Libre Silicon process specification

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Abstract

This is the specification of the free silicon manufacturing standard for manufacturing the LibreSilicon standard logic cells[1] and related free technology nodes from the LibreSilicon project.

[1] https://github.com/chipforge/StdCellLib

Contents

1 CMOS in a nutshell

This basic initial project is dedicated to the CMOS Technology only and for this reason two types of metal–oxide–semiconductor field-effect transistors (MOSFET) are required.
Historicaly, the first chips with MOSFETs on the mass market were p-channel MOSFETs in enhancement-mode.

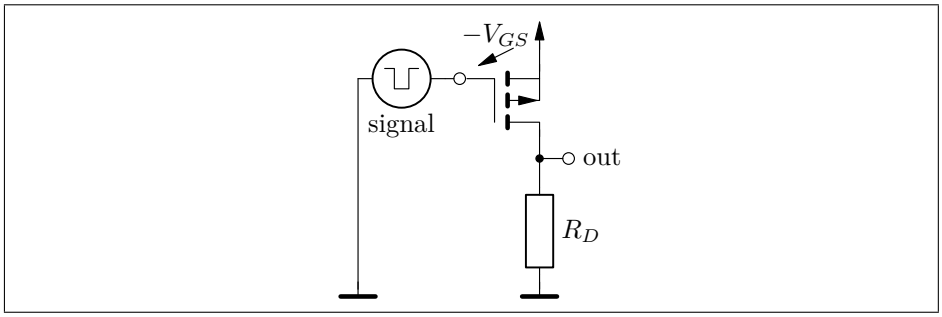

Figure 1: enhancement-mode PMOS transistor use-case

The sectional view of a PMOS transistor in silicon is being shown below

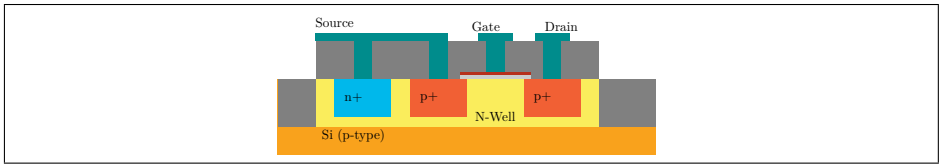

Figure 2: Sectional view of a PMOS transistor

Historicaly later, faster chips with MOSFETs on the mass market were marked as n-channel MOSFETs in enhancement mode also.

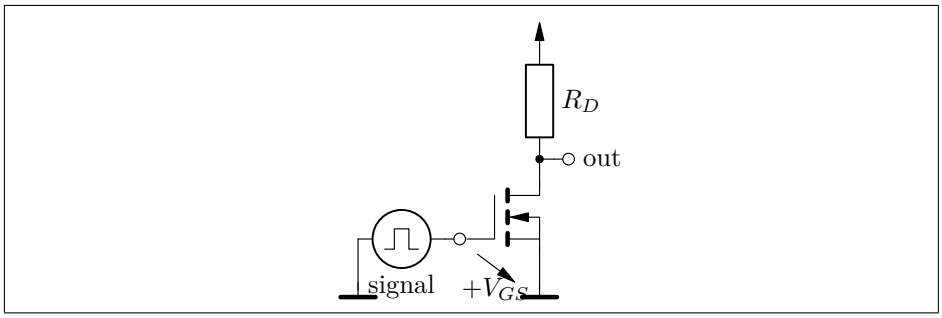

Figure 3: enhancement-mode NMOS transistor use-case

The sectional view of a NMOS transistor in silicon is being shown here also.

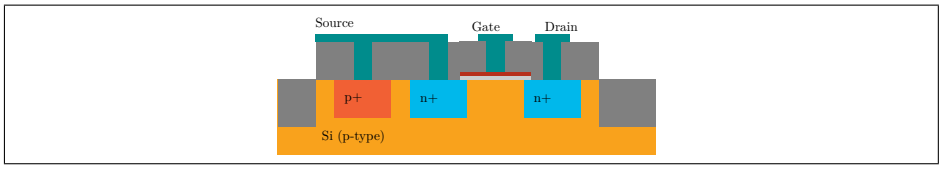

Figure 4: Sectional view of a NMOS transistor

Both technologies, the older NMOS as the newer PMOS, have the same disadvantage. Every time, the transistor is switched on, the current between Drain and Source of the transistor is limited by the Resistor on Drain only. Higher currents here meaning also higher power consumption for the chip where the transistors are integrated also. If the transistors are switched off, now currents flows between Drain and Source anymore, the power consumption of the chip also goes low. Et violà, the US-Patent with Number 3356858[2] changed the world and combines both technologies to the new complementary metal-oxide-semiconductor (CMOS) technology. Instead of every transistor is working against a weak resistor, the transistor works against a complementary switched-off transistor. With the Eyes of our antecessor CMOS doubles the transistor count, but contemporary chips all are build in CMOS.

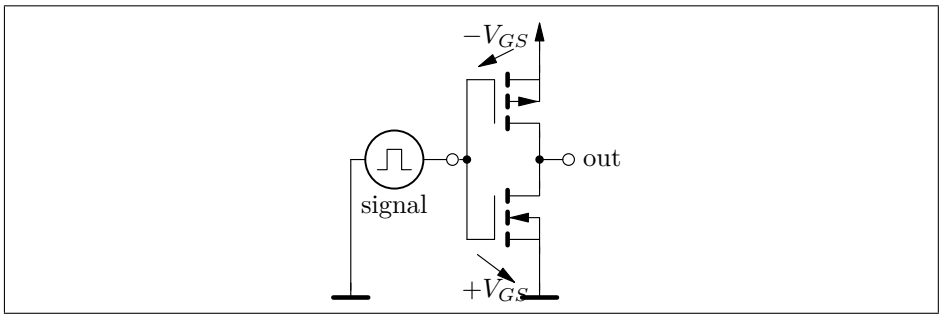

Figure 5: complementary PMOS and NMOS transistor couple use-case

Below the sectional view of the inverter circuitry can be seen. For the run through of this process we will use this cross section diagram as reference.

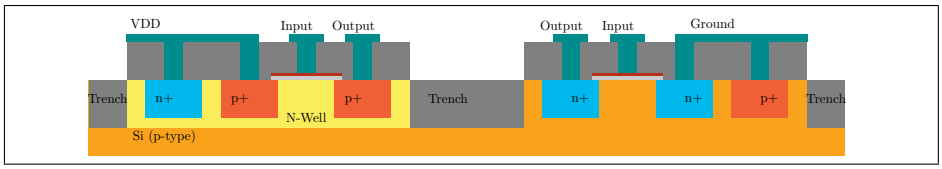

Figure 6: Sectional view of a NMOS-PMOS transistor circuit

[2]https://www.google.com/patents/US3356858

2 Physics

2.1 Infusion

The redistribution process depends on the ratio of the solubility of the doping material in silicon and SiO_2. At the Si/SiO_2 interface the dopants are redistributed by segregation until the ratio of their concentration at the interface is the same as the ratio of their solubility in both materials. The ratio of dopant solubility is expressed by the segregation coefficient m which is

$$m = \frac{\text{solubility in silicon}}{\text{solubility in } SiO_2} \tag{1}$$

As listed in Table 1 below there are dopant species which solubilize better in SiO_2 than in silicon ($m < 1$) and species which have a reversed behavior ($m > 1$). In case of $m < 1$, as for Boron, the dopant concentration is enhanced at the SiO_2 side, whereas beneath the interface, there is a dopant depletion at the silicon surface. For reversed solubility ratios ($m > 1$, like Phosphorus), only few dopant atoms penetrate the interface. In order to obtain the by m determined concentration ratio at the interface, dopant atoms from deeper silicon zones diffuse back to the surface zone. Therefore, the dopant concentration at the silicon surface is enhanced, as illustrated in Figure 7b. In Figure 7 C_c denotes the dopant concentration in the silicon surface zone before oxidation. x is the distance from the silicon surface.

