plot the as-implanted phosphorus distribution
$ x.min and x.max is x axis: length. y.min and ymax is y axis: depth of layers

select     z=log10(phos)
plot.2d    x.min=0 x.max=4.0 y.min=-1.5 y.max=0.2


$ Plot contours at decade intervals from 10^14cm^-3 up to 22
foreach x ( 13 to 22 step 1)
  contour value=x color=1
end

$RED = 2, GREEN= 3, BLUE = 4, CYAN = 5, MAGENTA=6, YELLOW=7

$color min is lowest concentration in a range, max is max conc.

color min.v=16 max.v=16.5 color= 7
color min.v=16.5 max.v=17 color= 2
color min.v=17 max.v=18 color= 3
color min.v=18 max.v=19 color= 4
color min.v=19 max.v=20 color= 5
color min.v=20 max.v=21 color= 6

$ Magic invocation to compute sheet resistance
electrical  x=0

$ Print junction depth information
select      z=doping
print.1d    layers

$+++++++++++++++++++++++++++++++++++++++++++++++++++++++++

stop
end
$+++++++++++++++++++++++++++++++++++++++++++++++++++++++++
```

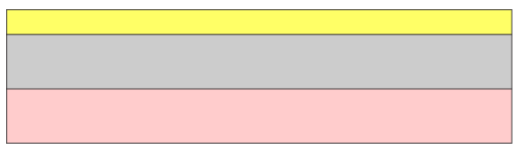
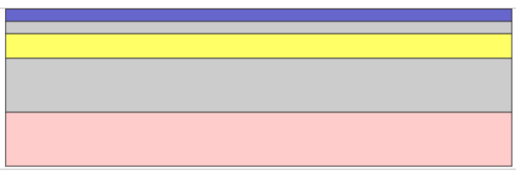
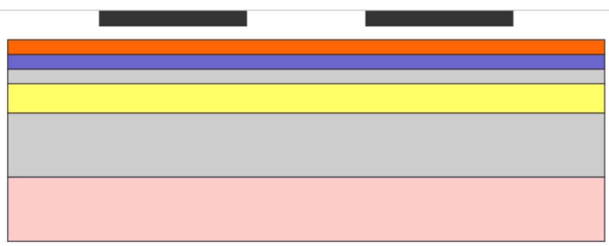
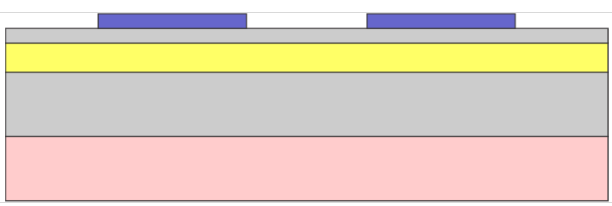
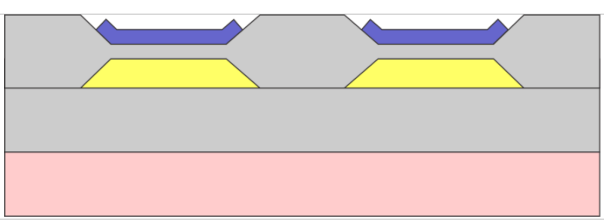
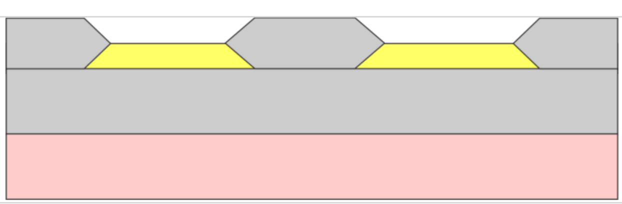
“pmos.inp” file for lateral diffusion plot of the PMOS

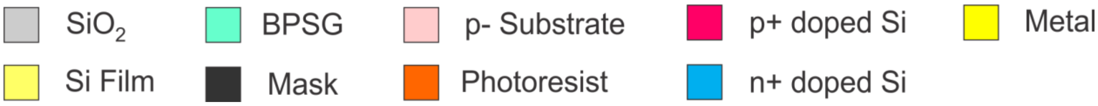
```
$ Lateral implant straggle example:  PMOS device

$ Full non-equilibrium point defect model
$(includes transient enhanced diffusion)
method     pd.full

$ Graphics written as postscript file
option     device="c/postscript" plot.out="pmos.ps"

$ Set the grid spacing, now a 2-dimensional grid, y is the depth co-ordinate
mesh      dy.surf=0.002

$ Set the structure width and background doping  10 ohm/cm
initialize width=4.0 boron=1.3889e15

$...............SOI structure.......................

$ specify SOI structure

$ specify buried oxide      1um
deposit    oxide thick=1.0

$ Set the Si film doping       150nm
deposit  silicon boron=1.3889e15 thick=0.15

$.............Threshold voltage adjustment............

implant boron dose=7.25e11 energy=21 gaussian

$ Deposit a cap oxide to seal surface during anneal
deposit    oxide thick=0.1 dy=0.001

diffusion  temp=1000 time=40
etch oxide

$.....................................................

