

Abstract

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This document is part of the specification of the free silicon manufacturing standard for manufacturing the LibreSilicon standard logic cells¹ and related free technology nodes from the LibreSilicon project.

For this initial revision 0.1 a gate-first approach has been chosen which led to the choice of polysilicon as the gate electrode material because of the simplicity of the gate alignment. For better isolation properties of the transistors and gates in overall a box-isolation approach has been chosen. All of these choices have been made with the future scale down from the recent $1\mu m$ to smaller structure sizes. **This process is for manufacturing $1\mu m$ only!** But further releases which will have been tested with smaller structure sizes can be expected.

¹<https://github.com/chipforge/StdCellLib>

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Libre Silicon process steps

David Lanzendörfer

July 9, 2019

The general flow chart of the overall process flow can be seen in [Figure 1](#). These process steps will be discussed within the following sections.

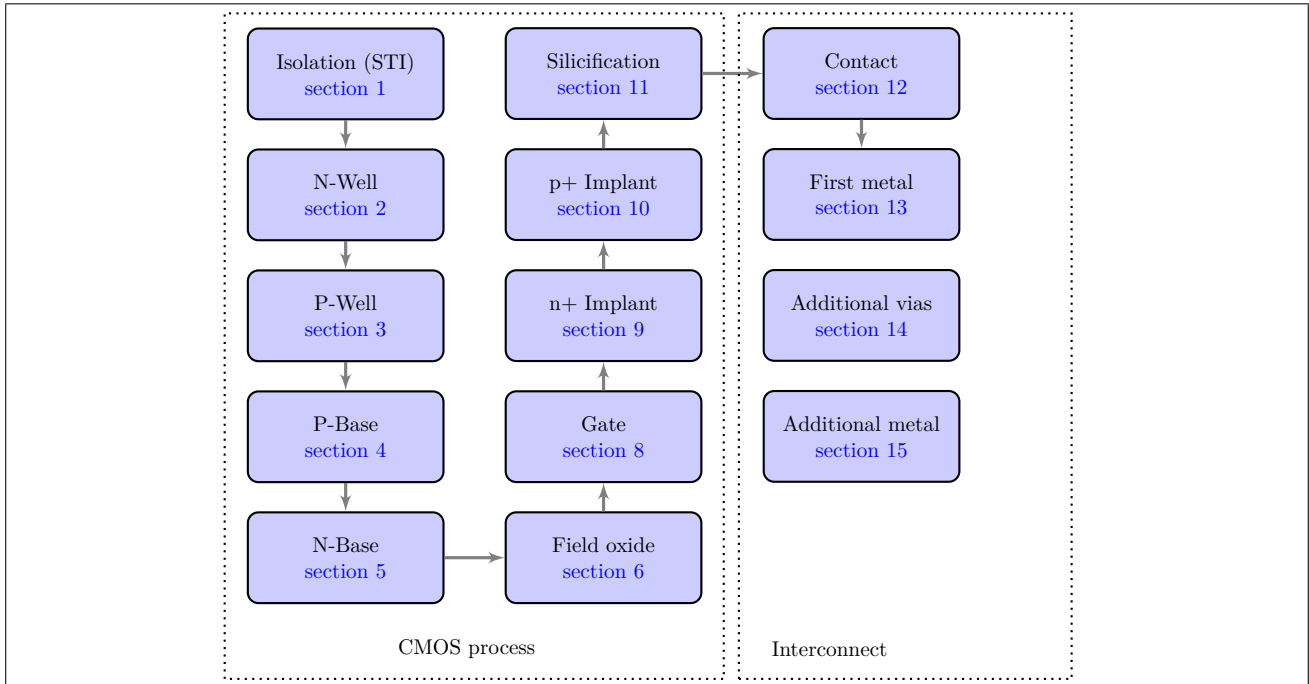


Figure 1: Frontend and backend process flow

The six 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, $\langle 100 \rangle$ oriented silicon with a doping concentration of $\approx 9 \times 10^{14} \text{ cm}^{-3}$.

Machines required:

- Ion implanter
- Plasma etcher
- Sputter engine (Metal deposition)
- Diffusion furnace
- Exposure unit

1 Shallow trench isolation

The geometry of a substrate with STI implemented can be seen in [Figure 2](#).

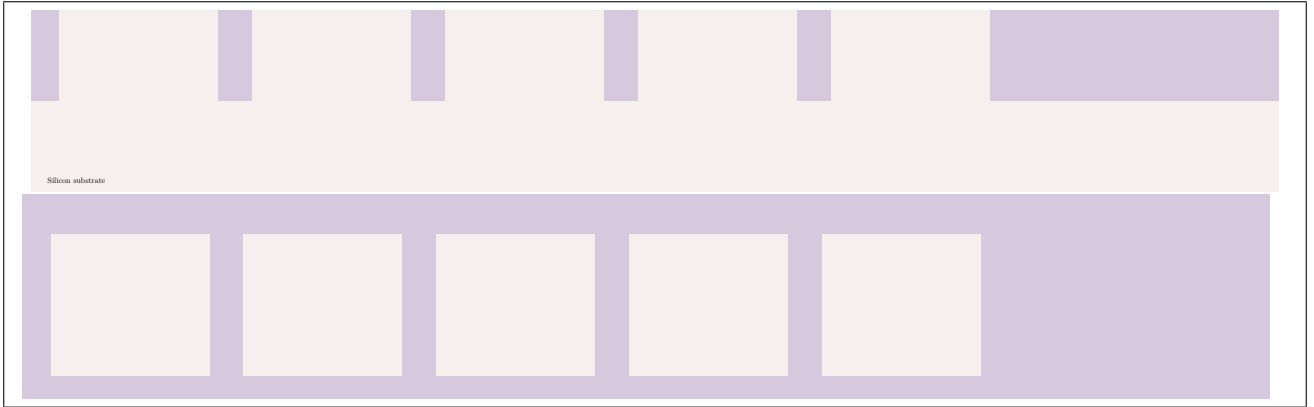


Figure 2: Shallow trench isolation target geometry

As can be seen in [Figure 23](#), the n-well and the STI trench are supposed to have approximately the same depth but the n-well and p-well go down a little bit further. Because the n-well will be $\approx 4\mu m$ in depth we have to match this with our trench depth. In order to allow a sufficiently low resistance of the ESD diode but at the same time a sufficient isolation of between the standard cells a trade-off has been done. The targeted depth of the box isolation is $\approx 4\mu m$.

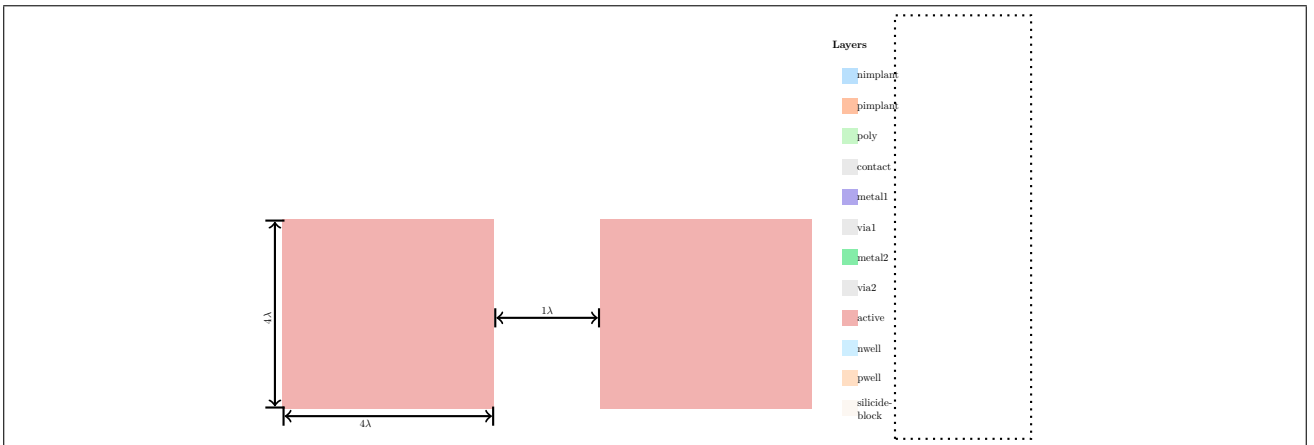


Figure 3: Shallow trench isolation layout

In [Figure 3](#) we can see the layout for the STI area. The STI area will be everywhere, where no well areas are. The field oxide needs to be grown out of trenches which can't be 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 silicon dioxide layer which has to be etched before hand. So the mask will be exposed onto positive resist on top of the hard mask oxide layer in order to form a protective mask covering the active areas from having etched trenches into them. After that we can either use a dry etching method or wet etching for cutting into the silicon substrate and making the active area become islands with trenches in between. After these steps we have to remove the hard mask. Our minimum width and height as well as the space between the active areas comes from the line space constrain of the silicon etcher and of course the optical limitations of the stepper which are as well $0.5\mu m$.

1.1 Patterning

The resist is being deposited using spin coating and then soft baked depending on the baking time for the specific resist. The requirement is a **positive** tone resist.

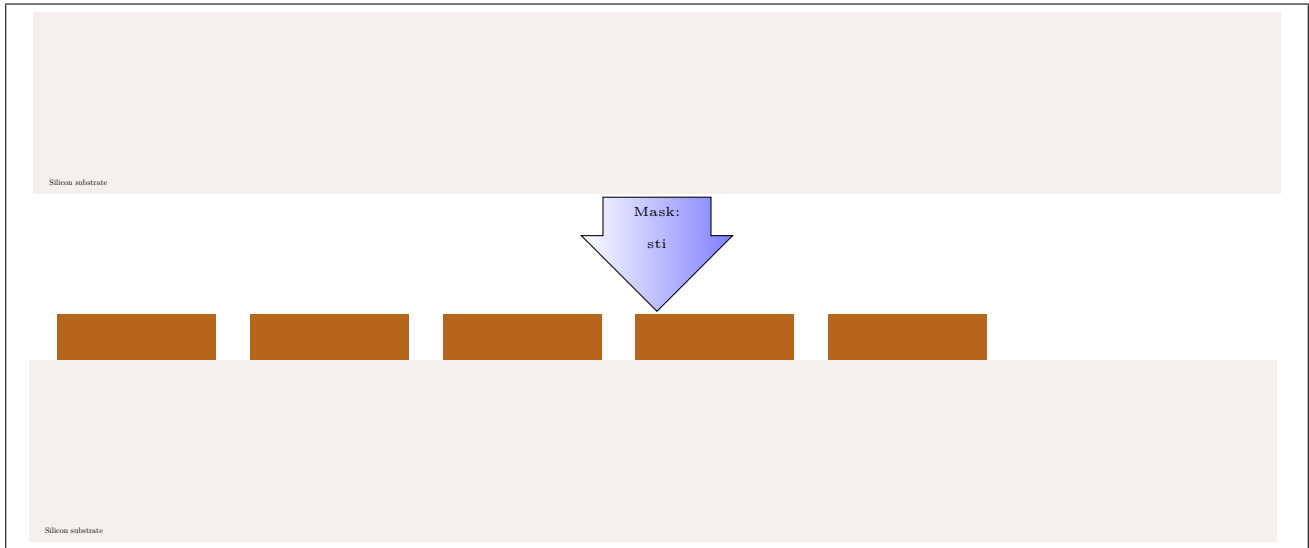


Figure 4: Patterning with positive resist

The layout for being exposed onto the resist is being extracted from the "active" layer within the GDS2 file onto a **bright field** mask because we need to use the same mask again in [section 6](#), so alignment needs to be possible.

1.2 Silicon etching

The trench depth has to be at least 4.5 microns deep, in order to compensate for sacrificial silicon polishing during the later CMP steps.

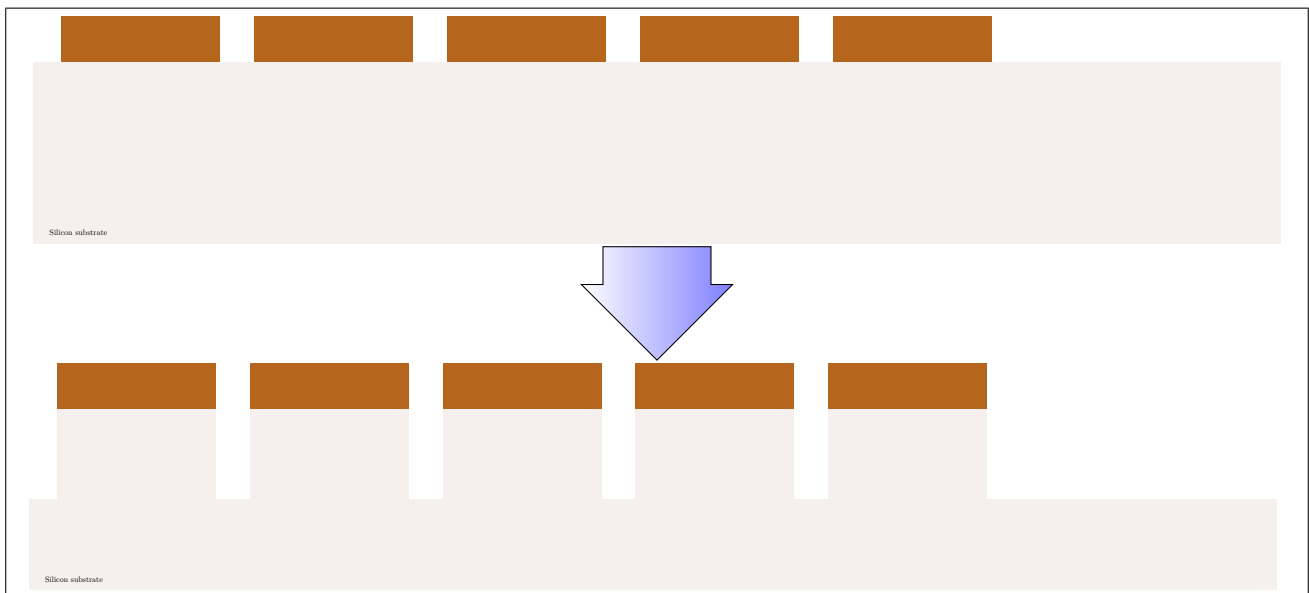


Figure 5: Trench etching

Typically it's a good approach to set the parameters of the DRIE recipe to an amount of cycles which will result in a depth of roughly 5 microns.

1.3 Resist removal

Now we need to remove the contaminants for further processing.

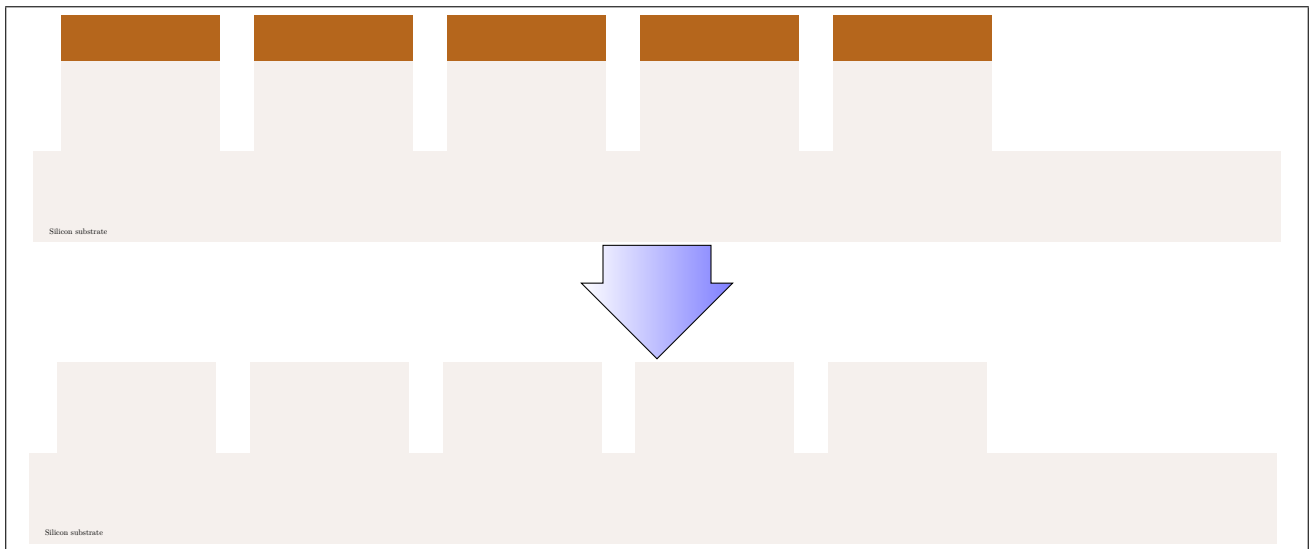


Figure 6: Resist removal

We strip the resist, rinse and perform sulfuric cleaning.