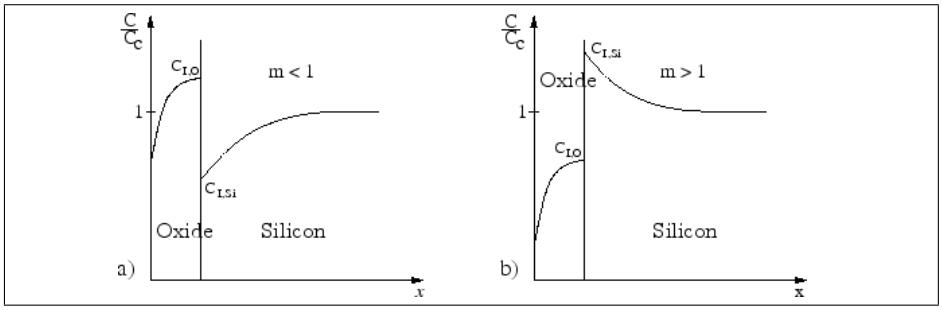

Figure 7: Schematic illustration of dopant redistribution

Dopant species	Boron	Phosphor	Antimon	Arsen	Gallium
m	0.1-0.3	10	10	10	20

Table 1: Segregation coefficients m for important dopant species in silicon

2.2 MOS Capacitance

https://ecee.colorado.edu/~bart/book/book/chapter6/ch6_3.htm

3 Chemistry

3.1 Etching silicon dioxide

A very "selective" chemical for SiO2 - i.e. does not etch silicon at all - is hydrofluoric acid (HF). If used directly such etchant has a too fast and aggresive action on the oxide, making very difficult the undercut and the linewidth control. For such reason, HF is universally used as a "buffered" solution, which can keep the etch rate low and constant, by moderating the PH level of the bath. This allows the etching time to be reliably correlated to the etching depth.
The industry standard buffered hydrofluoric acid solution (BHF) has the following formulation:

- 6 volumes of ammonium floride (NH4F, 40% solution)
- 1 volume of HF.

This can be prepared, for example, by mixing 113 g of NH4F in 170 ml of H2O, and adding 28 ml of HF.
The etch rate at room temperature can range from 1000 to 2500 Å/min (100-250nm/min). This depends on the actual density of the oxide which, as an amorphous layer, can have a more compact structure (if thermally grown in is oxygen) or less compact (if grown by CVD). The following etching reaction holds:

$$SiO_2 + 6HF \rightarrow H_2SiF_6 + H_2O \tag{2}$$

where H_2SiF_6 is water soluble.
A common buffered oxide etch solution comprises a 6:1 volume ratio of 40% NH4F in water to 49% HF in water. This solution will etch thermally grown oxide at approximately 2 nanometres per second at 25 degrees Celsius. [3]

Another popular etching formulation is the P-etch:
60 volumes of H_2O + 3 vol. of HF + 2 vol. of HNO_3, that is: 300 ml of H_2O + 15 ml of HF + 10 ml of HNO_3.
The P-etch action is strongly dependent on oxide density, as it results from the growth technique. An example is reported in the literature[4], indicating 120 Å/min for thermal oxide and 250-700 Å/min for sputtered oxide.
A slow etching bath is preferred for opening mask windows for a silicon substrate. However, the etching process could be used just for removing the oxide film from the whole surface. In this case the etching speed is not critical, and a fast solution can be used, such as HF diluited 1:10 in water. The etching time can be easily evaluated by visually inspecting the surface. Once the oxide film is removed, the metal-grey color of the silicon surface appears.
Sometimes a very light etch is required, for removing just a few atomic layers. This is the case of surface cleaning and decontamination. HF diluited 1 : 50 in water can be used. The etching speed will be around 70 Å / min. For example, a typical 50 Å "native" oxide on silicon can be removed with a 45 - 50 sec light etch.

[3] Wolf, S.; R.N. Tauber (1986). Silicon Processing for the VLSI Era: Volume 1 - Process Technology. pp. 532–533. ISBN 978-0-9616721-3-3
[4] A. Pliskin, J.Vac.Sci Technol., vol. 14, p.1064, 1977

3.2 Etching silicon nitride

Thin films made of amorphous silicon nitride (Si_3N_4) are usually deposited by chemical vapour deposition from silane (SiH_4) and ammonia (NH_3). Since they act as a barrier for water and sodium, they have a major role as passivation layers in microchip fabrication. Patterned nitride layers are also used as a mask for spatially selective silicon oxide growth, and as an etch mask when SiO_2 masks cannot be used.
One example of the latter situation is given by the anisotropic etching of silicon in KOH. The etching rate of SiO_2 in KOH is nearly 1000 times slower than the etching rate of silicon, and in most cases a SiO_2 mask can be used successfully. However, a very deep selective etch may require a long etching time, and the 1000:1 etching rate ratio may result still too small to prevent the SiO_2 mask from being etched off before the process is completed. In this circumstance Si_3N_4, thanks to its reduced etched rate, can successfully replace the oxide mask layer.
The wet etching of nitride films is often performed in concentrated hot orthophosphoric acid (H_3PO_4). The bath temperature can range from 150°C to 180°C (boiling point) with a corresponding etch rate between 10 and 100 Å/min. It is good practice to bring the vapours into contact with a cold surface and to drive the condensed liquid back into the etching bath. This technique is referred to as "reflux".
The etching rates of silicon nitride, silicon oxide, and silicon in H_3PO_4 are respectively in the $50 : 5 : 1$ ratio.

4 Process

The general flow chart of the overall process flow can be seen in Figure 8. These process steps will be discussed within the following sections.

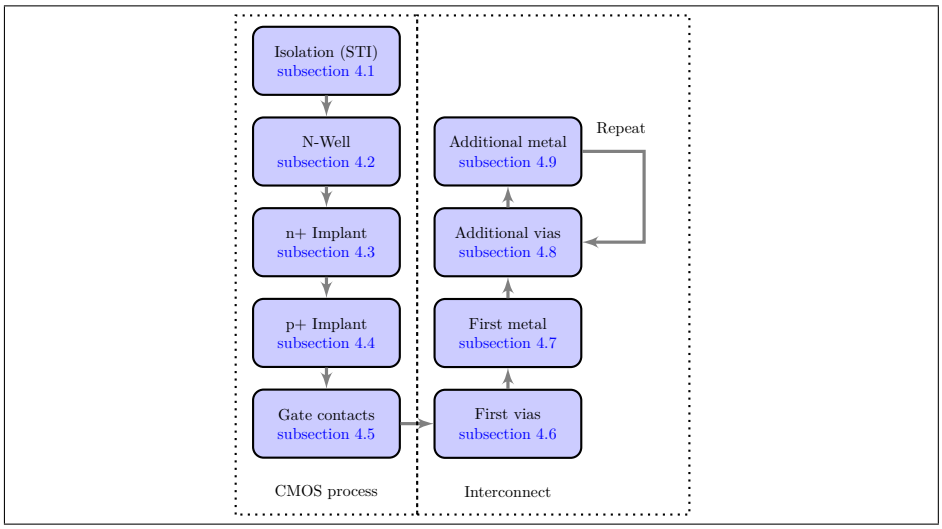

Figure 8: Frontend and backend process flow

The five overall process steps are part of an active part of the technology, while the final metal (respectively contact) layers will be used for making a contact between the logic gates and macro cells and making them available to the exterior world.
For this process p-substrate is the required basic substrate, but forks and modifications will be very well possible based on a Graphene substrate or alike, still under the LSPL. The starting material is a p-type, <100> oriented silicon with a doping concentration of $\approx 9 \times 10^{14} cm^{-3}$.