$ deposit gate oxide    25nm
deposit    oxide thick=0.025

$ deposit poly gate    100nm
deposit    polysilicon thick=0.1

$...........................................

$etch structure to pattern poly and oxide
$etch polysilicon
etch polysilicon p1.x=0.75 p1.y=-1.175 p2.x=0.75 p2.y=-1.275 left
etch polysilicon p1.x=3.25 p1.y=-1.175 p2.x=3.25 p2.y=-1.275 right

$etch oxide
etch oxide p1.x=0.75 p1.y=-1.15 p2.x=0.75 p2.y=-1.175 left
etch oxide p1.x=3.25 p1.y=-1.15 p2.x=3.25 p2.y=-1.175 right

$.........nmos phosphorus predep.........................

$phosphorus diffusion- gas
diffuse    phos=1e20 time=20 temp=1000

$..........Boron Ion implant.....................

$ set a cap on top of Poly gate
deposit  oxide thick=0.15

$etch oxide
etch oxide p1.x=0.75 p1.y=-1.15 p2.x=0.75 p2.y=-1.425 left
etch oxide p1.x=3.25 p1.y=-1.15 p2.x=3.25 p2.y=-1.425 right
```

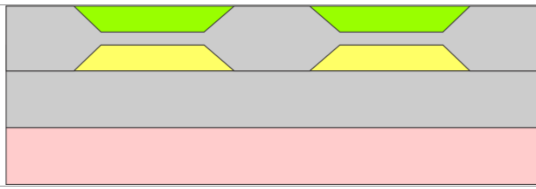
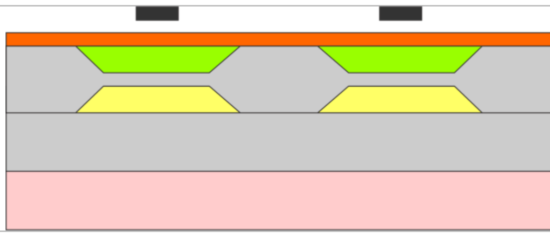
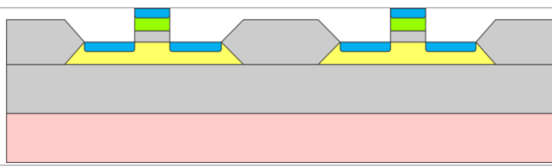
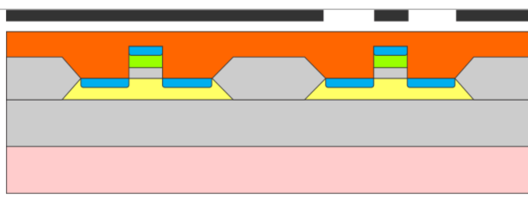
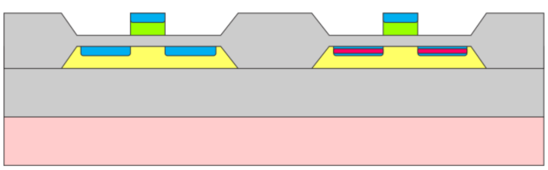
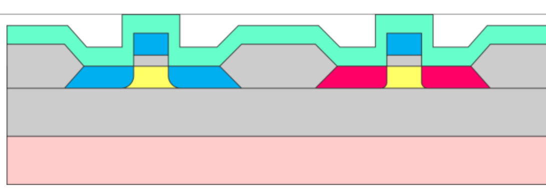
```
implant    boron dose=9e15 energy=10 gaussian

$etch the cap of the polygate
etch oxide p1.x=4.0 p1.y=-1.425 p2.x=4.0  p2.y=-1.275 left

$ Deposit a cap oxide to seal surface during anneal
$ With cap is has a higher concentration, good diffusion
deposit  oxide thick=0.1

$ Furnace anneal to activate implant
diffusion  temp=1000 time=20

$.....................................................
$remove oxide
etch oxide p1.x=0.75 p1.y=-1.15 p2.x=0.75  p2.y=-1.425 left
etch oxide p1.x=3.25 p1.y=-1.15 p2.x=3.25  p2.y=-1.425 right
etch oxide p1.x=4.0 p1.y=-1.275 p2.x=4.0  p2.y=-1.425 left

$..............Plotting.........................