1.4 LTO+CMP

Now the trenches need to be filled up with LTO and planarized until we meet a sufficiently low height differential between the oxide surface and the silicon surface.

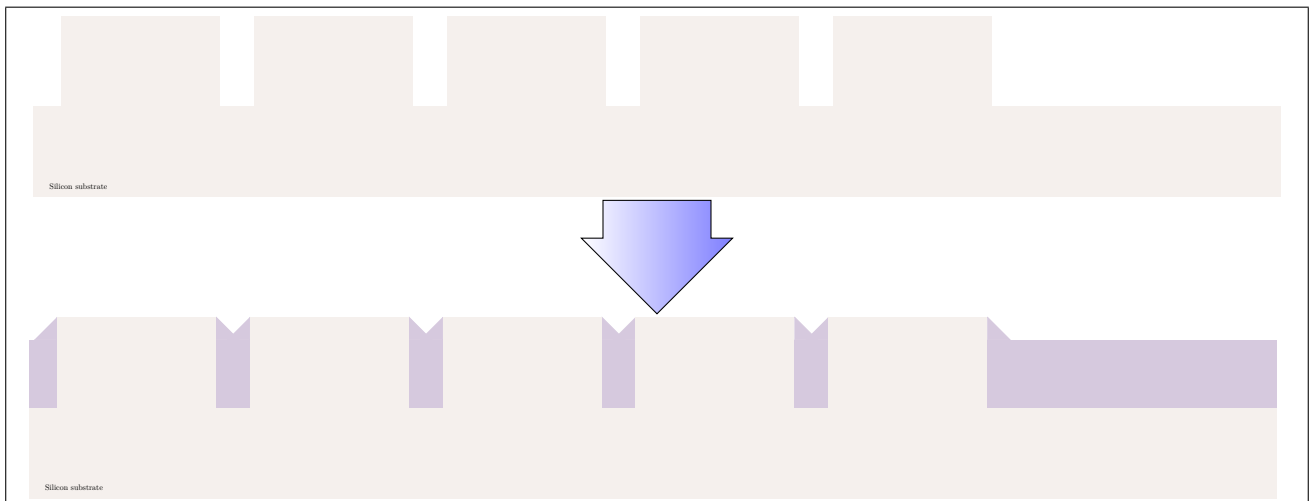


Figure 7: Resist removal

This process loop until a height differential below 200nm is being reached turned out to be a good approach. We start counting LTO+CMP steps at 1:

- Deposit 5 microns LTO ($\frac{5\mu}{2^{step-1}}$)
- CMP around 5 microns LTO
- Clean in hot ammonia
- Put into buffered oxide etch or DI:HF (50:1) for one or two minutes, until silicon surface on the islands is free of oxide
- Repeat until height differential lower than 200nm

2 N-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 23](#)

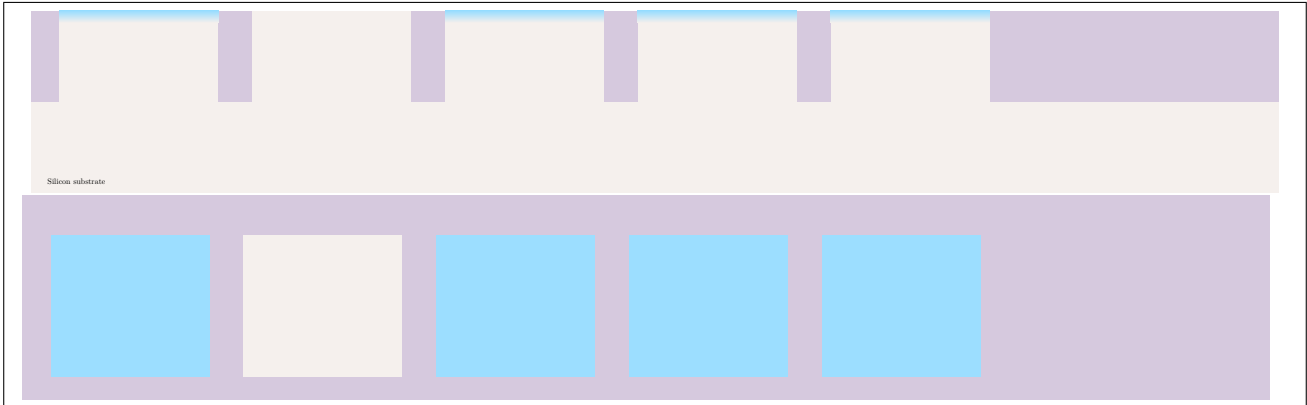


Figure 8: N-well target geometry

The N-well will serve us as an island of N-doped substrate within the P-doped basis substrate. The dopant dose will be $2.5 \times 10^{12} \text{cm}^{-2}$ as calculated in the documentation of the process design leading to these steps¹.

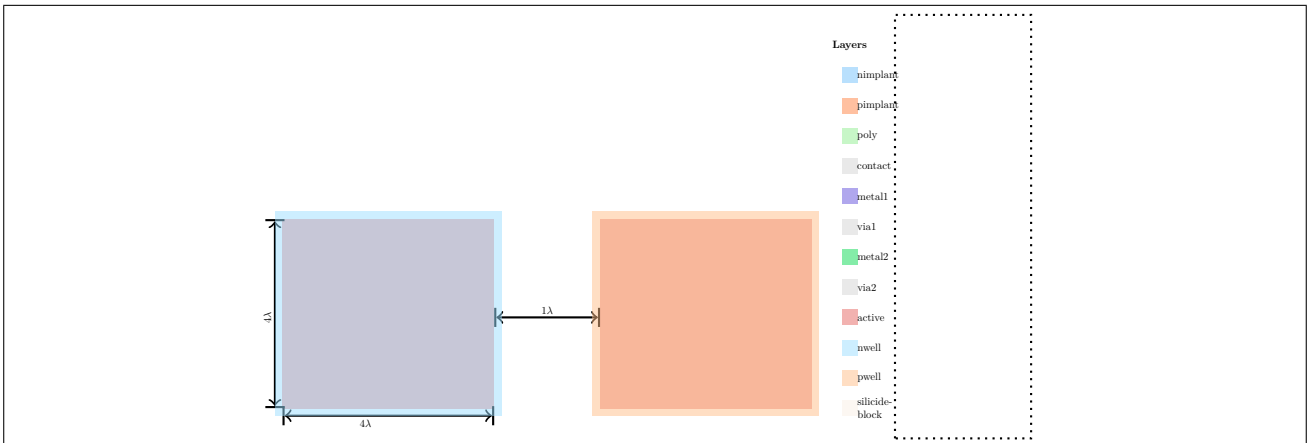


Figure 9: N-Well layout

In [Figure 24](#) the layout of the n-well region on top of the active area region can be seen. The n-well is being fit into the active area. It should even be a little bit bigger than the active area, because of possible alignment offsets. The layout is being automatically generated for GDS2 based on cifoutput rules, so you just have to draw you well.

¹https://github.com/leviathanch/libresiliconprocess/raw/master/process_design/process_design.pdf

2.1 Patterning

The resist is being deposited using spray coating because of the uneven nature of the oxide layer. After that the wafer is being soft baked depending on the baking time and temperature for the specific resist. The layout for being exposed onto the resist is being extracted from the "nwell" layer within the GDS2 file onto a **bright field** mask. The requirement is a **negative** tone resist.

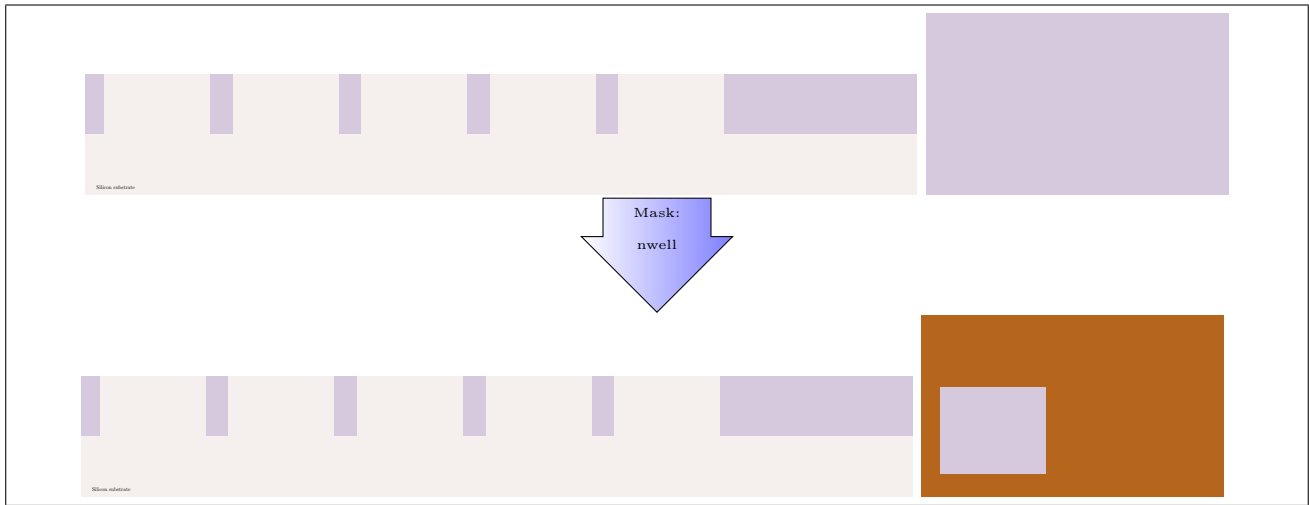


Figure 10: Cross/top view of n-well layout on resist

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. Also after the exposure and development, the hard baking shouldn't be forgotten!

2.2 Implantation

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.

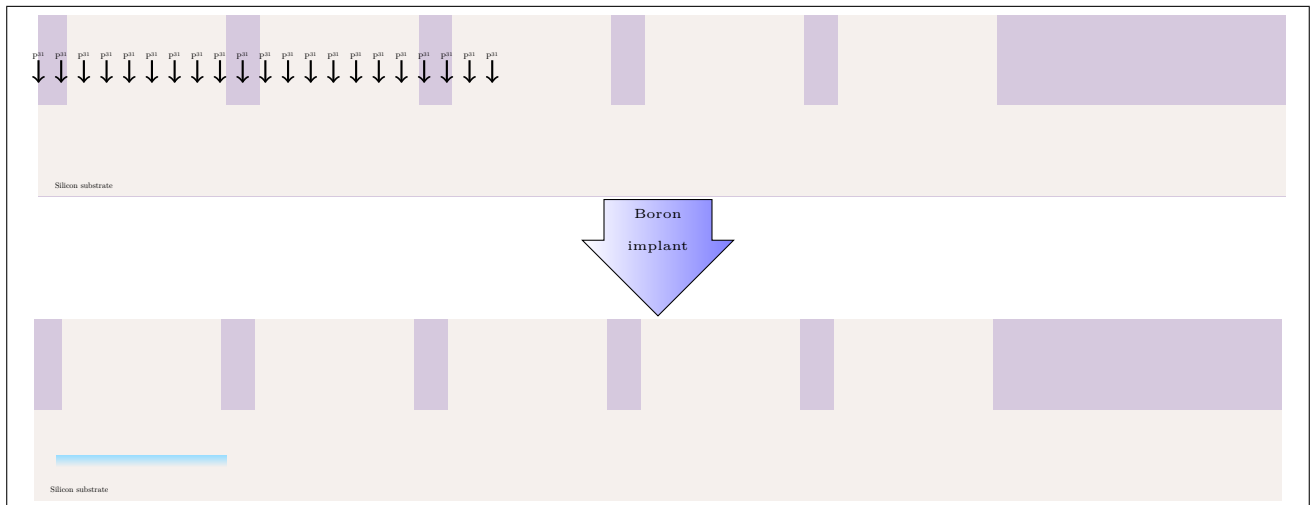


Figure 11: Implant process

Possible approaches:

- "CF-3000 Implanter (IMP-3000)" from HKUST

At HKUST we have an implanter which gives us better control over the initial surface concentration.

These steps are needed to arrive with the desired geometry: 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.

2.3 Resist strip

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

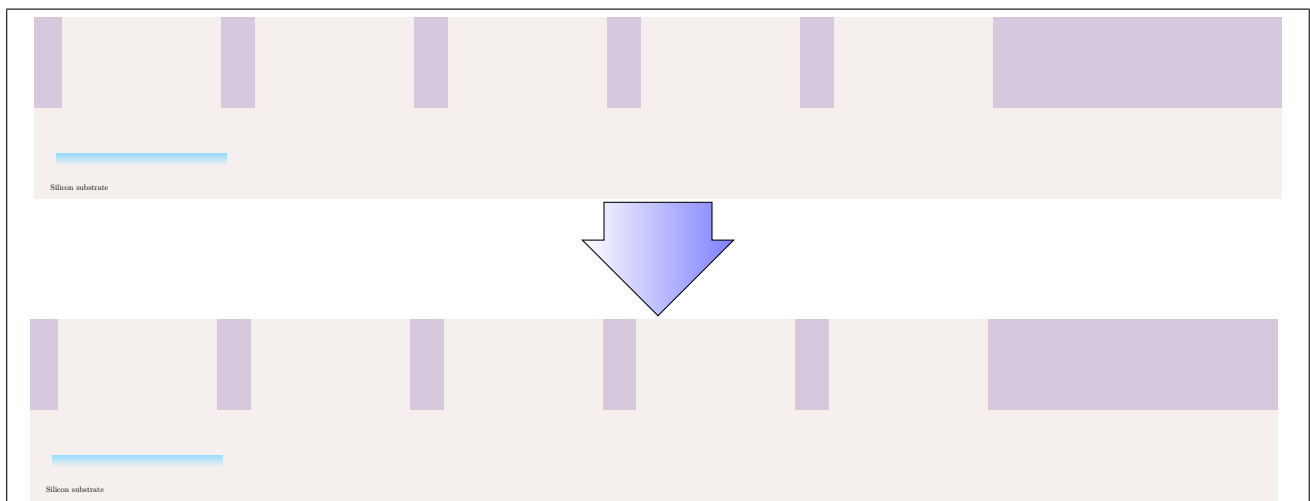


Figure 12: Resist removal

Please just use the solvent for the specific resist.

3 P-well

In order to build CMOS on the same substrate, a P-well is required for building the complementary N-channel transistor for a n-p-channel logic circuitry. The cross section as well as the top view of the targeted geometry are shown in [Figure 23](#)

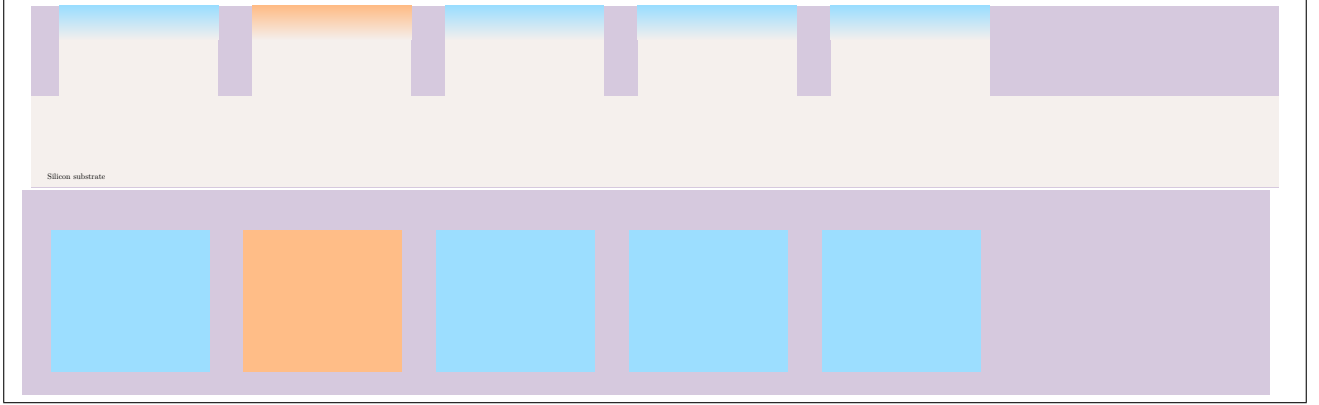


Figure 13: P-well target geometry

The P-well will serve us as an island of higher p-doped substrate within the slightly p-doped basis substrate. The dopant dose will be $2.5 \times 10^{12} \text{cm}^{-2}$ as calculated in the documentation of the process design leading to these steps².