Reasons for using p-substrate:

- We can't use two different substrates for our design because in the design both PMOS and NMOS is present. We have to choose which is more beneficial from fabrication point of view. In general or say it's true that NMOS devices are always more in the Semiconductor Industry in comparison to PMOS devices. For your reference-SRAM requires 6 transistors (4 NMOS, 2 PMOS).
- Another reason for more number of NMOS is because of difference of mobility of electron and holes. Electron mobility is almost twice of holes mobility and because of this ON-RESISTANCE of n-channel device is half of p-channel device with the same geometry and under the same operating conditions. That means to achieve same impedance size of n-channel transistors is almost half of p-channel devices. Same thing I can say in the different way that for same size of wafer, we can have more number of NMOS (means can perform more logical operation) in comparison to PMOS.

For the isolation (subsection 4.1) in this design the STI approach is being chosen. Shallow trench isolation (STI), also known as box isolation technique, is an integrated circuit feature which prevents electric current leakage between adjacent semiconductor device components.[5] STI is generally used on CMOS process technology nodes of 250 nanometers and smaller.
Reasons for using box isolation:

- We want to be forward compatible to future LibreSilicon nodes with a size of 100nm or smaller
- It simplifies the construction of the gate and allows us to use Aluminum instead of Polysilicon for the gate contact

The interconnects and the gate electrode are being made using Aluminum.
Reasons for using Aluminum:

- Aluminum is easy to etch compared to copper
- It doesn't doing "strange things" when making contact with doped areas, like copper does

[5] https://www.google.com/patents/US7985656

4.1 Shallow trench isolation

The geometry of a substrate with STI implemented can be seen in Figure 9.

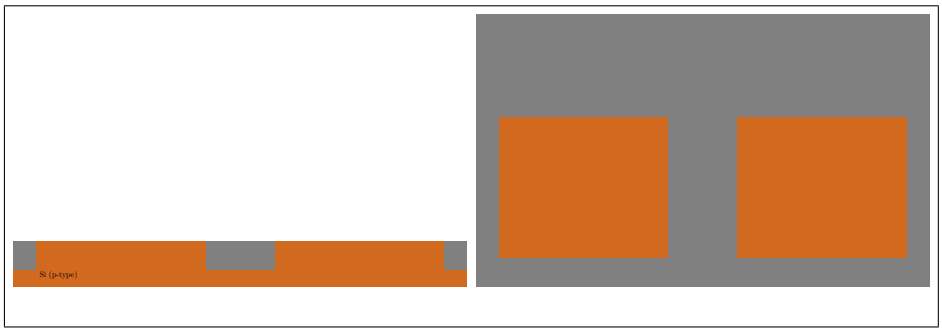

Figure 9: Shallow trench isolation target geometry

As can be seen in section 1, the n-well and the STI trench are supposed to have approximately the same depth. Because the n-well will be $\approx 4\mu m$ in depth (subsection 4.2) we have to match this with our trench depth.

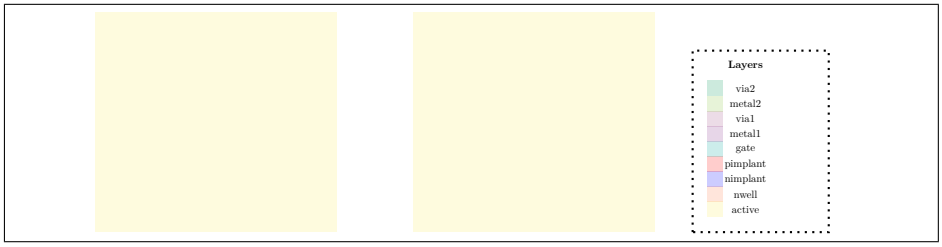

Figure 10: Shallow trench isolation layout

In Figure 10 we can see the layout for the STI area. The STI area will be everywhere, where no active areas are. The deep isolating oxide needs to be grown out of trenches which can't been etched out of the silicon by using resist as a mask. For that reason we will have to resort to a protective mask made from a nitride layer which has to be etched before hand. So the mask will be exposed onto positive resist on top of the nitride in order to form a protective mask covering the active areas from having etched trenches into them as show in subsubsection 4.1.7. After that we will use a dry etching method for cutting into the silicon substrate and making the active area become islands with trenches in between, as shown in subsubsection 4.1.9. After these steps we have to remove the nitride mask, for which we expose the same mask again, only this time to a layer of inverted resist.

4.1.1 Initial cleaning

In order to remove the initial naturally grown silicon dioxide from the wafer, acid is being applied to the wafer which leads to a pure silicon substrate wafer as in the process illustration shown in Figure 11.

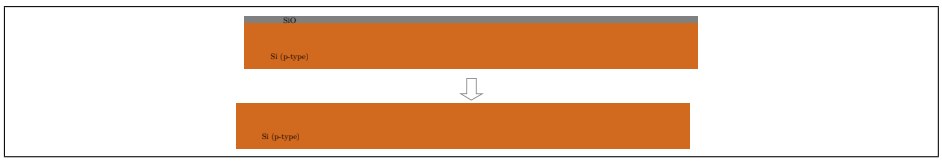

Figure 11: Initial cleaning

This needs to be done because the naturally grown initially existing silicon oxide is not pure and may contain contamination which may render the final product unusable.

4.1.2 Sulfuric Cleaning

The sulfuric acid mixture, $H_2SO_4 + H_2O_2$ is being applied to the wafer for 10 minutes at a temperature of 120 °C.

4.1.3 HF dip

After the sulfuric cleaning a HF (HF:H_2O,1:50) dip is being performed for one minute.
Hydrofluoric acid (HF) is used to remove native silicon dioxide from wafers. Since it acts quickly, one needs to only expose the wafer for a short time (”dip”). After that the wafer needs to be dried and quickly processed further before new uncontrolled natural oxide can build up on the wafer through the contact with air.

4.1.4 Pad oxide

We need a thin layer of oxide as surface to grow our protective nitride layer on top.

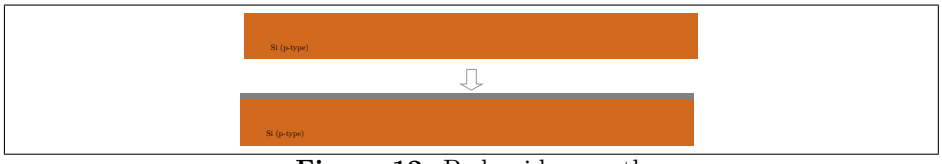

Figure 12: Pad oxide growth

The thin layer of ”pad” oxide (around 300nm) is grown in dry ambient for 45 minutes at 1000°C.[6]

[6]http://cleanroom.byu.edu/OxideTimeCalc

4.1.5 Nitride layer

We need a protective nitride layer for dry etching the trenches into the silicon. This nitride will be grown in this step.