$ x.min and x.max is x axis: length. y.min and ymax is y axis: depth of layers

$select     z=log10(phos)
select     z=log10(boron)
plot.2d    x.min=0 x.max=4.0 y.min=-1.5 y.max=0.2


$ Plot contours at decade intervals from 10^14cm^-3 up to 22
foreach x ( 13 to 22 step 1)
  contour value=x color=1
end

$RED = 2, GREEN= 3, BLUE = 4, CYAN = 5, MAGENTA=6, YELLOW=7

$color min is lowest concentration in a range, max is max conc.

color min.v=16 max.v=16.5 color= 7
color min.v=16.5 max.v=17 color= 2
color min.v=17 max.v=18 color= 3
color min.v=18 max.v=19 color= 4
color min.v=19 max.v=20 color= 5
color min.v=20 max.v=21 color= 6

$ Magic invocation to compute sheet resistance
electrical  x=0

$ Print junction depth information
select      z=doping
print.1d    layers

$++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

stop
end

$++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
```

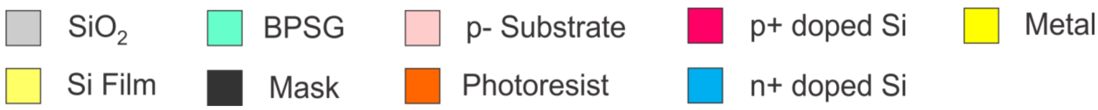
CMOS Process Flow Described

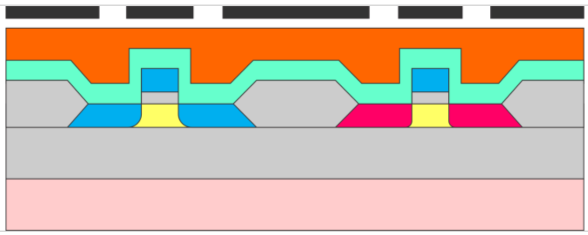
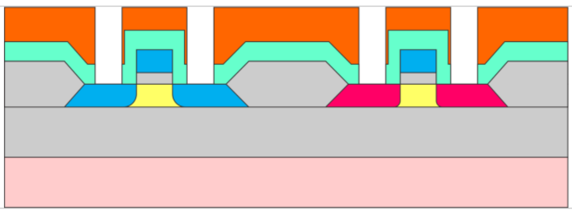
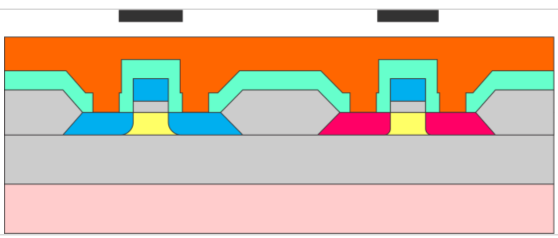
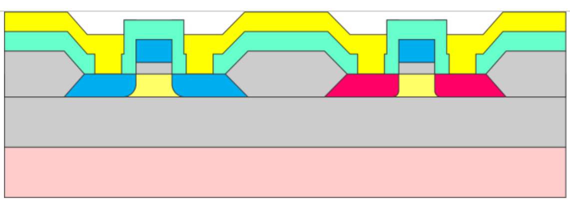


	Adjust the thickness of the Si film up to 150nm. Add Boron using Ion Implantation for Threshold Voltage adjustment, V_{TN}=0.343V, with a dose Q=$7.25x10^{11}$ atoms/cm^2 at 1000°C for 40 minutes.
	Grow an 80nm Oxide pad layer, using dry O_2 at 1100°C. Deposit Silicon Nitride by LPCVD.
	**PE 1:** Deposit a Photoresist layer. Use a photomask to pattern the Silicon Nitride for LOCOS process. Apply UV light.
	Etch the exposed photoresist. Etch the unprotected Silicon Nitride. Etch the rest of the photoresist.
	LOCOS process: Grow 1um Field Oxides using dry O_2 at 1100°C.
	Etch the Silicon Nitride and pad oxide.



	Grow the Gate Oxide layer, 25nm thick, using dry O_2 at 1100°C. Deposit 100nm of Polysilicon layer by LPCVD
	**PE 2:** Apply photoresist and a mask to pattern the gates of the CMOS.
	Apply a Phosphorus predeposition on the CMOS with a concentration of $1x10^{20}$ atoms/cm^3 for 20 minutes at 1000°C.
	**PE 2:** Apply a photoresist layer. Pattern the holes to access the Source and Drain on PMOS prior to Boron Ion Implantation.
	Apply a Boron Ion Implantation on the Source and Drain of the PMOS. Use a dose $Q=9x10^{15}$ atoms/cm^2 and an energy implant of 10KeV. Etch the photoresist. Grow an oxide layer as a cap prior the annealing step.
	Anneal the CMOS for 10 minutes at 1000°C. Remove the oxide layer cap. Apply a 500nm BPSG layer.



	**PE 4:** Deposit a photoresist layer and mask to pattern the Source and Drain contact windows for device interconnection
	Etch the exposed photoresist. Etch the BPSG. Remove the rest of the photoresist.
	**PE 5:** Apply a photoresist layer and mask to pattern the protective layers of the gates. Etch the exposed photoresist.
	Deposit 1um Aluminum. Using lift-off process, remove the stacked metal on top of the gates. Metal anneal using H_2 at 400°C.