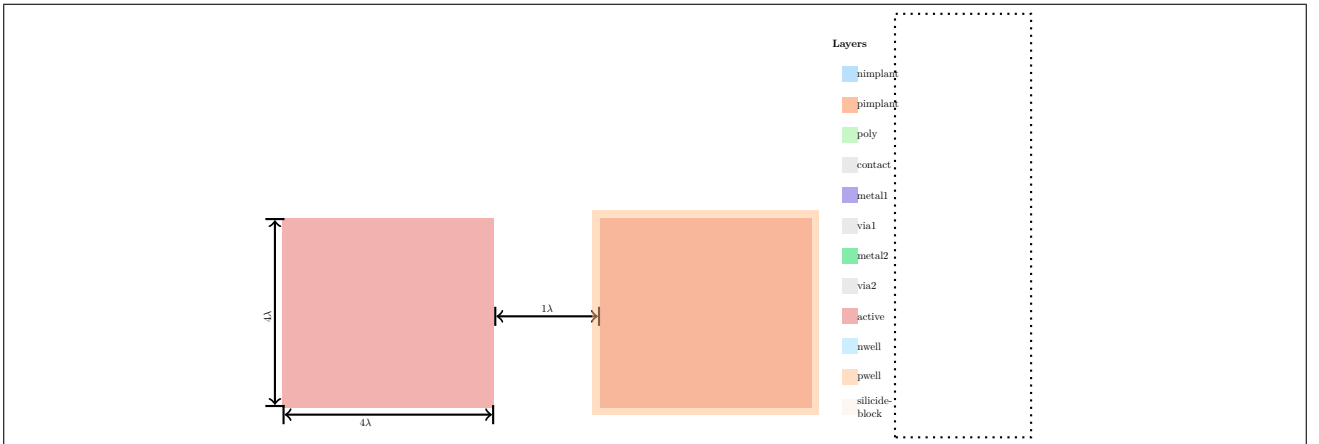


Figure 14: P-Well layout

In [Figure 19](#) the layout of the P-well region on top of the active area region can be seen.

The p-well is being fit into the active area.

It should even be a little bit bigger than the active area, because of possible alignment offsets.

The layout is being automatically generated for GDS2 based on cifoutput rules, so you just have to draw you well.

²https://github.com/leviathanch/libresiliconprocess/raw/master/process_design/process_design.pdf

3.1 Patterning

The resist is being deposited spray or spin coating (spray coating is better because of the uneven surface!) and then soft baked depending on the baking time for the specific resist. The layout for being exposed onto the resist is being extracted from the "pwell" layer within the GDS2 file onto a **bright field** mask. The requirement is a **negative** tone resist.

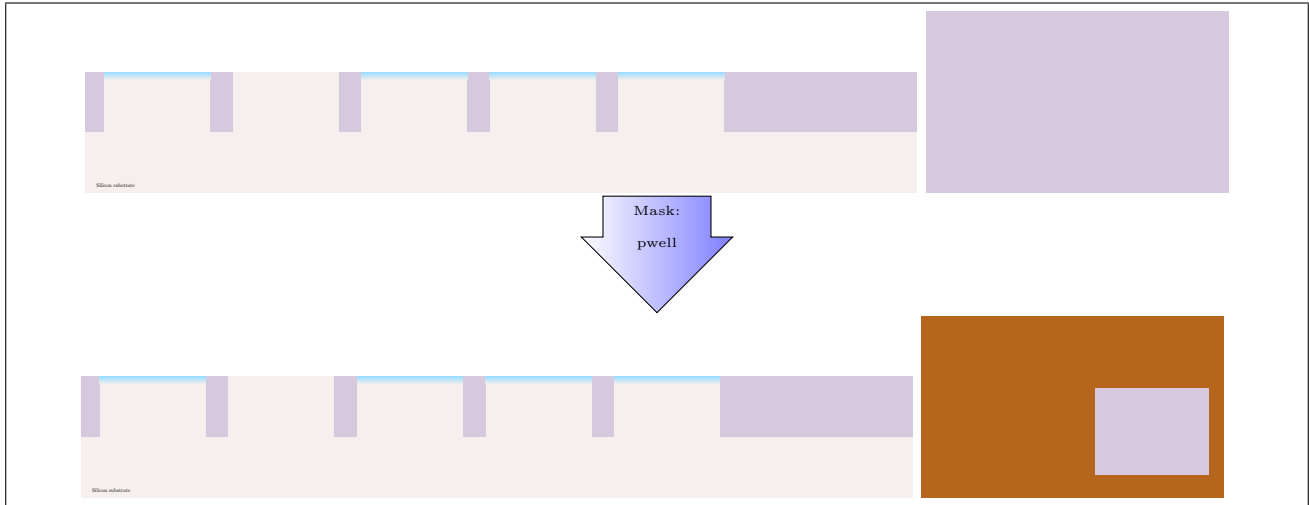


Figure 15: Cross/top view of P-well layout on resist

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. Also after the exposure and development, the hard baking shouldn't be forgotten!

3.2 Implantation

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.

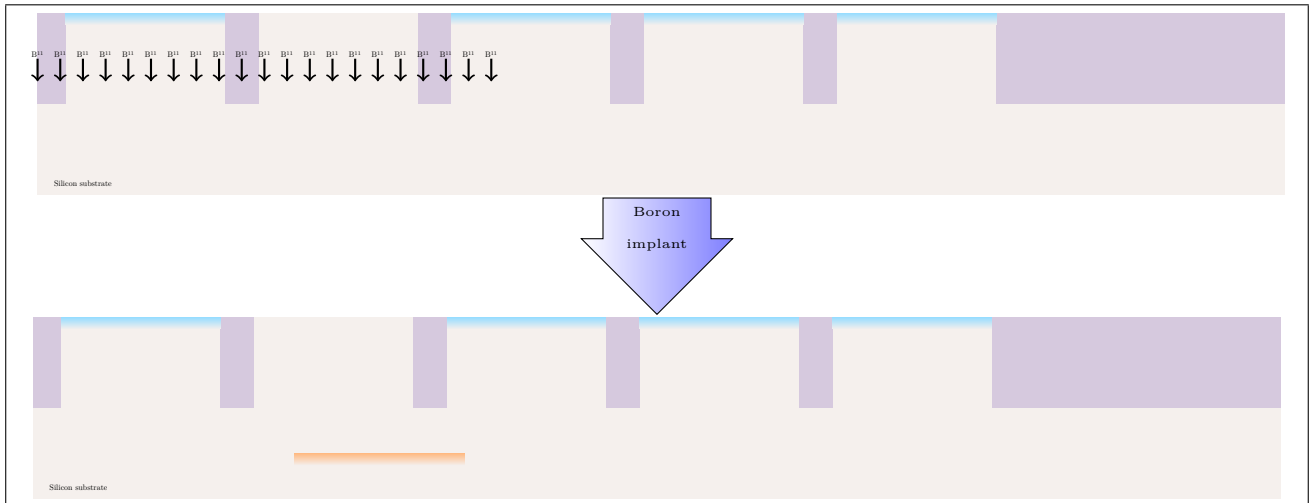


Figure 16: Doping process

Possible approaches:

- "CF-3000 Implanter (IMP-3000)" from HKUST

At HKUST we have an implanter which gives us better control over the initial surface concentration.

These steps are needed to arrive with the desired geometry: The P-well is implanted with a Boron (B^{11}) dose of $2.5 \times 10^{12} cm^{-2}$ at an energy of 100 keV

3.3 Resist strip

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

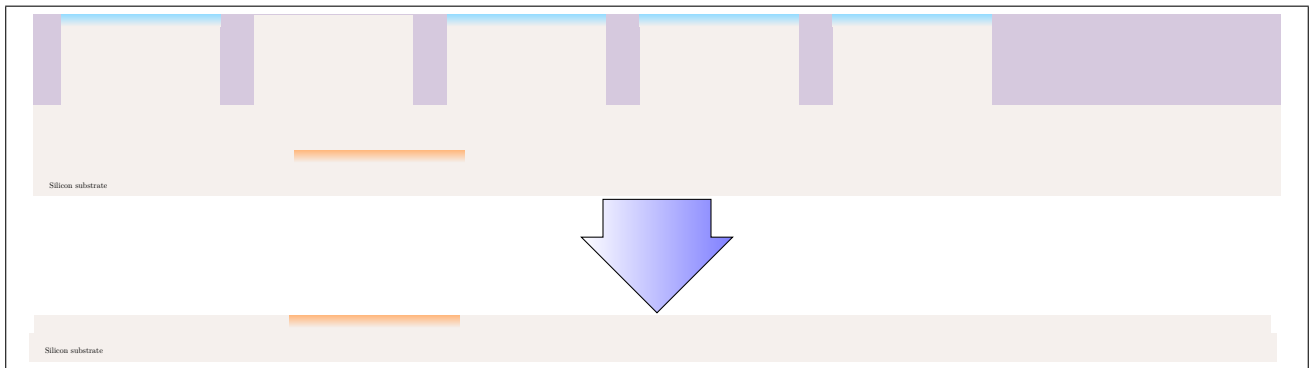


Figure 17: Resist removal

Please just use the solvent for the specific resist.

4 P-base

In order to build CMOS on the same substrate, a P-well is required for building the complementary N-channel transistor for a n-p-channel logic circuitry. The cross section as well as the top view of the targeted geometry are shown in [Figure 23](#)

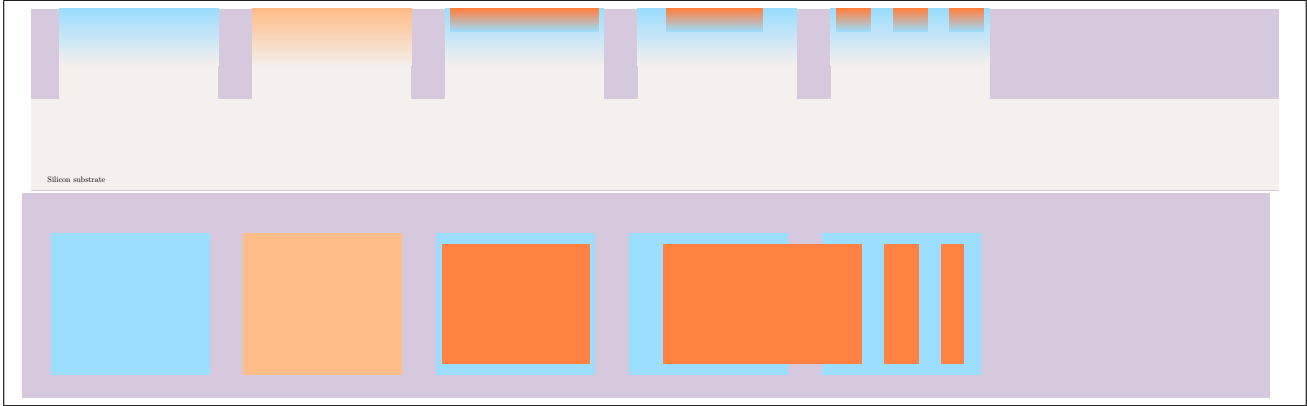


Figure 18: P-well target geometry

The P-well will serve us as an island of higher p-doped substrate within the slightly p-doped basis substrate. The dopant dose will be $2.5 \times 10^{12} \text{cm}^{-2}$ as calculated in the documentation of the process design leading to these steps³.

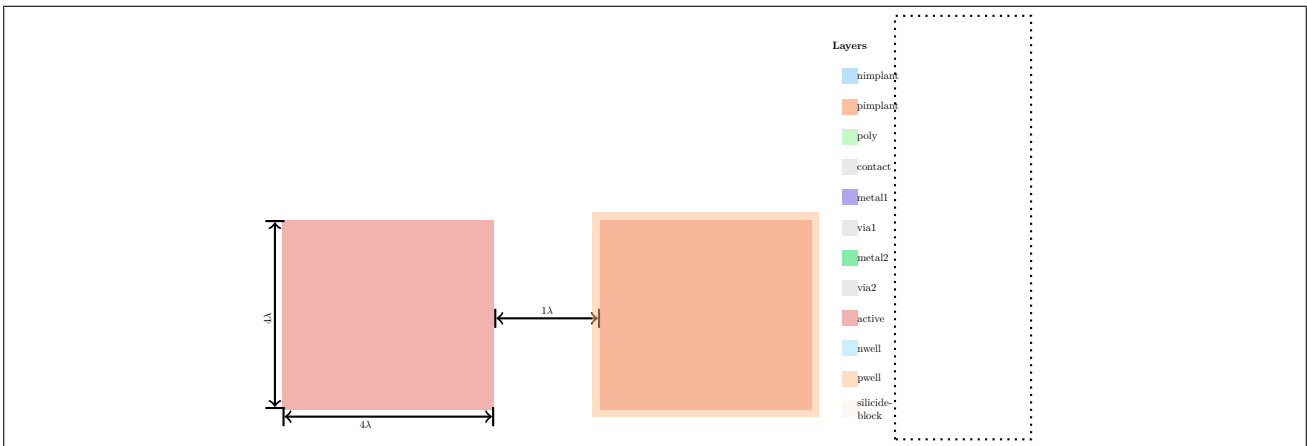


Figure 19: P-Well layout

In [Figure 19](#) the layout of the P-well region on top of the active area region can be seen.

The p-well is being fit into the active area.

It should even be a little bit bigger than the active area, because of possible alignment offsets.

The layout is being automatically generated for GDS2 based on cifoutput rules, so you just have to draw you well.

³https://github.com/leviathanch/libresiliconprocess/raw/master/process_design/process_design.pdf

4.1 Patterning

The resist is being deposited spray or spin coating (spray coating is better because of the uneven surface!) and then soft baked depending on the baking time for the specific resist. The layout for being exposed onto the resist is being extracted from the "pwell" layer within the GDS2 file onto a **bright field** mask. The requirement is a **negative** tone resist.

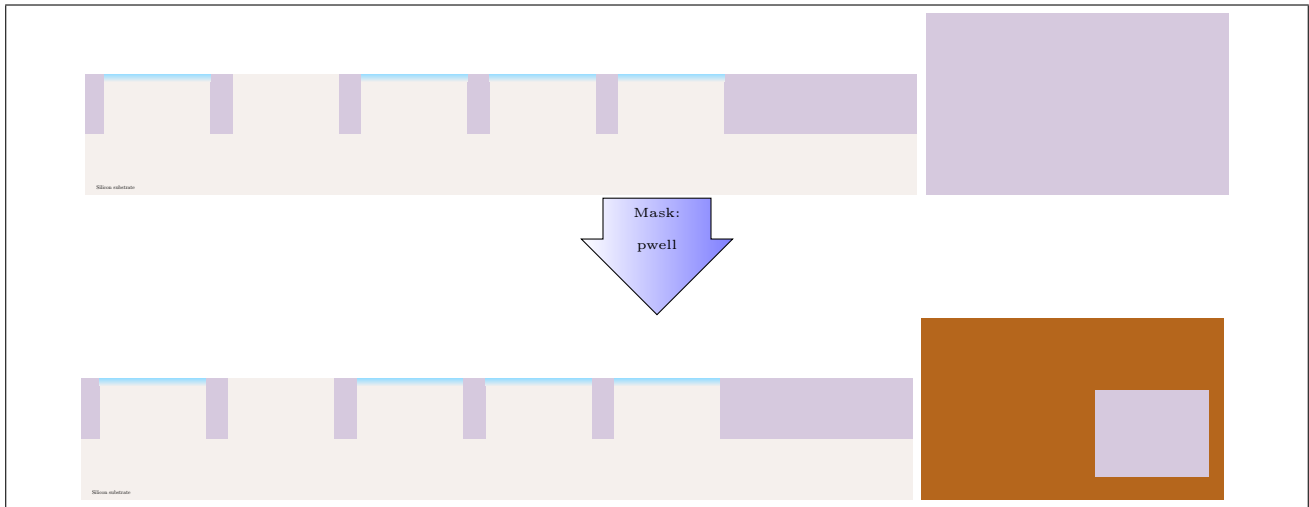


Figure 20: Cross/top view of P-well layout on resist

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. Also after the exposure and development, the hard baking shouldn't be forgotten!

4.2 Implantation

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.