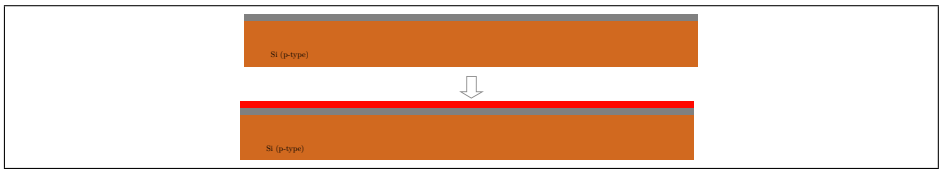

Figure 13: Nitride growth

The required thickness of this layer is not that critical, it can very well variate between 6nm and 10nm.[7]

4.1.6 Patterning positive

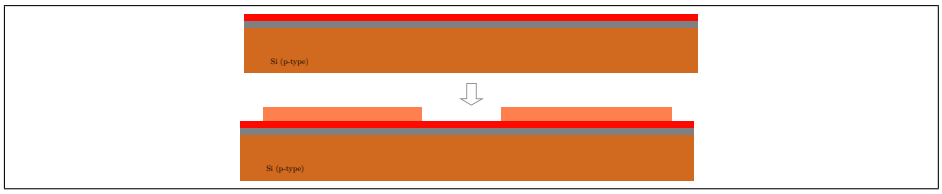

Figure 14: Patterning with positive resist

4.1.7 Nitride etching

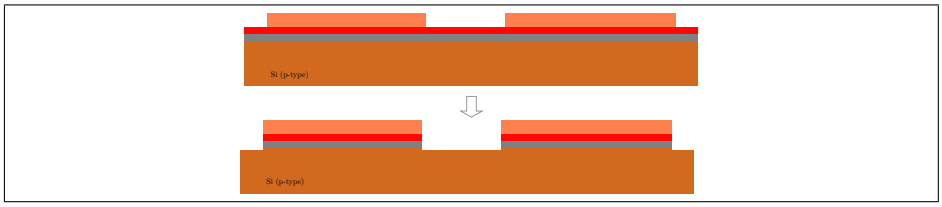

Figure 15: Nitride mask etching

4.1.8 Resist removal

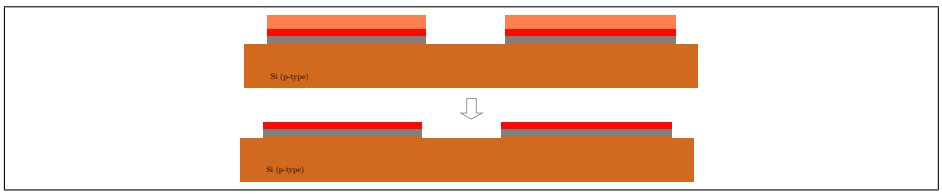

Figure 16: Resist removal

[7] https://www.google.com/patents/US7985656

4.1.9 Silicon etching

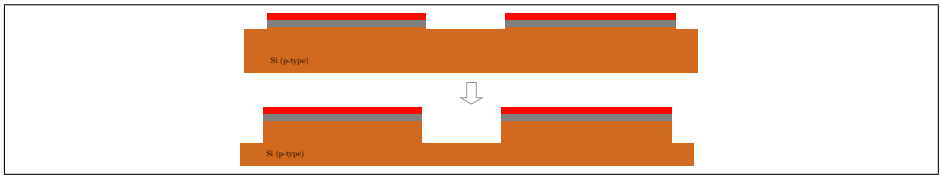

Figure 17: Trench etching

Dry etching (RIE)

4.1.10 Deep oxidation

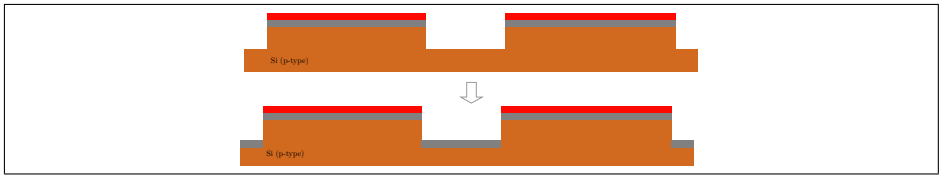

Figure 18: Resist removal

4.1.11 Oxide deposition

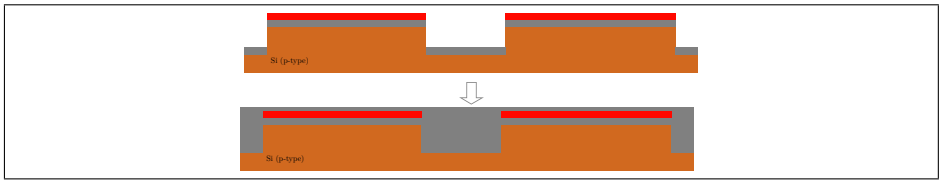

Figure 19: Resist removal

4.1.12 Patterning negative

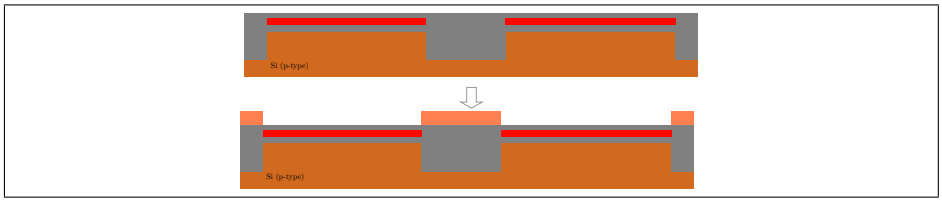

Figure 20: Patterning with negative resist

4.2 Well

In order to build CMOS on the same substrate, an n-well is required for building the complementary P-channel transistor for a n-p-channel logic circuitry as shown above in the example section. The cross section as well as the top view of the targeted geometry are shown in Figure 21

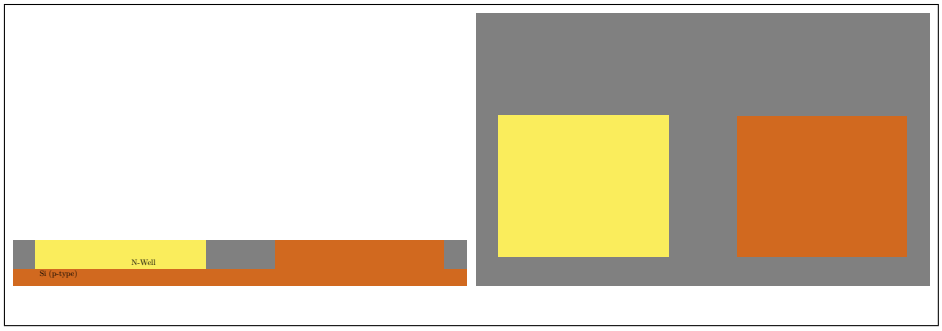

Figure 21: N-well target geometry

The n-well will serve us as an island of n-doped substrate within the p-doped basis substrate. the n-well forms a natural p-n-junction to the later on implanted channel-stop which has a nice side effect of being an additional polarity protection. The dopant dose will be: $2.5 \times 10^{12} cm^{-2}$
The surface concentration of the n-well ($\approx 1 \times 10^{16} cm^{-3}$) is determined primarily by the need to maintain a sufficient high surface concentration to prevent field inversion of the n-well. The depth of the n-well ($\approx 4 \mu m$) is then determined by the need to prevent punch-through of the parasitic vertical pnp transistor under worst case bias conditions.

Figure 22: N-Well layout

In Figure 22 the layout of the n-well region on top of the active area region can be seen. You should make the active area always a little bit bigger than the n-well area in order to avoid hitting parts of the trench oxide with your dopant.

4.2.1 Mask dioxide layer

In order to selectively inject charge carrying atoms into the crystalline structure a protective dioxide (SiO_2) layer needs to be grown on top of a p-type substrate.

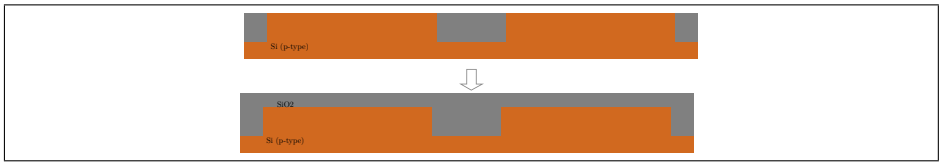

Figure 23: Dioxide layer growth

The industrial best practice is a layer of around (500nm≈5000Å) thickness or more. For this purpose the wafer is being oxidized for at least 90 minutes at 1000°C using wet oxidation which results in a dioxide layer at least 500nm(≈5000Å) in thickness.

4.2.2 Patterning

The resist is being deposited using spin coating and then baked depending on the baking time for the specific resist. The layout for being exposed onto the resist is being extracted from the ”nwell” layer within the GDS2 file.

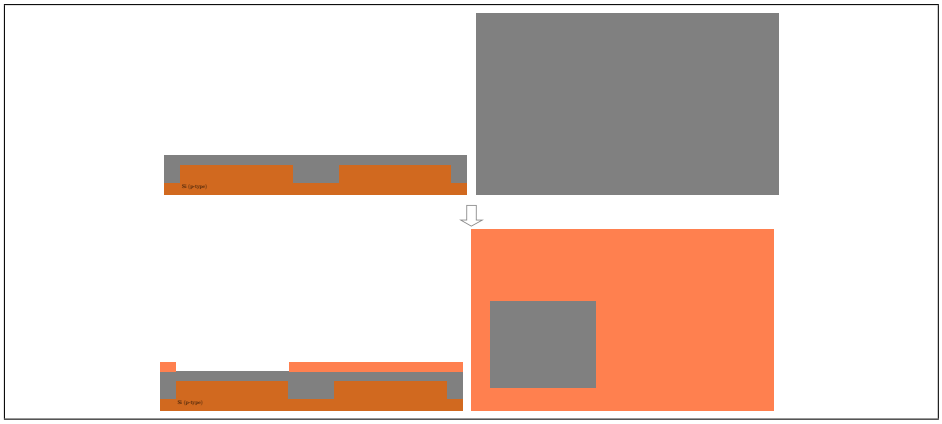

Figure 24: Cross/top view of n-well layout on resist

The thickness of the resist layer and the baking duration will variate depending on the specific equipment for which this process will be implemented with.

4.2.3 Etching

We now need to open a window in the dioxide layer, through which we will inject carrier atoms into the silicon crystal structure.

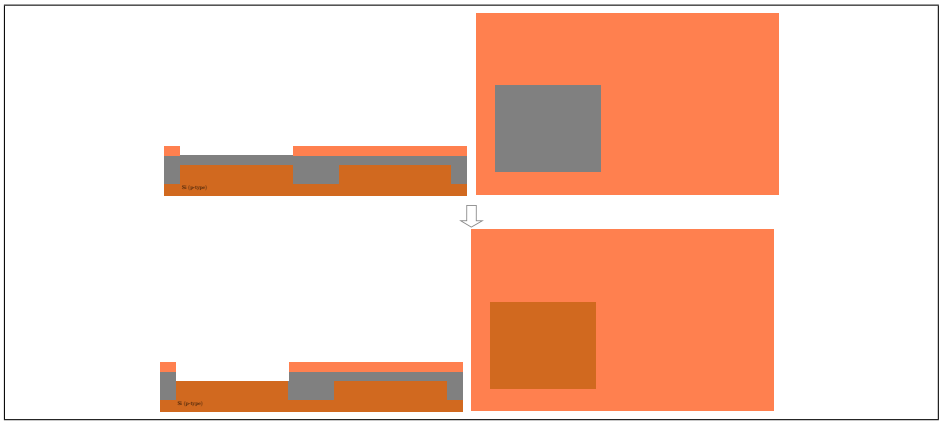

Figure 25: Cross/top view of n-well oxide window

Since the silicon dioxide layer is 500nm thick and we wanna reach the silicon below we can use wet etching as described in the chemistry chapter. Using BHF (6:1) (Equation 3.1) we can etch with a speed of approximately 2 nm/s at 25 °C, we can calculate the etching time to be $\frac{500nm}{2nm/s}$=250s=4 minutes 10 seconds (or make it rather 30 seconds instead of 10)

4.2.4 Cleaning

In order to avoid contamination of the machines we need to make sure all the resist has been stripped off from the wafer.

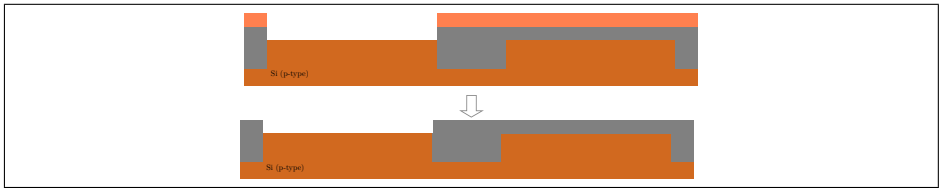

Figure 26: Resist removal

Please just use the solvent for the specific resist.

4.2.5 Injection

We now need to inject the carriers into the upper level of the n-channel area so that we can later on drive them into the crystal during the drive-in step.

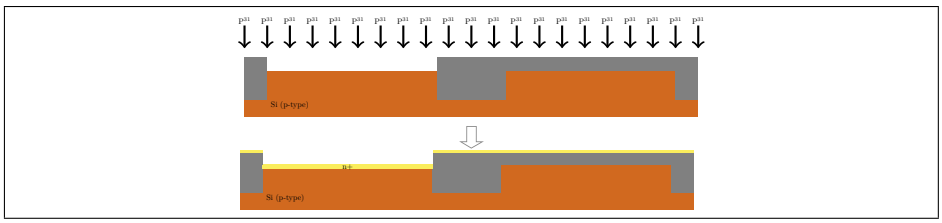

Figure 27: Doping process

The n-well is implanted with a Phosphorus (P^{31}) dose of $2.5 \times 10^{12} cm^{-2}$ at an energy of 100 KeV. The n-well is then annealed.

4.2.6 Oxide for drive-in

Now we need to cover the now doped and annealed areas with an oxide layer for the drive-in phase.

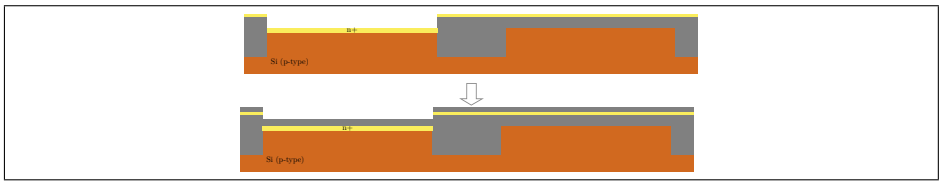

Figure 28: Oxide growth

The wafer is being oxidized for 32 minutes at 1000°C in order to achieve a cover silicon layer of 250nm thickness (≈2500Å).

4.2.7 Drive-in

In order to drive the carrier atoms deeper into the crystalline structure the wafer needs to be driven in after predeposition.

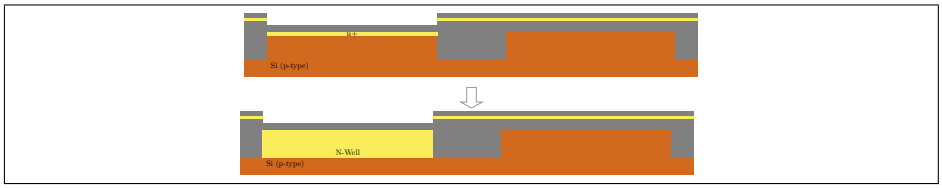

Figure 29: Drive-in process

In this step the wafer is driven-in for 960 minutes at 1150°C in an inert ambient.

4.2.8 Oxide mask removal

We want to remove the silicon mask from the wafer so that the n-well becomes accessible for the further process steps but we don't want to etch "way too much" of the trench material.