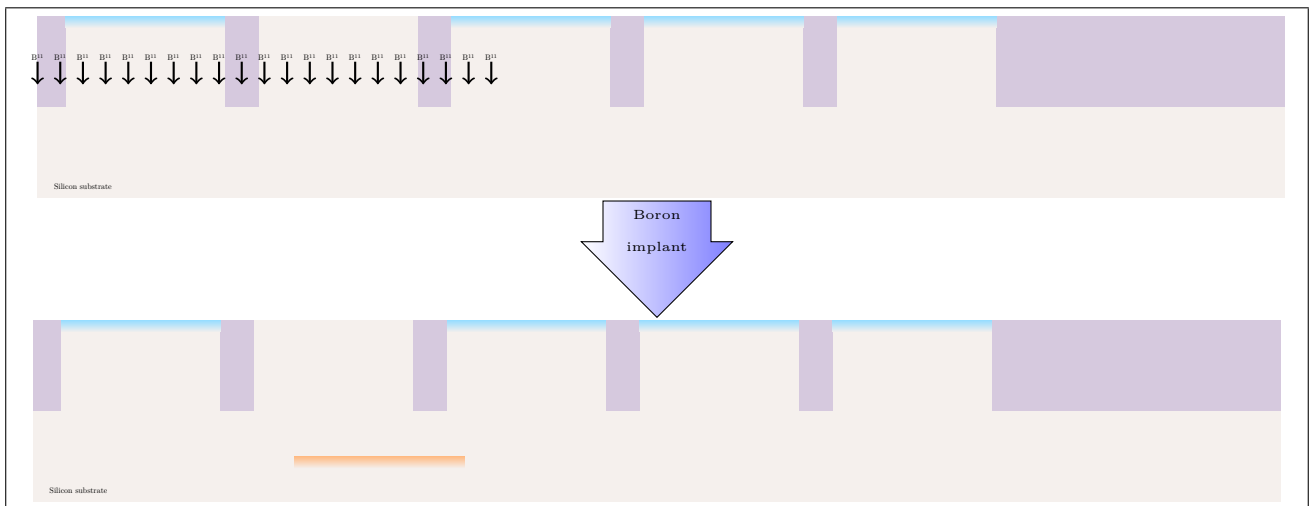


Figure 21: Doping process

Possible approaches:

- "CF-3000 Implanter (IMP-3000)" from HKUST

At HKUST we have an implanter which gives us better control over the initial surface concentration.

These steps are needed to arrive with the desired geometry: The P-well is implanted with a Boron (B^{11}) dose of $2.5 \times 10^{12} cm^{-2}$ at an energy of 100 keV

4.3 Resist strip

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

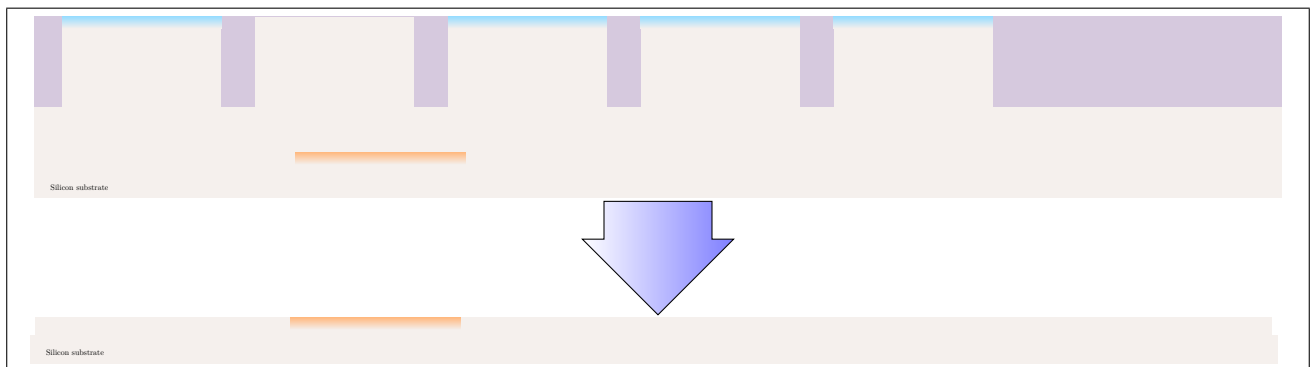


Figure 22: Resist removal

Please just use the solvent for the specific resist.

5 N-base

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 23](#)

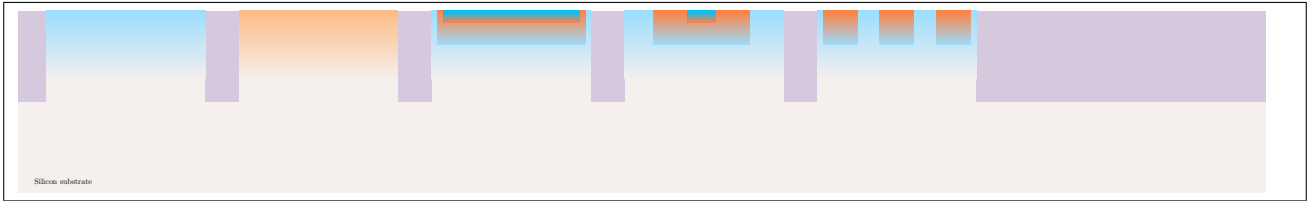


Figure 23: N-well target geometry

The N-well will serve us as an island of N-doped substrate within the P-doped basis substrate. The dopant dose will be $2.5 \times 10^{12} \text{cm}^{-2}$ as calculated in the documentation of the process design leading to these steps⁴.

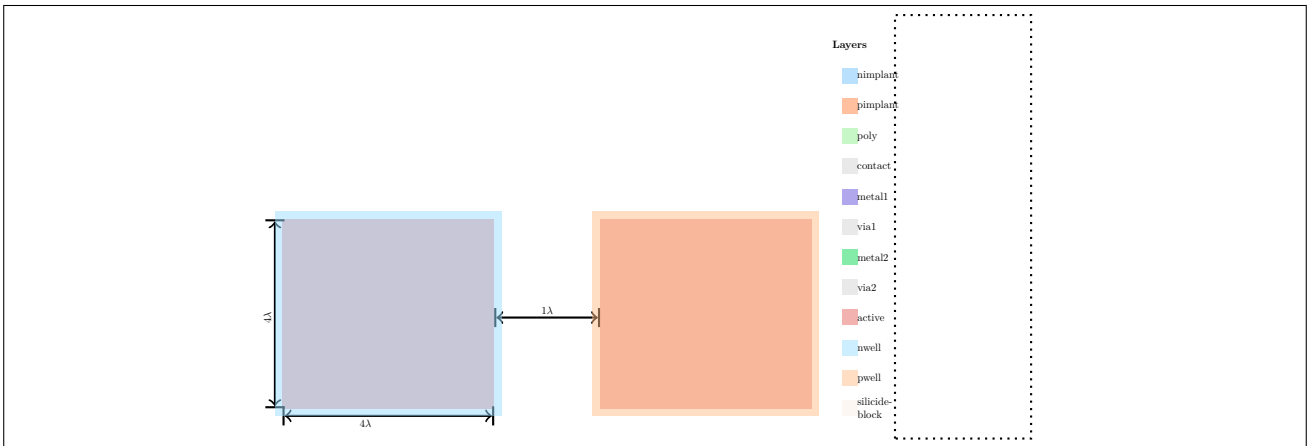


Figure 24: N-Well layout

In [Figure 24](#) the layout of the n-well region on top of the active area region can be seen.

The n-well is being fit into the active area. It should even be a little bit bigger than the active area, because of possible alignment offsets.

The layout is being automatically generated for GDS2 based on cifoutput rules, so you just have to draw you well.

⁴https://github.com/leviathanch/libresiliconprocess/raw/master/process_design/process_design.pdf

5.1 Patterning

The resist is being deposited using spray coating because of the uneven nature of the oxide layer. After that the wafer is being soft baked depending on the baking time and temperature for the specific resist. The layout for being exposed onto the resist is being extracted from the "nwell" layer within the GDS2 file onto a **bright field** mask. The requirement is a **negative** tone resist.

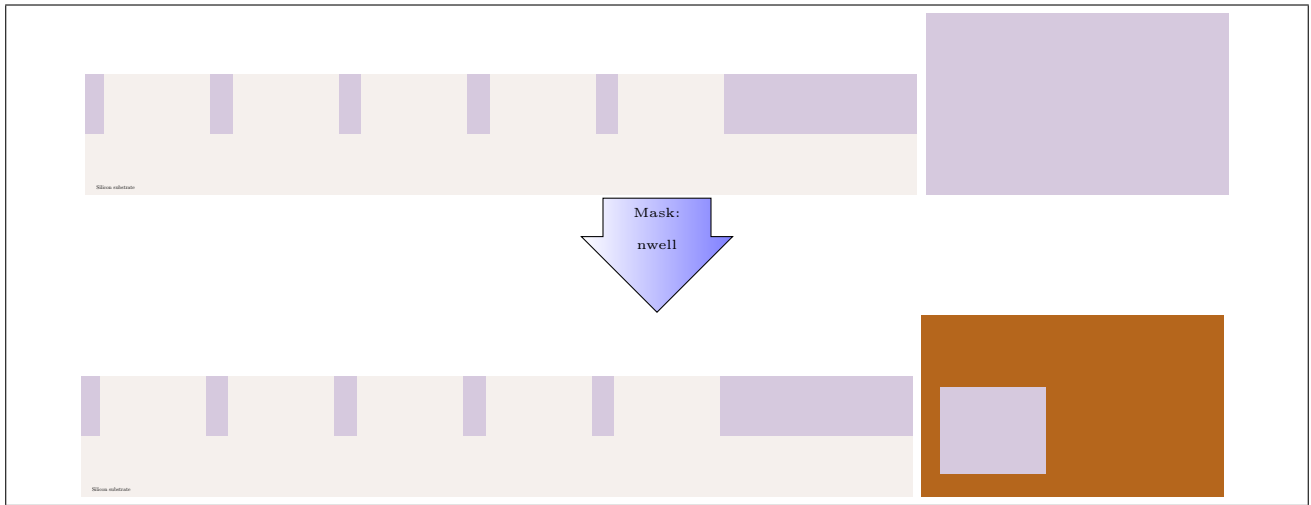


Figure 25: Cross/top view of n-well layout on resist

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. Also after the exposure and development, the hard baking shouldn't be forgotten!

5.2 Implantation

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.

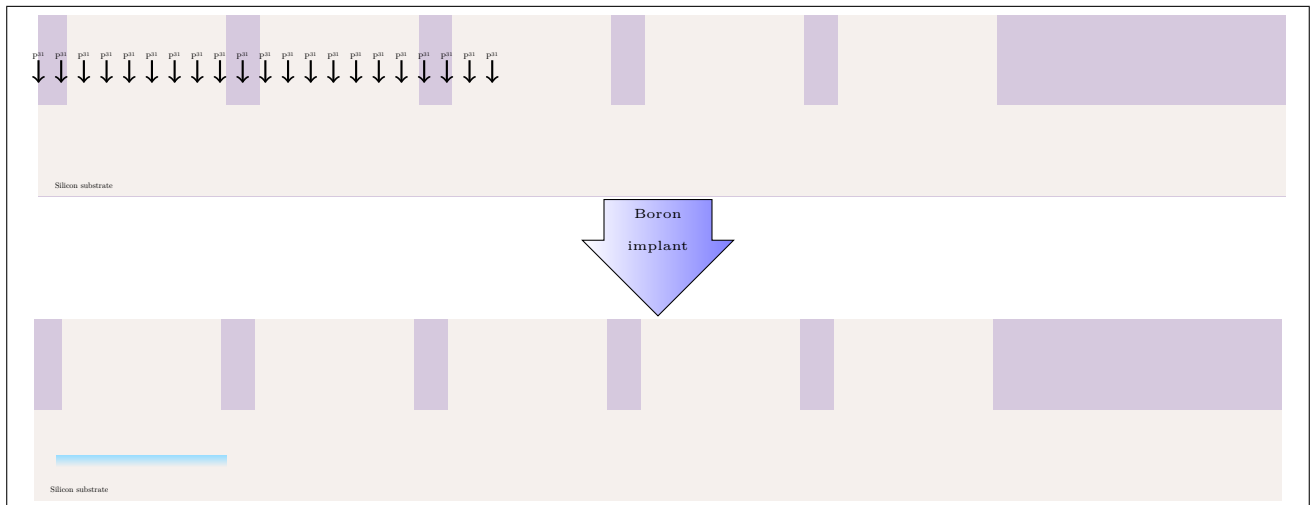


Figure 26: Implant process

Possible approaches:

- "CF-3000 Implanter (IMP-3000)" from HKUST

At HKUST we have an implanter which gives us better control over the initial surface concentration.

These steps are needed to arrive with the desired geometry: 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.

5.3 Resist strip

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

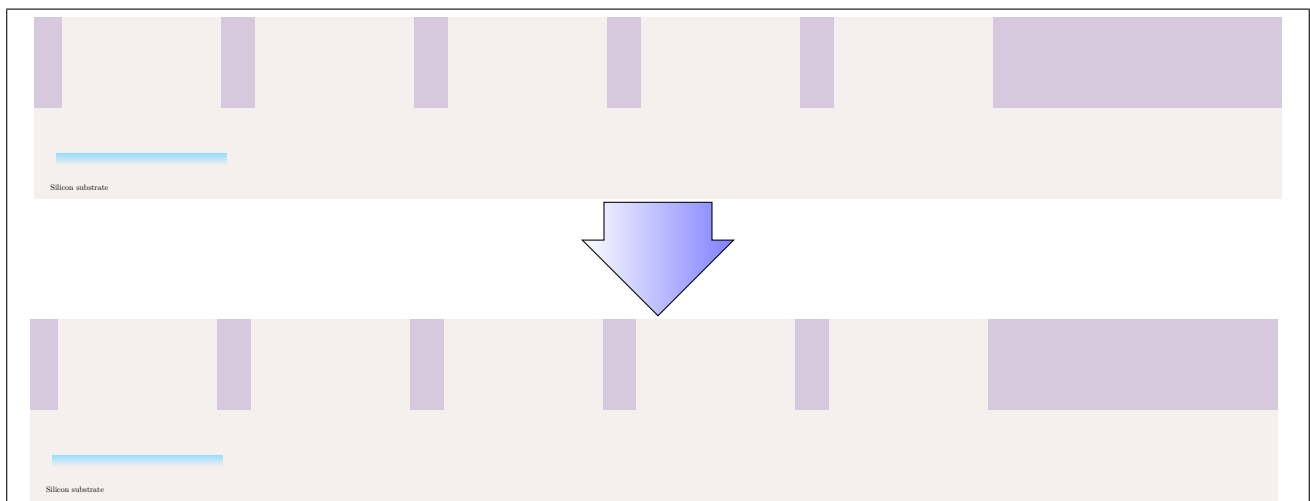


Figure 27: Resist removal

Please just use the solvent for the specific resist.

6 Field oxide

The geometry of a substrate with the field oxide filling the shallow trench from [section 1](#) now needs to be made.

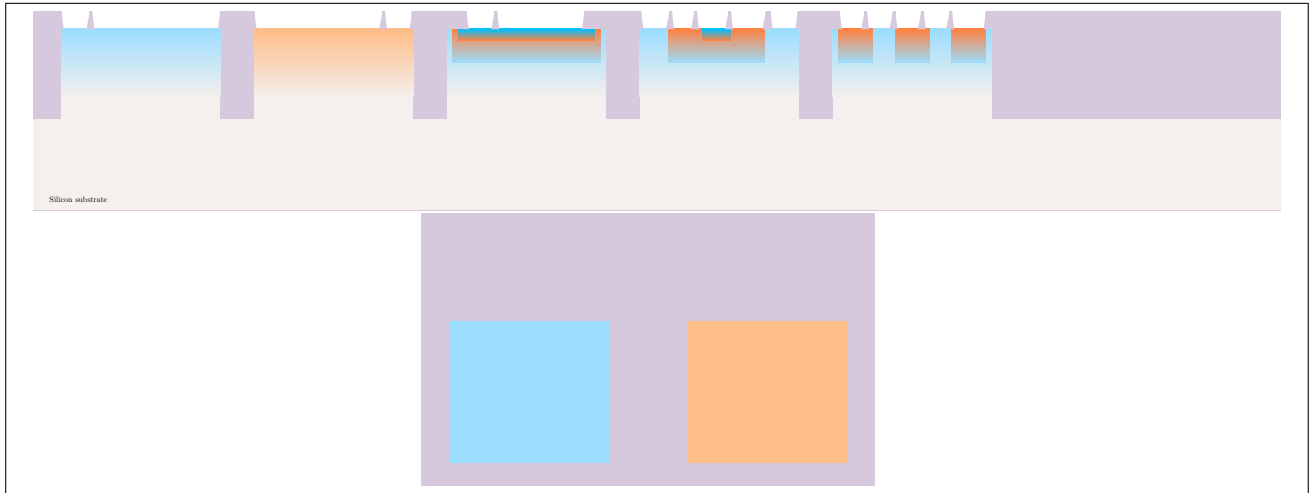


Figure 28: Shallow trench isolation target geometry

As can be seen in [Figure 28](#), the STI trenches need to be filled with silicon oxide and windows need to be etched into them so that the gate can be constructed later on. The windows are needed so that the poly silicon is far enough away from the non-active areas so that the threshold voltage of the parasitic FETs is so high that they will never switch. Only within the active areas we want to allow the poly layer to touch down closer to the silicon.