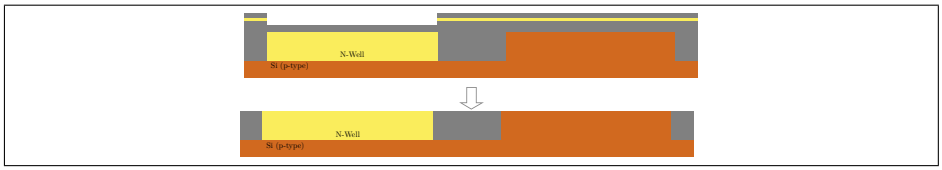

Figure 30: Oxide removal

Since the silicon dioxide layer is 750nm (500nm+250nm) thick and we wanna reach the silicon below we can use wet etching as described in the chemistry chapter. Using BHF (6:1) (Equation 3.1) we can etch with a speed of approximately 2 nm/s at 25 °C. We can calculate the etching time to be $\frac{750nm}{2nm/s}$=375s=6 Minutes and 15 Seconds.

Etching away a ”little bit too much” of the oxide isn't that bad, because the oxide within the trenches will be ”filled up” again during the later steps.

4.3 n+ Implant

For the bulk of the PMOS transistors and for the source and drain of the NMOS transistors highly doped n+ areas are required. In this step we're going to build these.

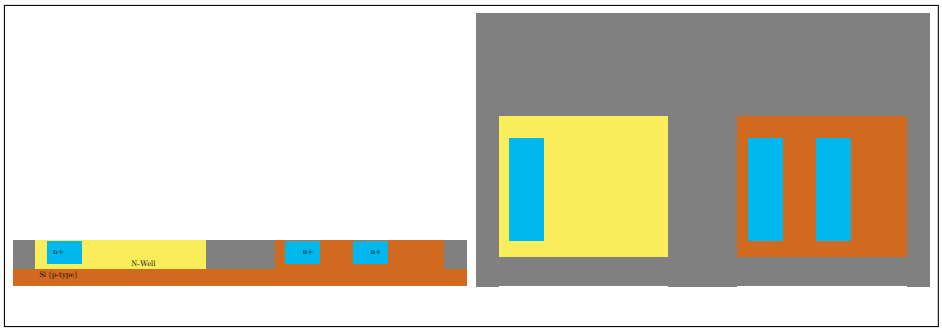

Figure 31: N+ implant geometry target

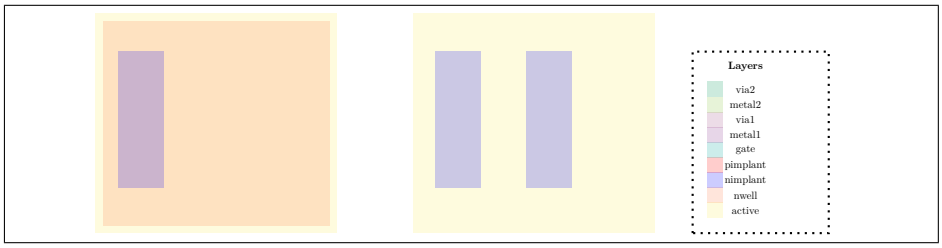

Figure 32: N+ layout

4.3.1 Mask dioxide layer

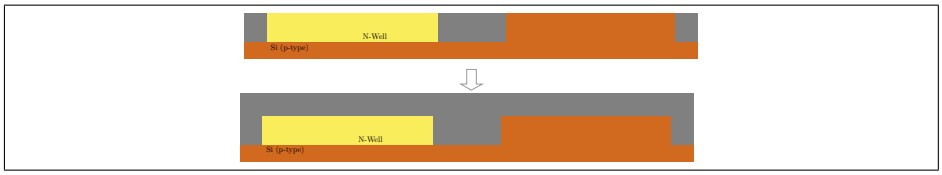

Figure 33: Oxide layer

4.3.2 Pattering

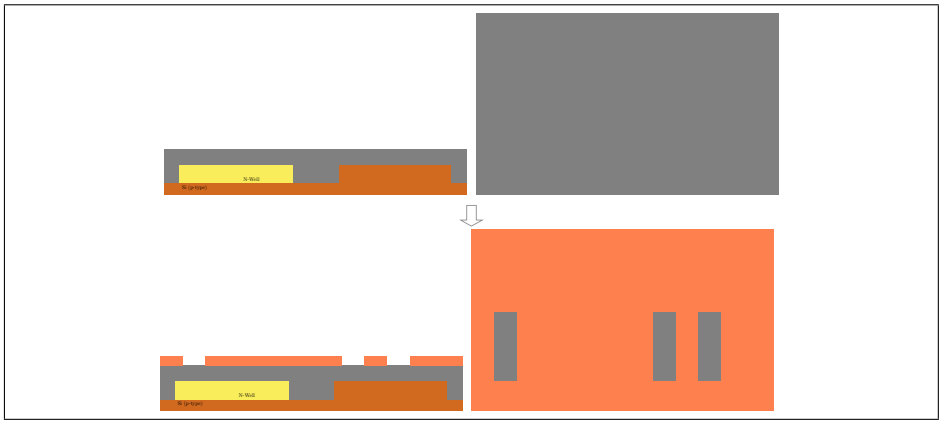

Figure 34: N+ region resist mask

4.3.3 Etching

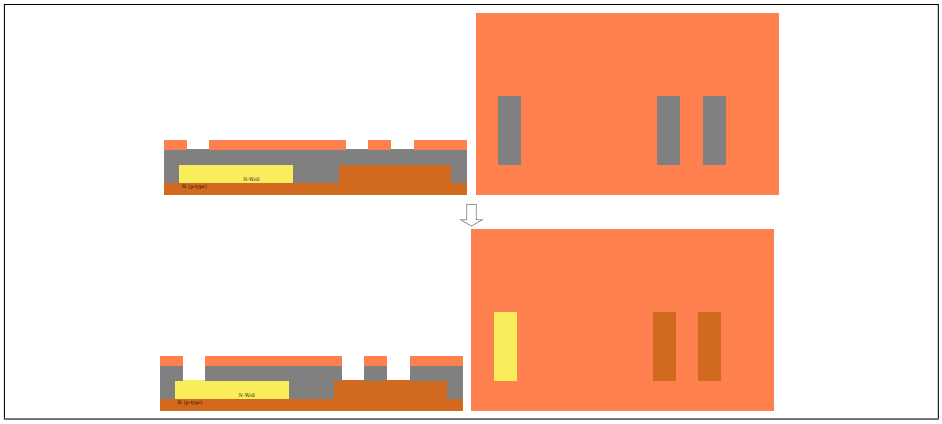

Figure 35: N+ region opened

4.3.4 Cleaning

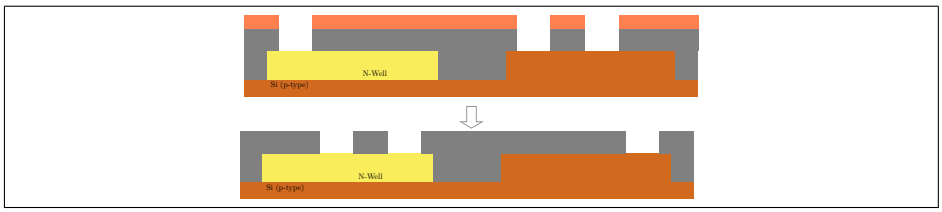

Figure 36: Resist removal

4.3.5 Injection

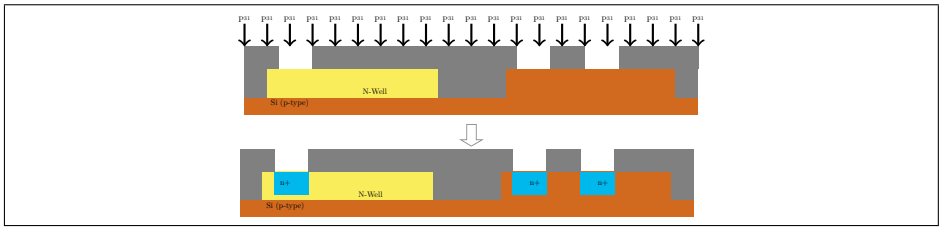

Figure 37: N+ injection process

4.3.6 Oxide removal

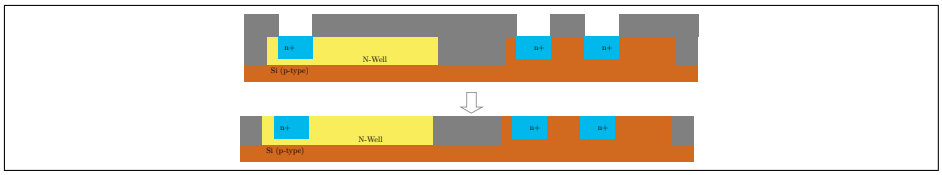

Figure 38: Oxide removal

4.4 p+ Implant

For the bulk of the NMOS transistors and for the source and drain of the PMOS transistors highly doped p+ areas are required. In this step we're going to build these.