During the oxidation the dopants will be further driven in which will lead to the final formation of the N-well with an approximate depth of $4\mu m$ and the P-well with an approximate depth of $5\mu m$.

6.1 Oxide growth/Drive-in

Now we need to fill the trenches with silicon dioxide which will provide a spacer between the non active area and the polysilicon gate layer. within the non-active areas.

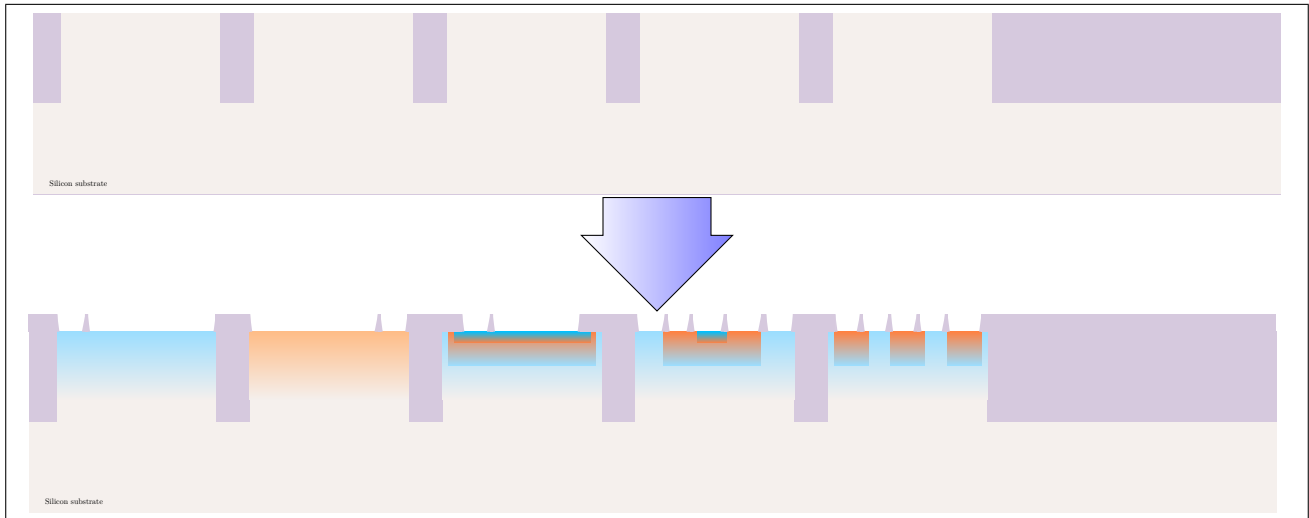


Figure 29: Hard mask growth

We grow a roughly $1.23\mu m$ thick layer of silicon dioxide by putting the wafer into the furnace at $1050^{\circ}C$ for 4 hours and 30 minutes in a wet environment.

During the oxidation the dopants will be further driven in which will lead to the final formation of the N-well with an approximate depth of $4\mu m$ and the P-well with an approximate depth of $5\mu m$.

6.2 Patterning

We reuse the mask from [section 1](#), because it's exactly the same layout, only inverted. The requirement is a **negative** tone resist.

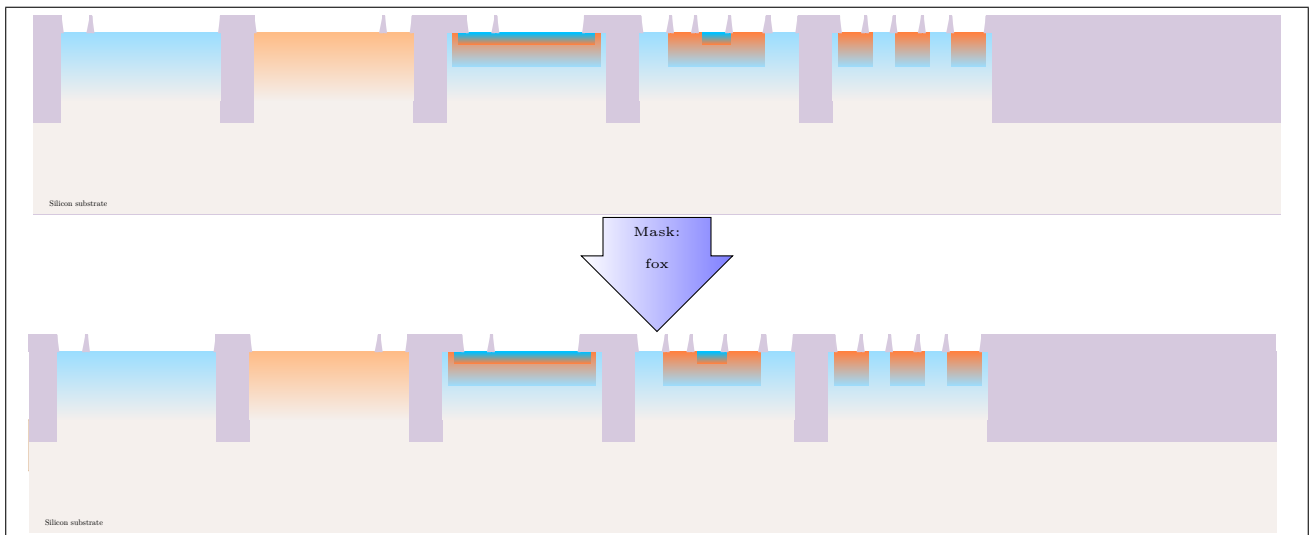


Figure 30: Patterning with positive resist

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. Also after the exposure and development, the hard baking shouldn't be forgotten!

6.3 Etching

We open the access to the silicon inside of the active areas in order to touch down with the polysilicon further on.

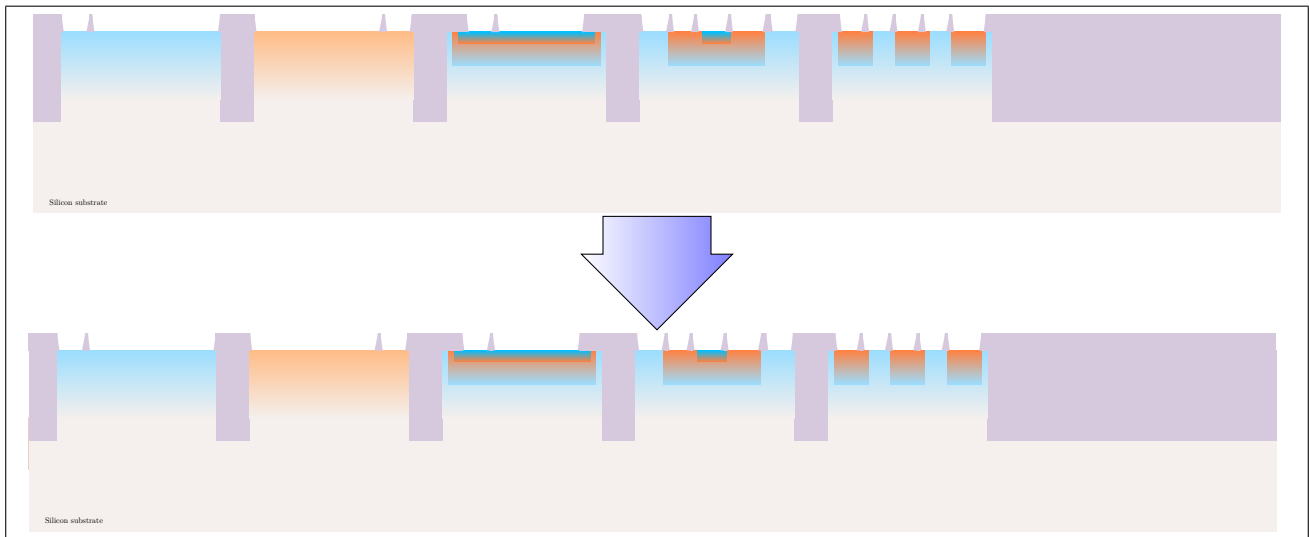


Figure 31: Nitride mask etching

There are dry etching and wet etching methods available for etching the thick field oxide. The downside of wet etching is that it also etches horizontally, however the chemical BHF is readily available and allows for easy implementation of the process.

Possible approaches:

- **"AOE Etcher (DRY-AOE)" from HKUST**
We can use anisotropic plasma etching for sharper borders.
- **Chemical solution**
We can use buffered hydrofluoric acid (BOE (1:6)) at room temperature for a little bit over 3 minutes in order to get through the 300nm of oxide.
Too long over 3 minutes might cause under-etch however!

6.4 Resist strip

Now we need to remove the contaminants for further processing.

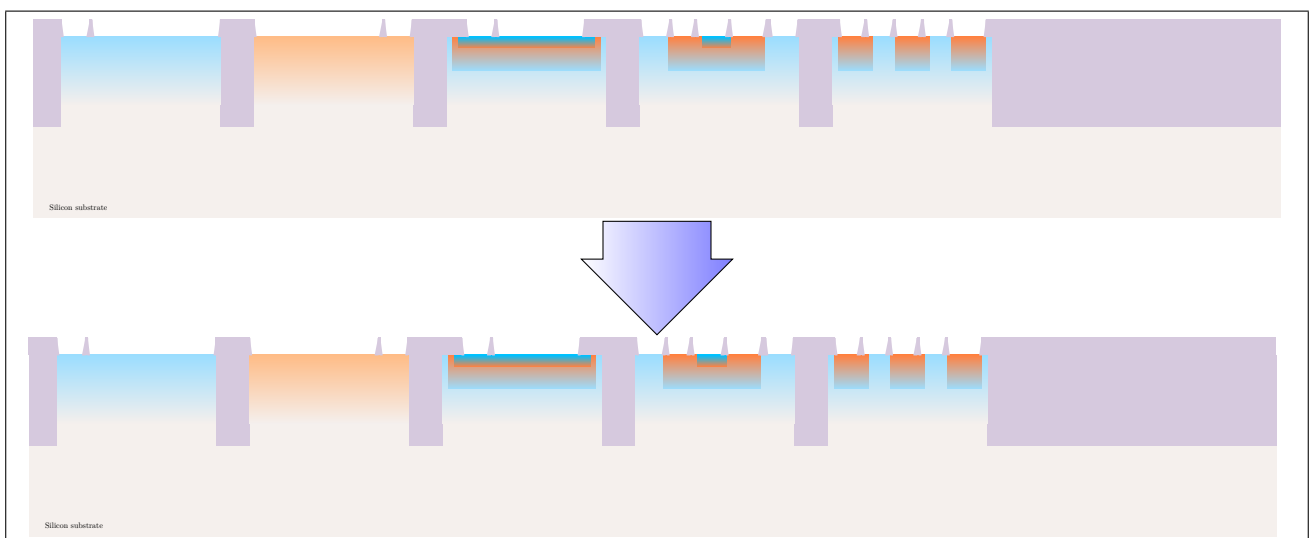


Figure 32: Resist removal

We strip the resist, rinse and perform sulfuric cleaning.

7 SONOS

Now we have to build the initial gate structure which contains of the 40nm thick dielectric (in our case just silicon dioxide) and the polysilicon electrode.

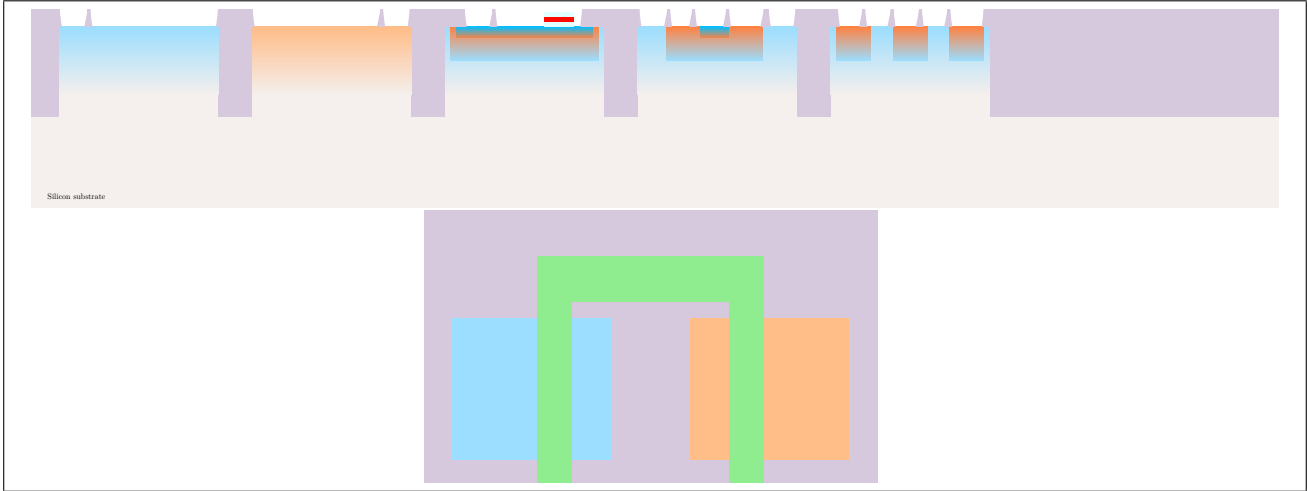


Figure 33: Poly silicon gate contacts with gate oxide

The line spacing of the polysilicon electrode shape has to be at least $0.5\mu\text{m}$ because of the resolution of the stepper and also because of the etching process which has $0.5\mu\text{m}$ as the minimum line spacing.

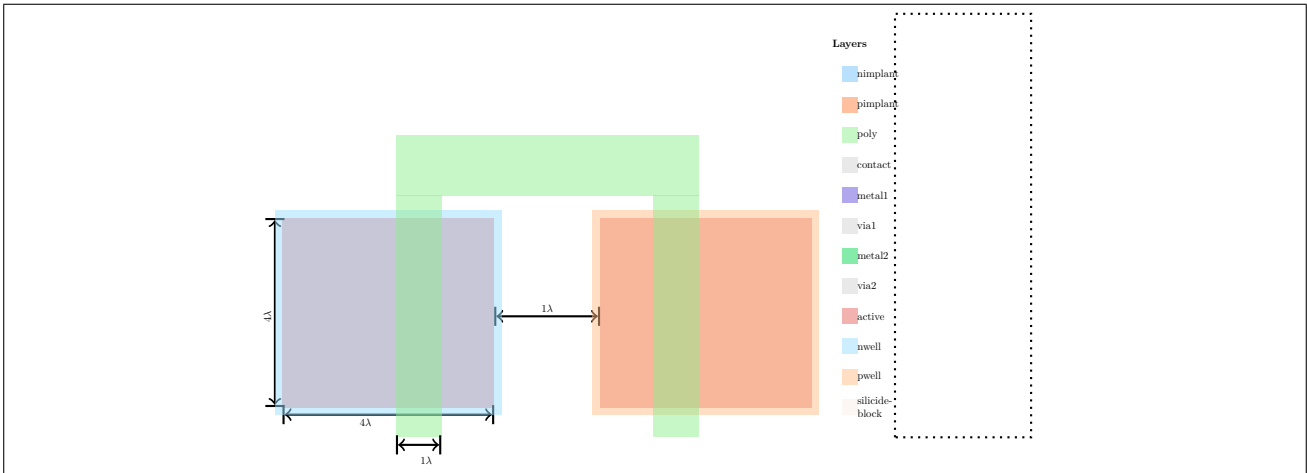


Figure 34: Gate layout

In [Figure 41](#) we can see the layout honoring the $0.5\mu\text{m}$ spacing design rule for the gate structure shape and poly-layer interconnect between NMOS and PMOS.

7.1 Gate oxide deposition

Now we have to deposit the dielectric isolator between the gate electrode and the channel. As designed in the process design document, the layer will be 40nm thick.

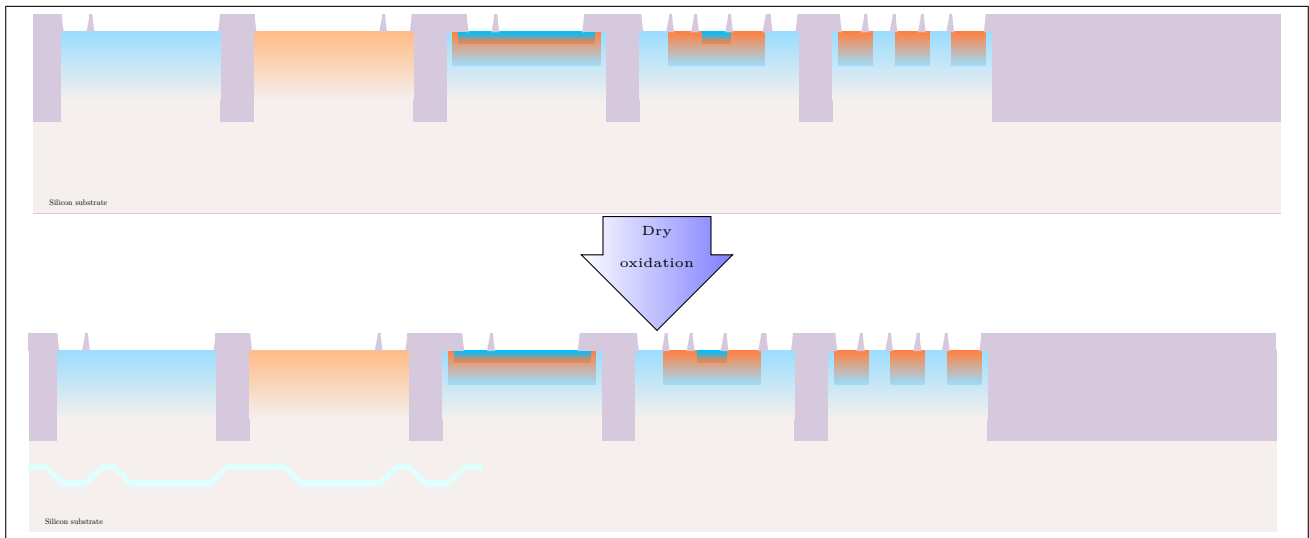


Figure 35: Thin oxide

The thickness of this layer decides over many critical key properties of the transistor, hence there should be little to no variation in the thickness of the gate oxide layer. For that reason we put the wafer into the diffusion furnace and perform dry oxidation at 1050°C for 33 minutes and 14 seconds.⁵

7.2 Polysilicon deposition

Now we need to add the polysilicon layer for forming the gate structure after etching.

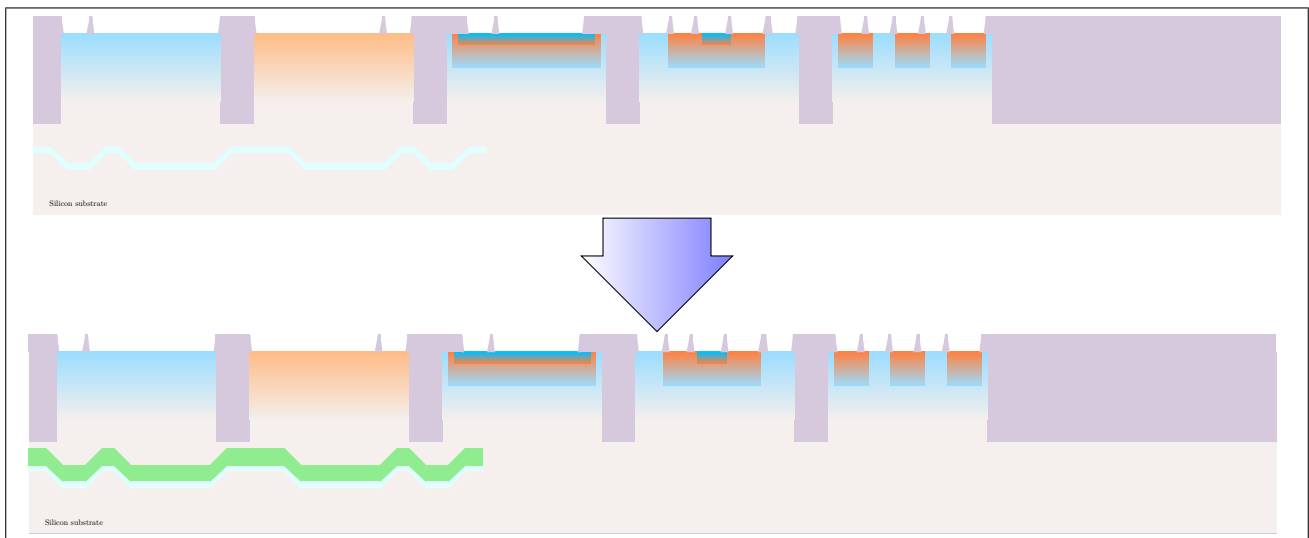


Figure 36: Polysilicon

We use the LPCVD machine and deposit a layer of around 600nm polysilicon⁶.

We set the temperature to 650°C , the gas will be Silane (SiH_4 ($\text{Si} + 2\text{H}_2$)), the pressure will be set to 300 mTorr with a flow of 90sccm.

This will give us a growth rate of roughly 23.5 nm per minute, so for 600nm we let it grow half an hour.

⁵<http://cleanroom.byu.edu/OxideTimeCalc>

⁶https://people.rit.edu/lffeee/LPCVD_Recipes.pdf

7.3 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 "poly" layer within the GDS2 file onto a **bright field** mask. The requirement is a **positive** tone resist.

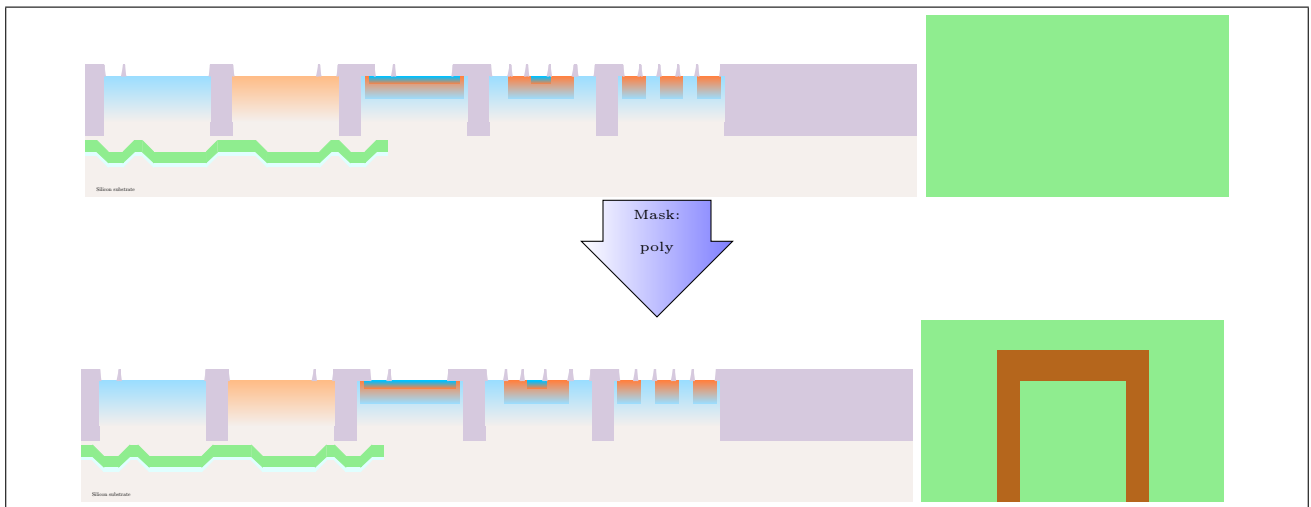


Figure 37: Resist

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. Also after the exposure and development, the hard baking shouldn't be forgotten!

7.4 Etching

Now we've got to etch the gate structures.

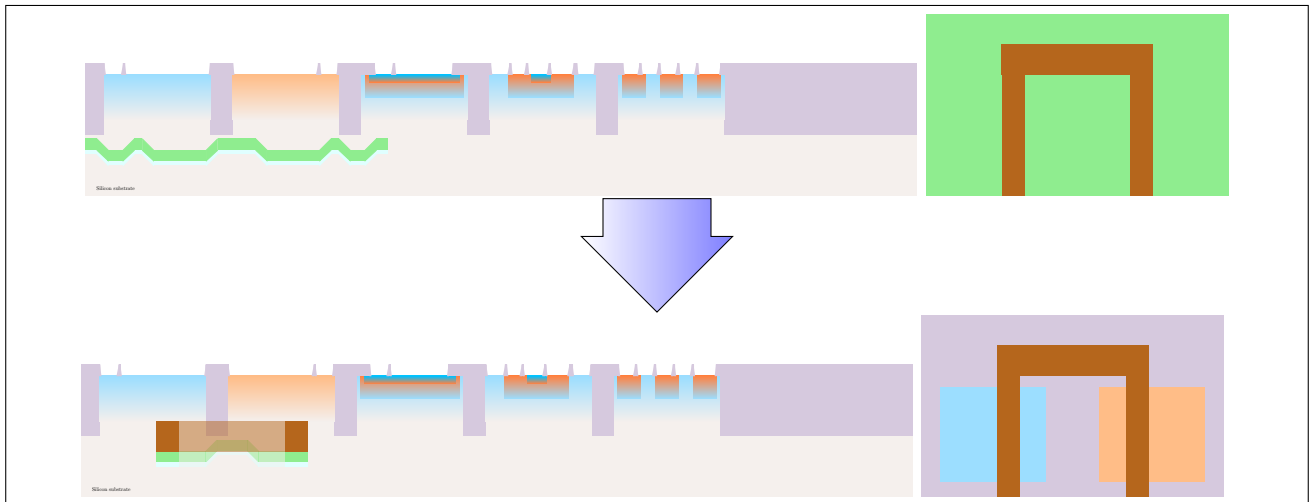


Figure 38: Resist

For now we only have the plasma etcher variant being verified because chemically etching polysilicon isn't allowed at the HKUST labs for contamination control reasons. In case you can verify this in your lab with a chemical etching method, please update this chapter and make a pull request!

Possible approaches:

- **"Poly Etcher (DRY-Poly)" from HKUST**

An anisotropic plasma etcher, in order to etch the polysilicon and gate oxide layer. In [subsection 8.2](#) we've grown 600nm of polysilicon which takes 200 seconds (= 3 minutes 20 seconds) (at 180nm/min) to etch. The selectivity to oxide is 13:1 which leads to an oxide etching speed of around 14nm/min, in [subsection 8.1](#) we've grown a 40nm thick oxide layer which leads to the oxide adding another 2 minutes 51 seconds to the etching time. All together, we will have to etch for around **6 minutes and 10 seconds**.

- **Chemical method**

Please add a verified method here!

7.5 Resist removal

Now we need to remove the contaminants for further processing.

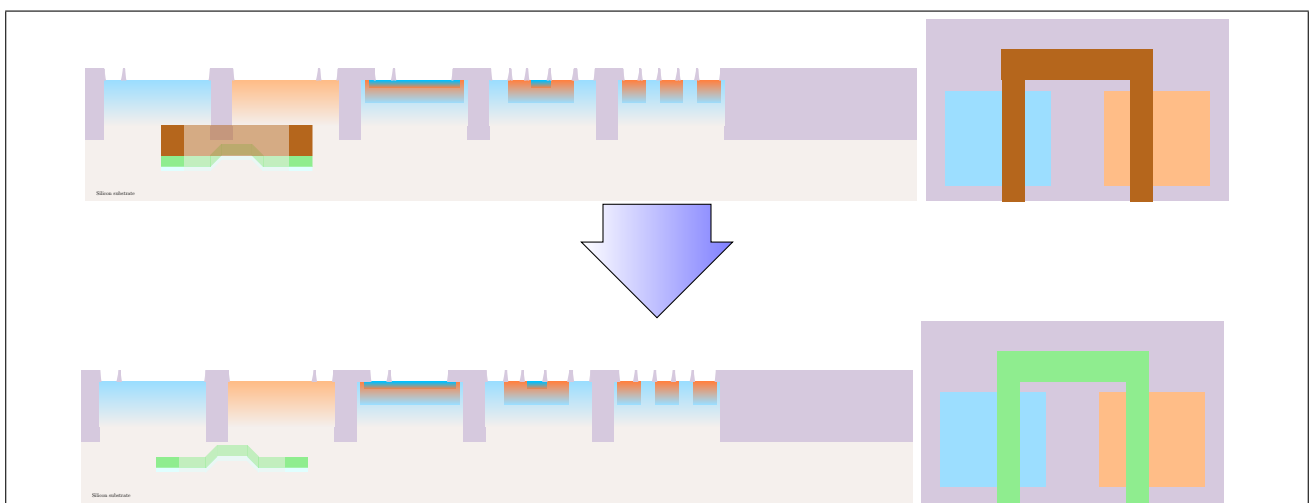


Figure 39: Resist

We strip the resist, rinse and perform sulfuric cleaning.

8 Gate

Now we have to build the initial gate structure which contains of the 40nm thick dielectric (in our case just silicon dioxide) and the polysilicon electrode.

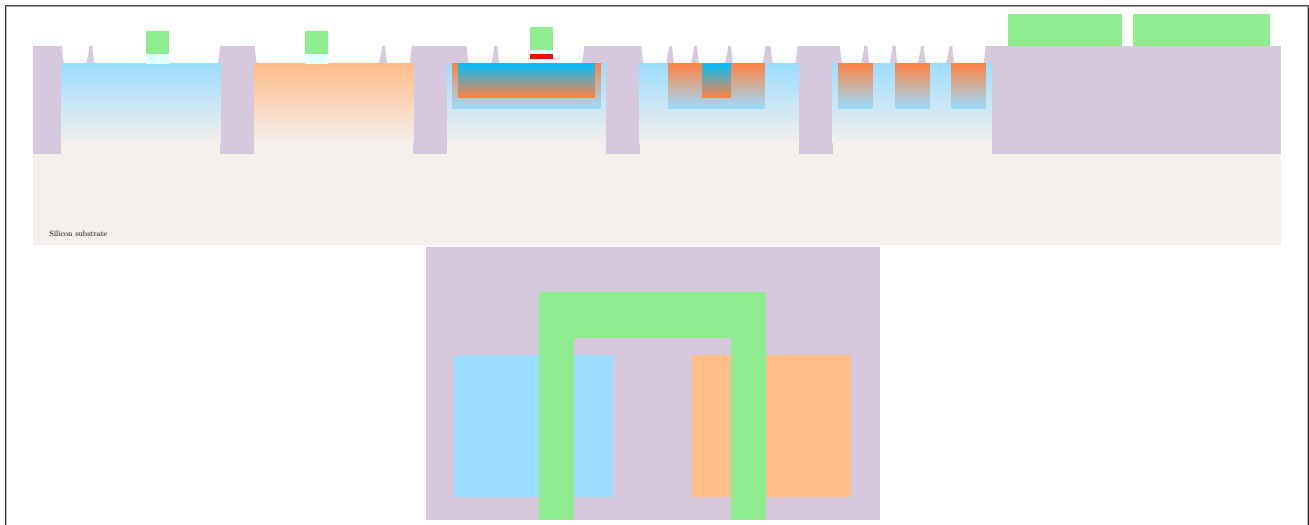


Figure 40: Poly silicon gate contacts with gate oxide

The line spacing of the polysilicon electrode shape has to be at least $0.5\mu m$ because of the resolution of the stepper and also because of the etching process which has $0.5\mu m$ as the minimum line spacing.

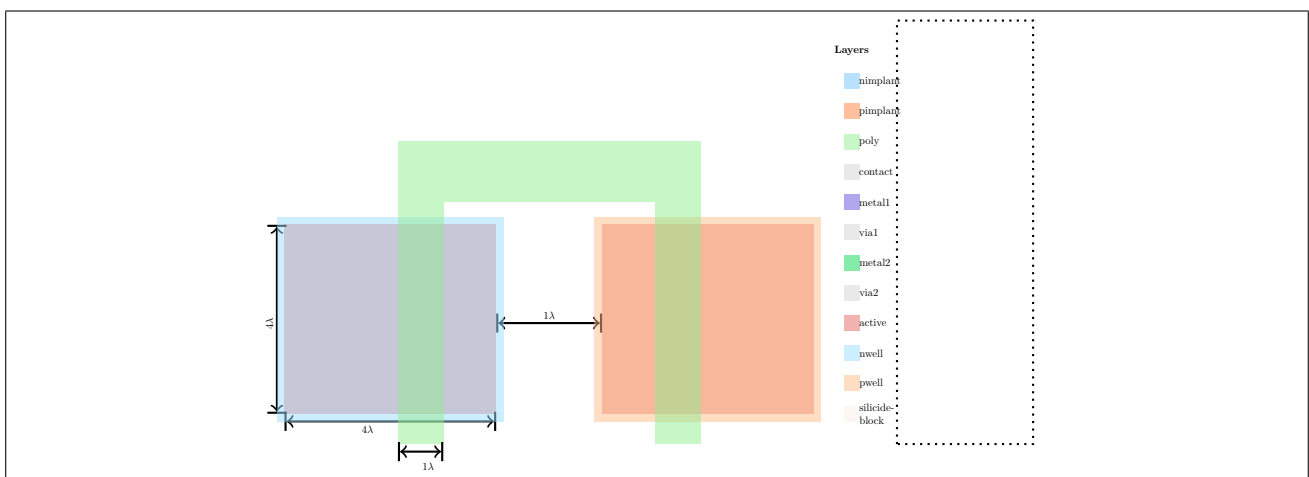


Figure 41: Gate layout

In [Figure 41](#) we can see the layout honoring the $0.5\mu m$ spacing design rule for the gate structure shape and poly-layer interconnect between NMOS and PMOS.