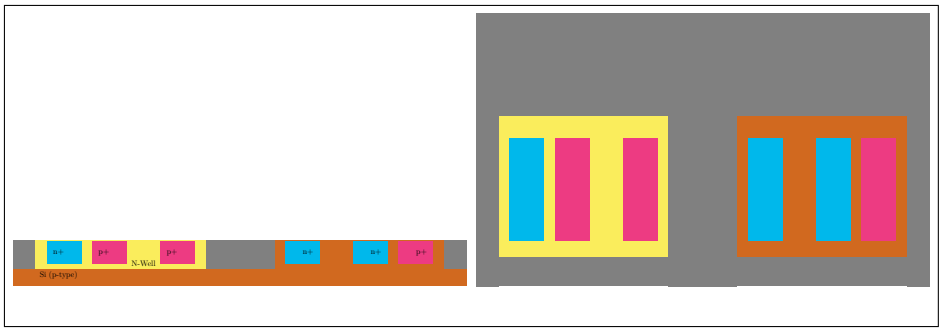

Figure 39: P+ implant geometry target

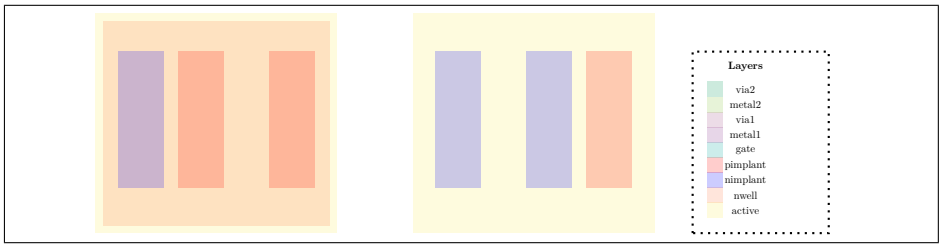

Figure 40: P+ layout

4.4.1 Mask dioxide layer

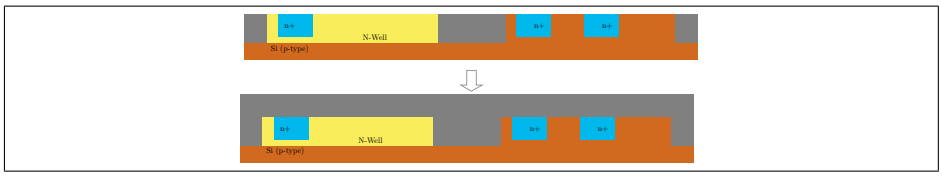

Figure 41: Oxide layer

4.4.2 Pattering

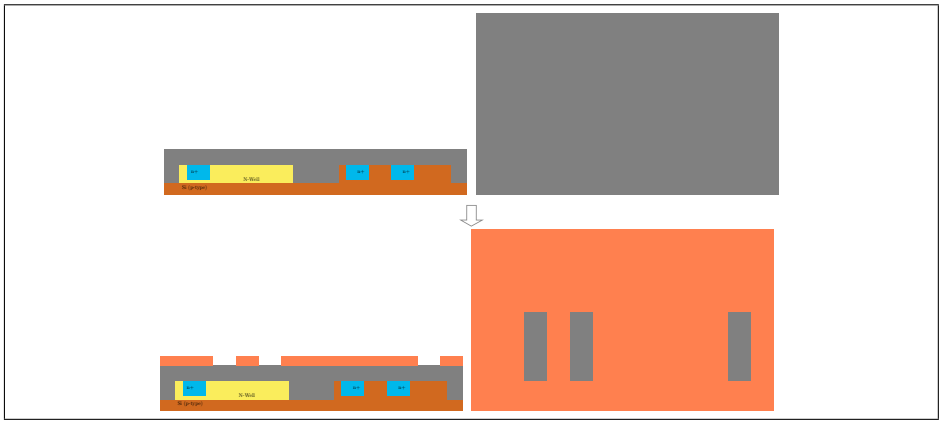

Figure 42: P+ region resist mask

4.4.3 Etching

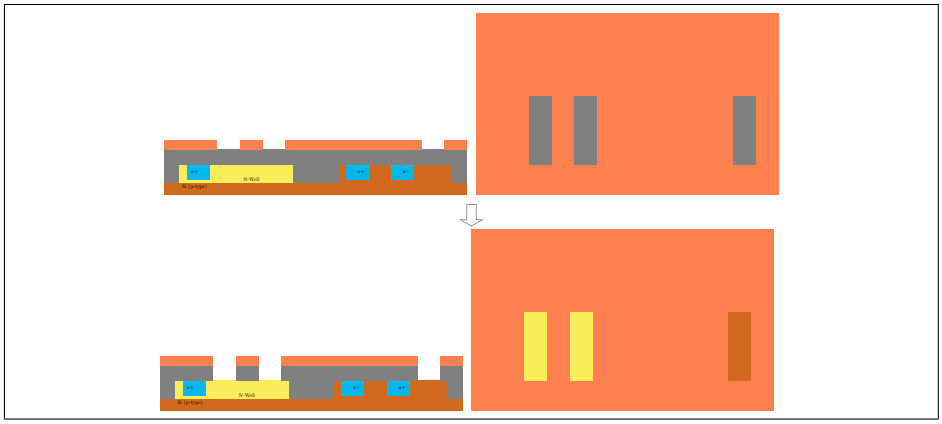

Figure 43: P+ region opened

4.4.4 Cleaning

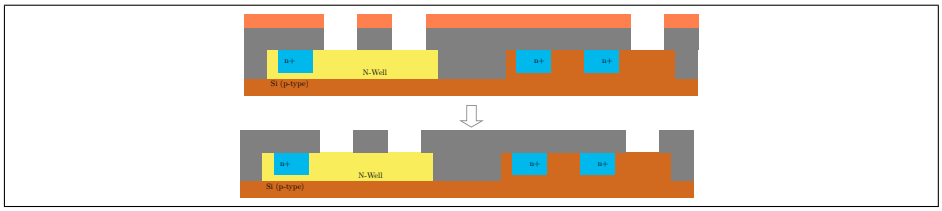

Figure 44: Resist removal

4.4.5 Injection

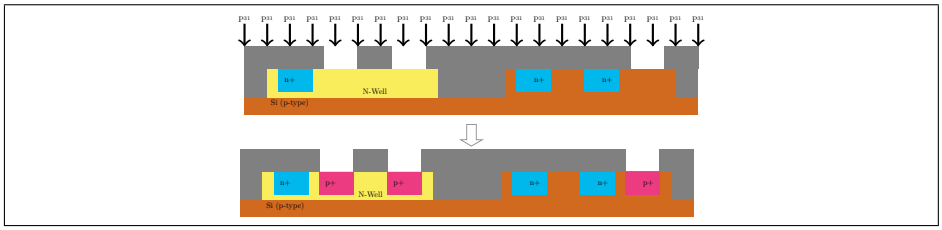

Figure 45: P+ injection process

4.4.6 Oxide removal