8.1 Gate oxide deposition

Now we have to deposit the dielectric isolator between the gate electrode and the channel. As designed in the process design document, the layer will be 40nm thick.

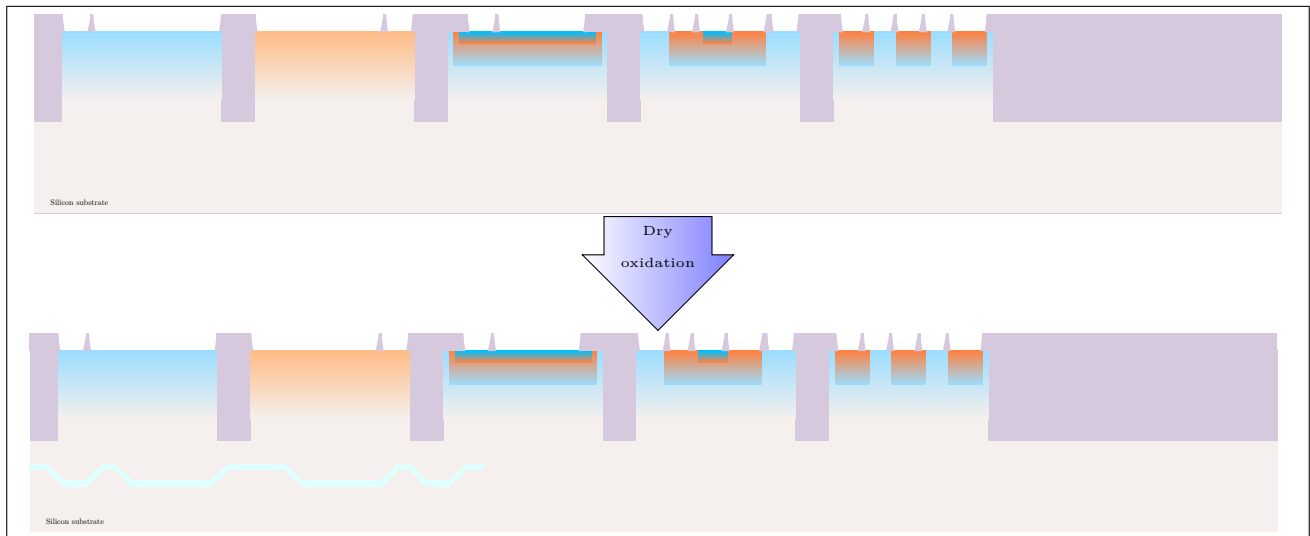


Figure 42: Thin oxide

The thickness of this layer decides over many critical key properties of the transistor, hence there should be little to no variation in the thickness of the gate oxide layer. For that reason we put the wafer into the diffusion furnace and perform dry oxidation at 1050°C for 33 minutes and 14 seconds.⁷

8.2 Polysilicon deposition

Now we need to add the polysilicon layer for forming the gate structure after etching.

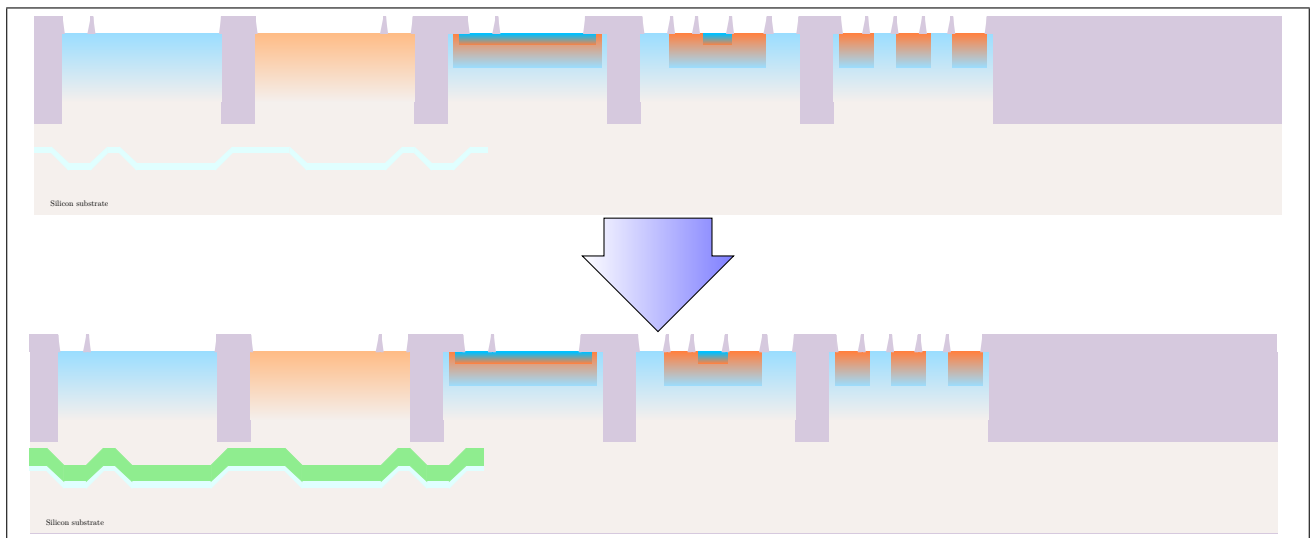


Figure 43: Polysilicon

We use the LPCVD machine and deposit a layer of around 600nm polysilicon⁸.

We set the temperature to 650°C , the gas will be Silane (SiH_4 ($\text{Si} + 2\text{H}_2$)), the pressure will be set to 300 mTorr with a flow of 90sccm.

This will give us a growth rate of roughly 23.5 nm per minute, so for 600nm we let it grow half an hour.

⁷<http://cleanroom.byu.edu/OxideTimeCalc>

⁸https://people.rit.edu/lffeee/LPCVD_Recipes.pdf

8.3 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 "poly" layer within the GDS2 file onto a **bright field** mask. The requirement is a **positive** tone resist.

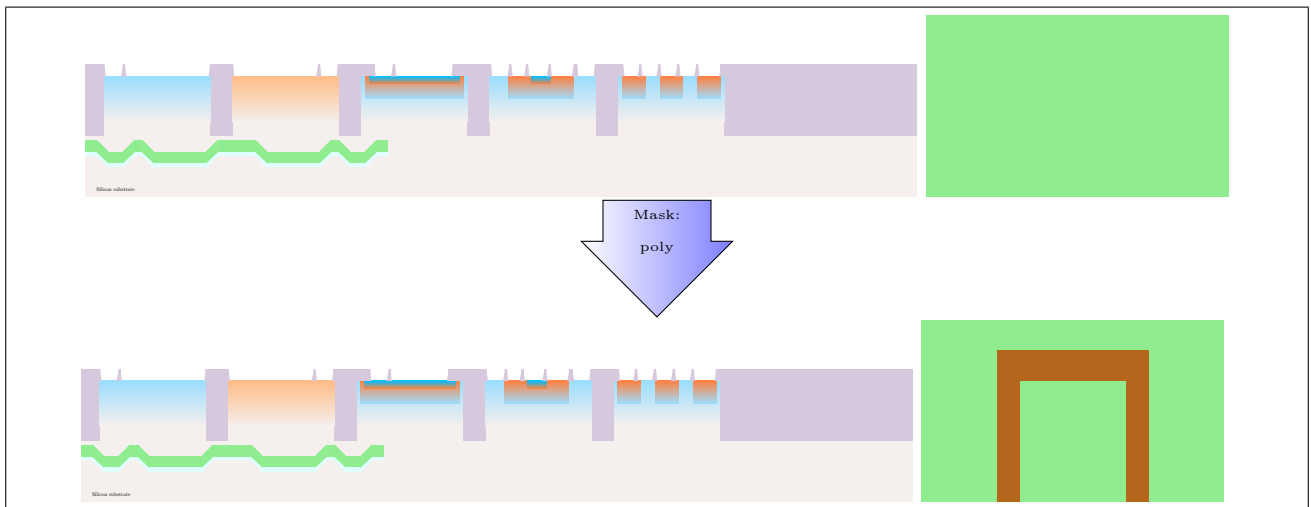


Figure 44: Resist

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. Also after the exposure and development, the hard baking shouldn't be forgotten!

8.4 Etching

Now we've got to etch the gate structures.

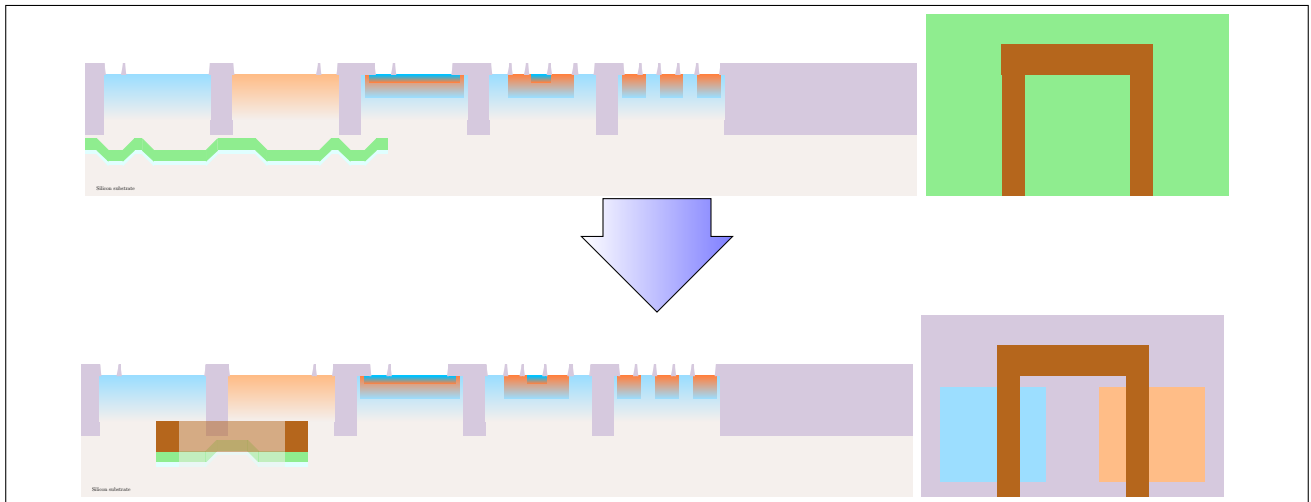


Figure 45: Resist

For now we only have the plasma etcher variant being verified because chemically etching polysilicon isn't allowed at the HKUST labs for contamination control reasons. In case you can verify this in your lab with a chemical etching method, please update this chapter and make a pull request!

Possible approaches:

- **"Poly Etcher (DRY-Poly)" from HKUST**

An anisotropic plasma etcher, in order to etch the polysilicon and gate oxide layer. In [subsection 8.2](#) we've grown 600nm of polysilicon which takes 200 seconds (= 3 minutes 20 seconds) (at 180nm/min) to etch. The selectivity to oxide is 13:1 which leads to an oxide etching speed of around 14nm/min, in [subsection 8.1](#) we've grown a 40nm thick oxide layer which leads to the oxide adding another 2 minutes 51 seconds to the etching time. All together, we will have to etch for around **6 minutes and 10 seconds**.

- **Chemical method**

Please add a verified method here!

8.5 Resist removal

Now we need to remove the contaminants for further processing.

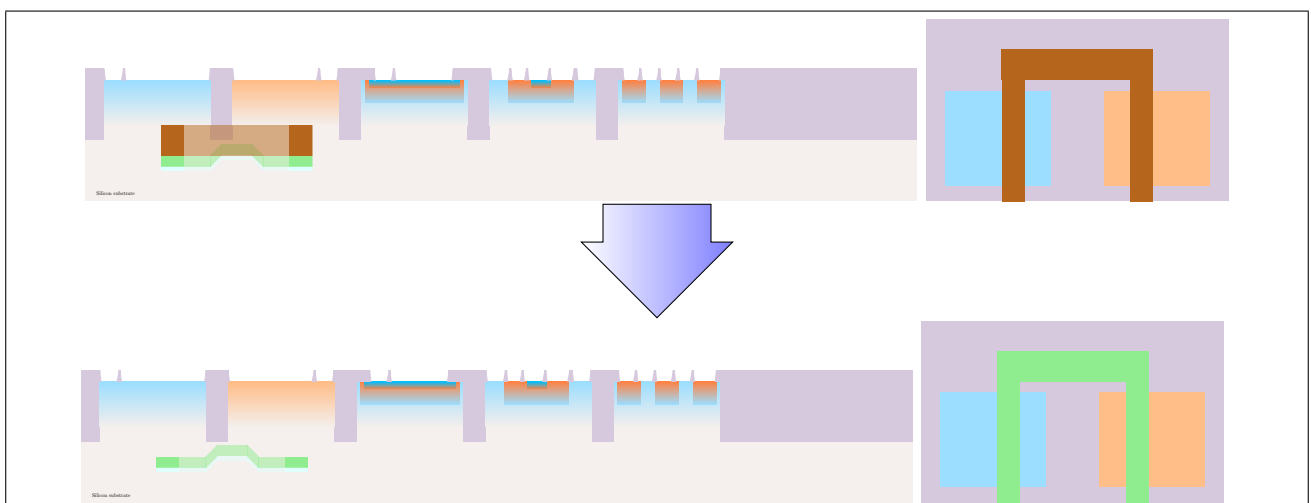


Figure 46: Resist

We strip the resist, rinse and perform sulfuric cleaning.

9 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.

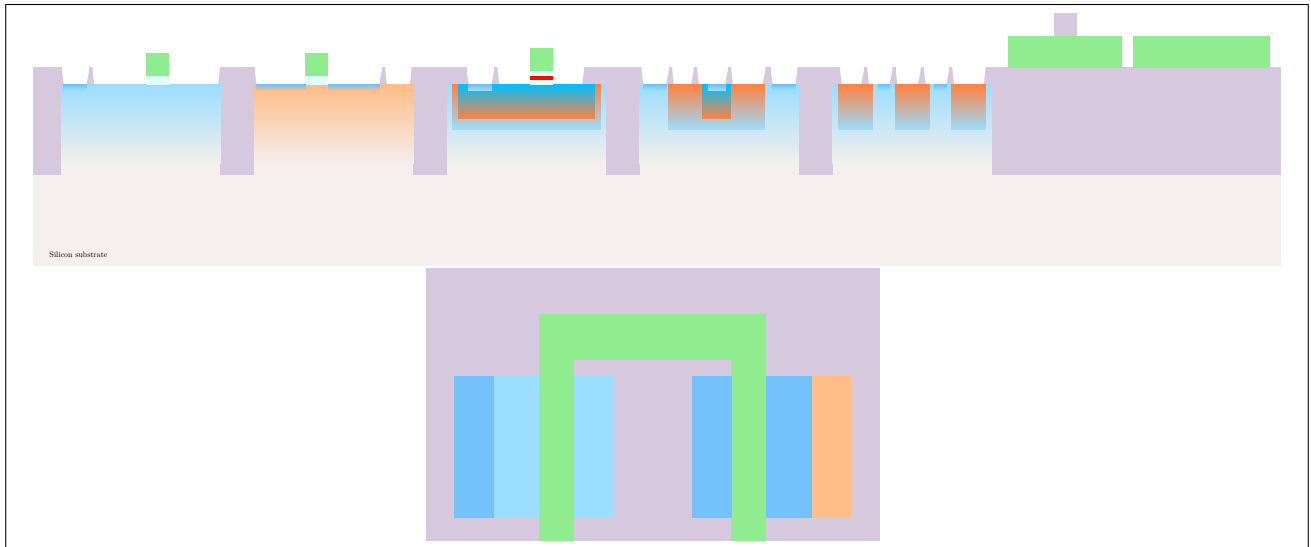


Figure 47: N+ implant geometry target

The tricky thing here is to have a reasonable implant depth but not too deep because the deeper the junction, the higher the junction capacity which in turn limits the switching performance of the CMOS circuitry.