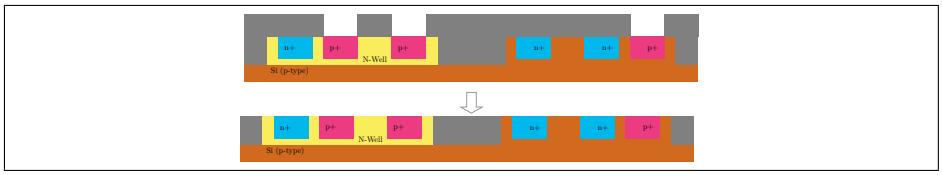

Figure 46: Oxide removal

4.5 Gate contact

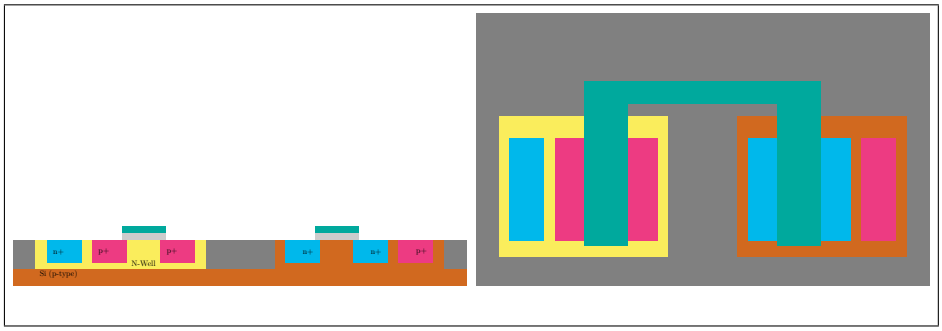

Figure 47: Aluminum gate contacts with gate oxide

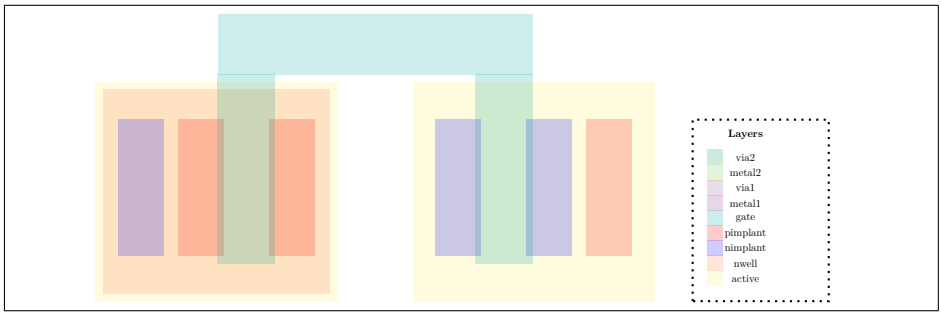

Figure 48: Gate layout

4.6 First vias

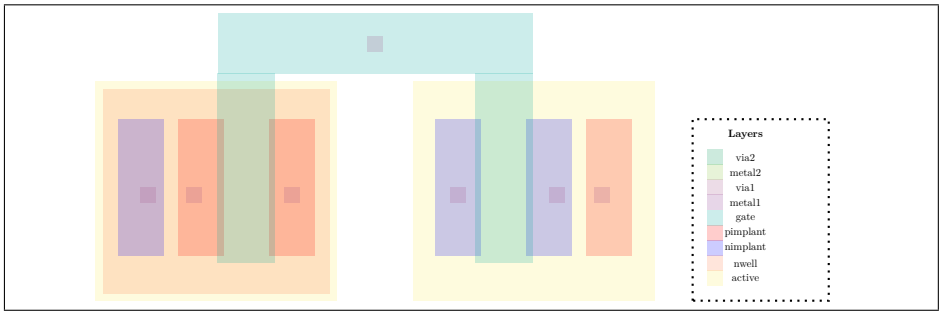

Figure 49: First via layout

4.7 First metal layer

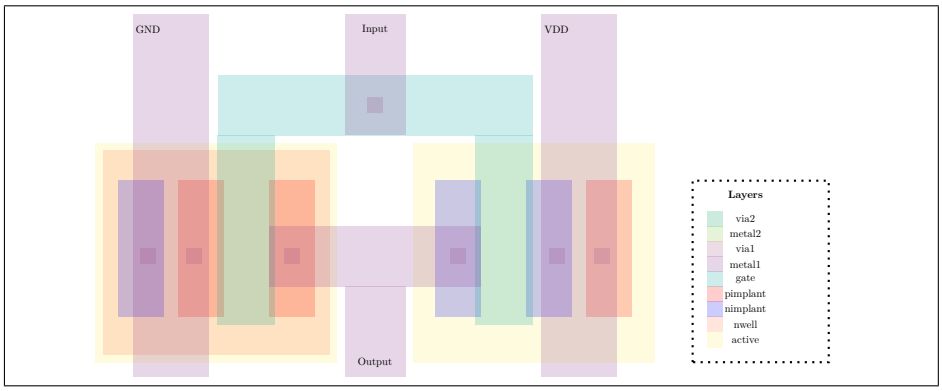

Figure 50: First metal layout

4.8 Additional vias

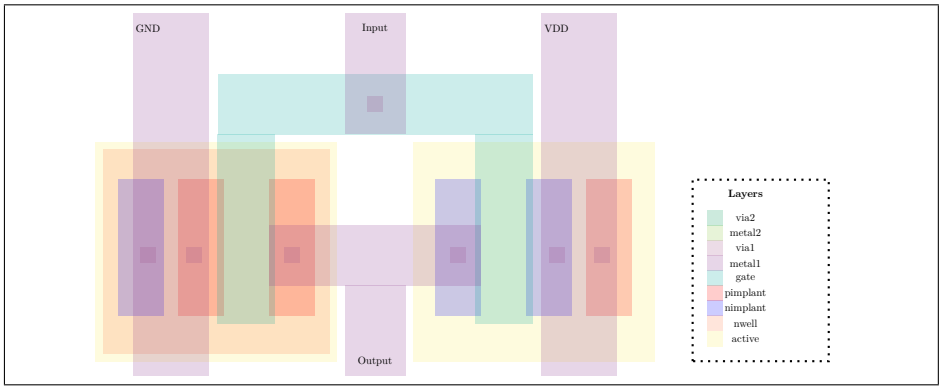

Figure 51: Additional via layout

4.9 Additional metal layer

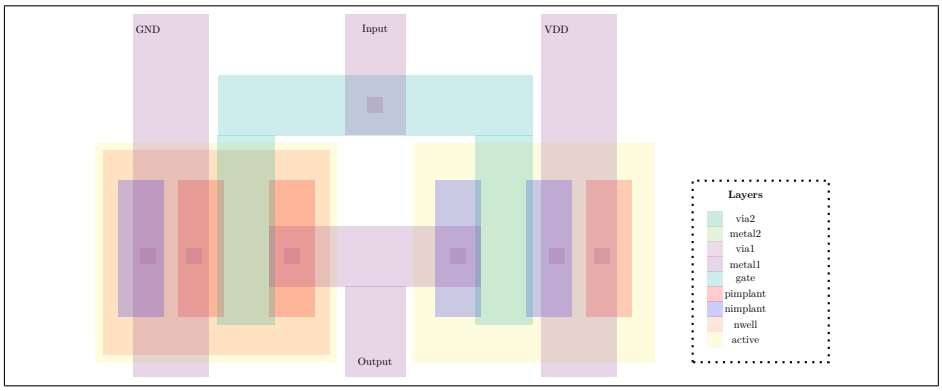

Figure 52: Additional metal layout