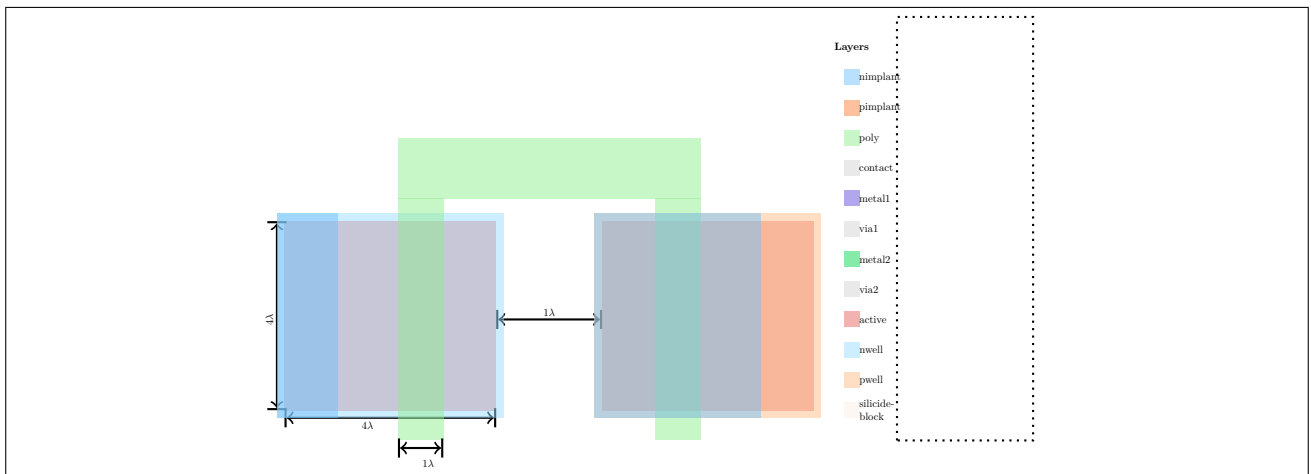


Figure 48: N+ layout

An example layout of p-implants can be seen in [Figure 48](#), the mask is being extracted from the layer "n_plus_select".

Also important to notice is that this example layout is just for demonstration purposes only, please have a look at the standard cell documentation for the actual layouts.

9.1 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 "n_plus_select" layer within the GDS2 file onto a **bright field** mask. The requirement is a **negative** tone resist.

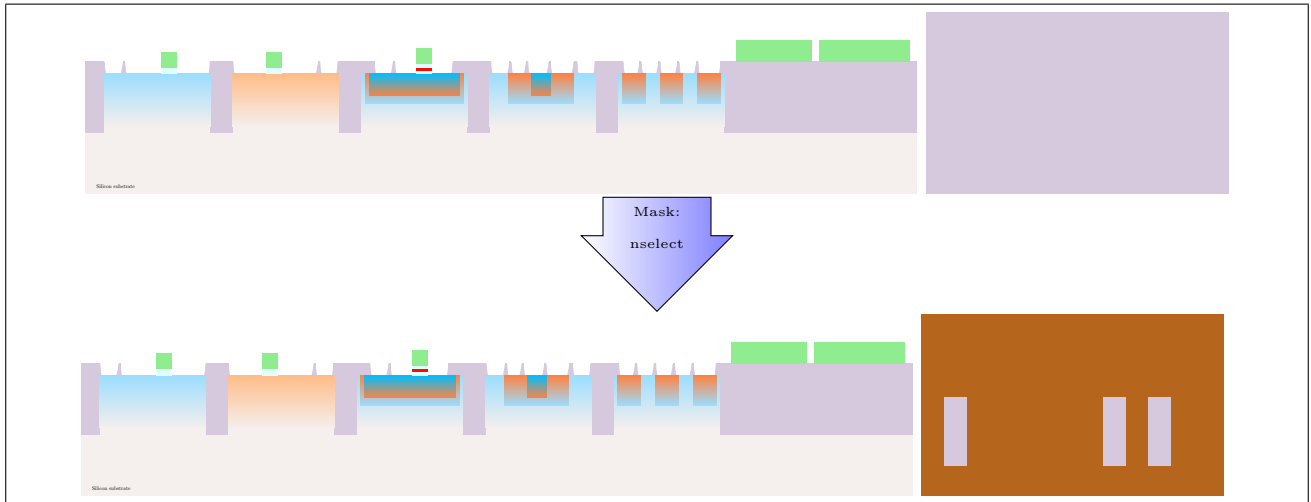


Figure 49: N+ region resist mask

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. Also after the exposure and development, the hard baking shouldn't be forgotten!

9.2 Implantation

We now need to bring in the carriers in order to build the n-junctions.

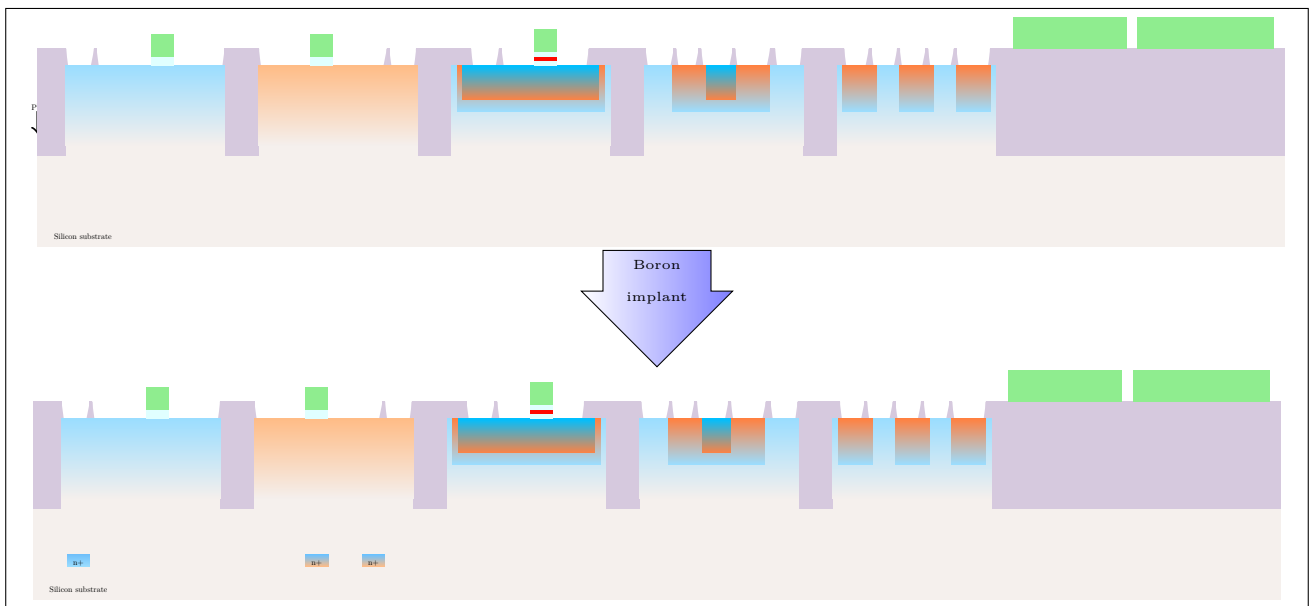


Figure 50: N+ implant process

Possible approaches:

- "CF-3000 Implanter (IMP-3000)" from HKUST

At HKUST we have an implanter which gives us better control over the initial surface concentration.

These steps are needed to arrive with the desired geometry: The nselect is implanted with a Phosphorus (P^{31}) dose of $2.5 \times 10^{12} cm^{-2}$ at an energy of 35 keV (43nm \pm 18nm deep)

9.3 Resist strip

Now we need to remove the contaminants for further processing.

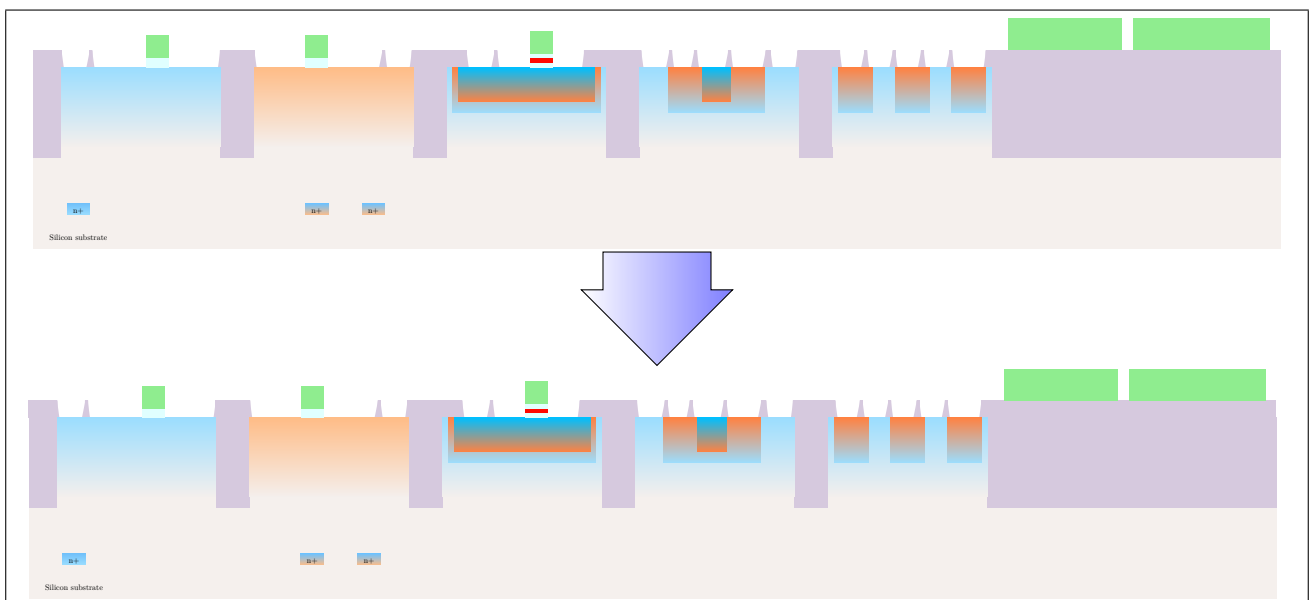


Figure 51: Resist removal

We strip the resist, rinse and perform sulfuric cleaning.

10 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.

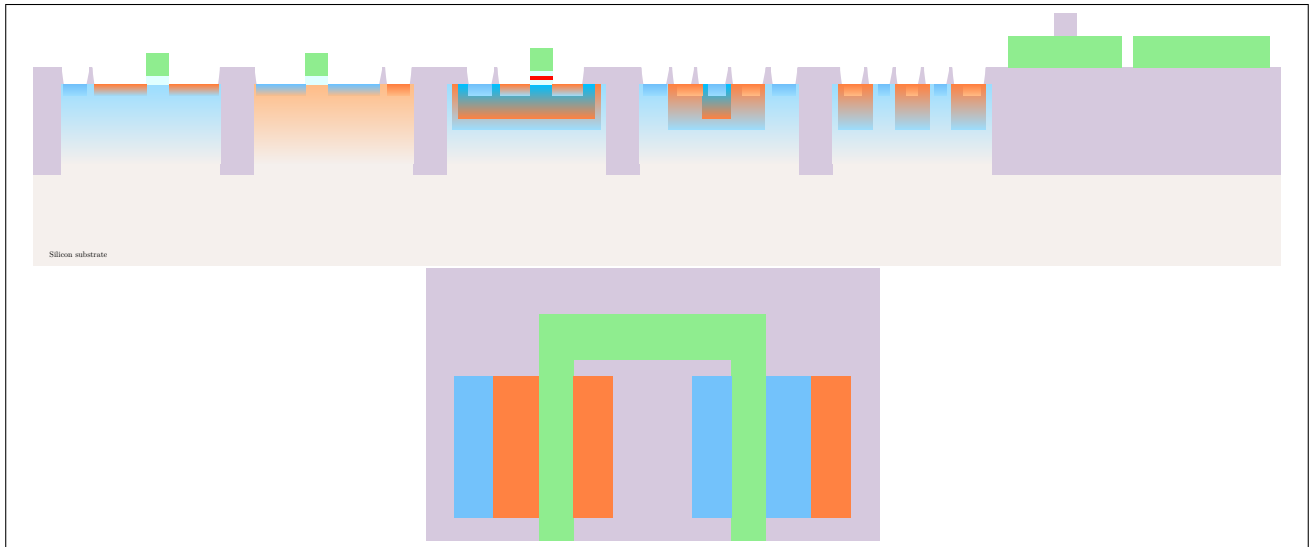


Figure 52: P+ implant geometry target

The tricky thing here is to have a reasonable implant depth but not too deep because the deeper the junction, the higher the junction capacity which in turn limits the switching performance of the CMOS circuitry.

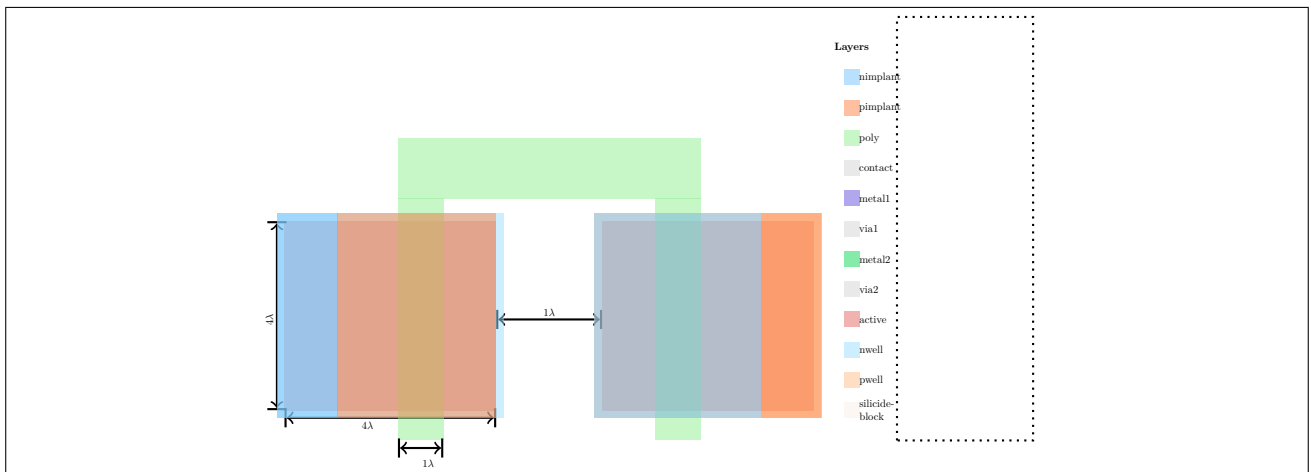


Figure 53: P+ layout

An example layout of p-implants can be seen in [Figure 53](#), the mask is being extracted from the layer "p_plus_select"

Also important to notice is that this example layout is just for demonstration purposes only, please have a look at the standard cell documentation for the actual layouts.

10.1 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 "p_plus_select" layer within the GDS2 file onto a **bright field** mask. The requirement is a **negative** tone resist.

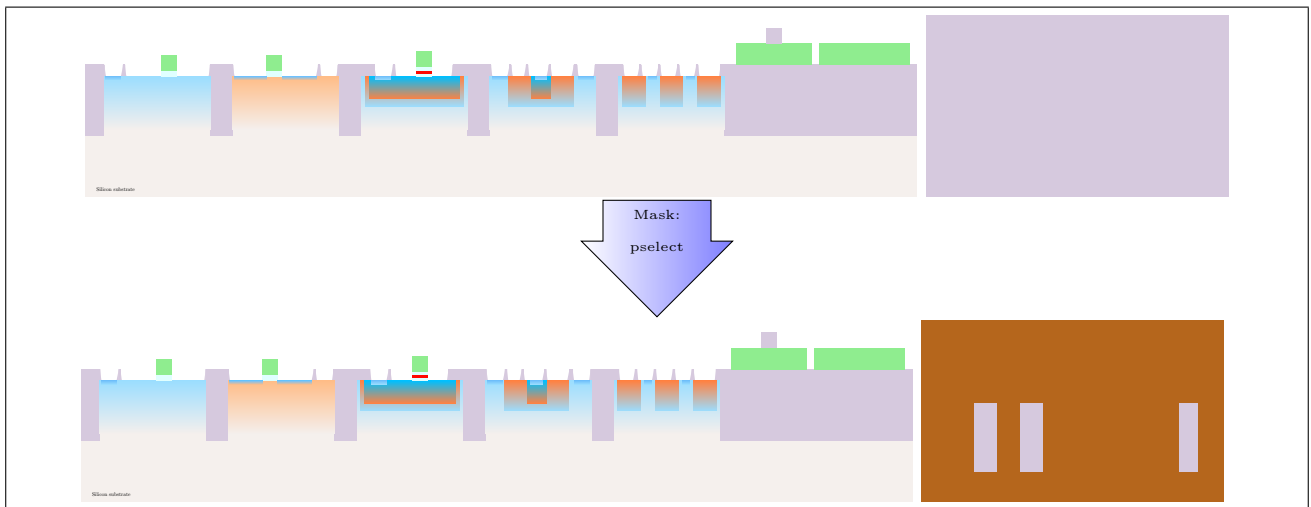


Figure 54: P+ region resist mask

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. Also after the exposure and development, the hard baking shouldn't be forgotten!

10.2 Implantation

We now need to bring in the carriers in order to build the p-junctions.

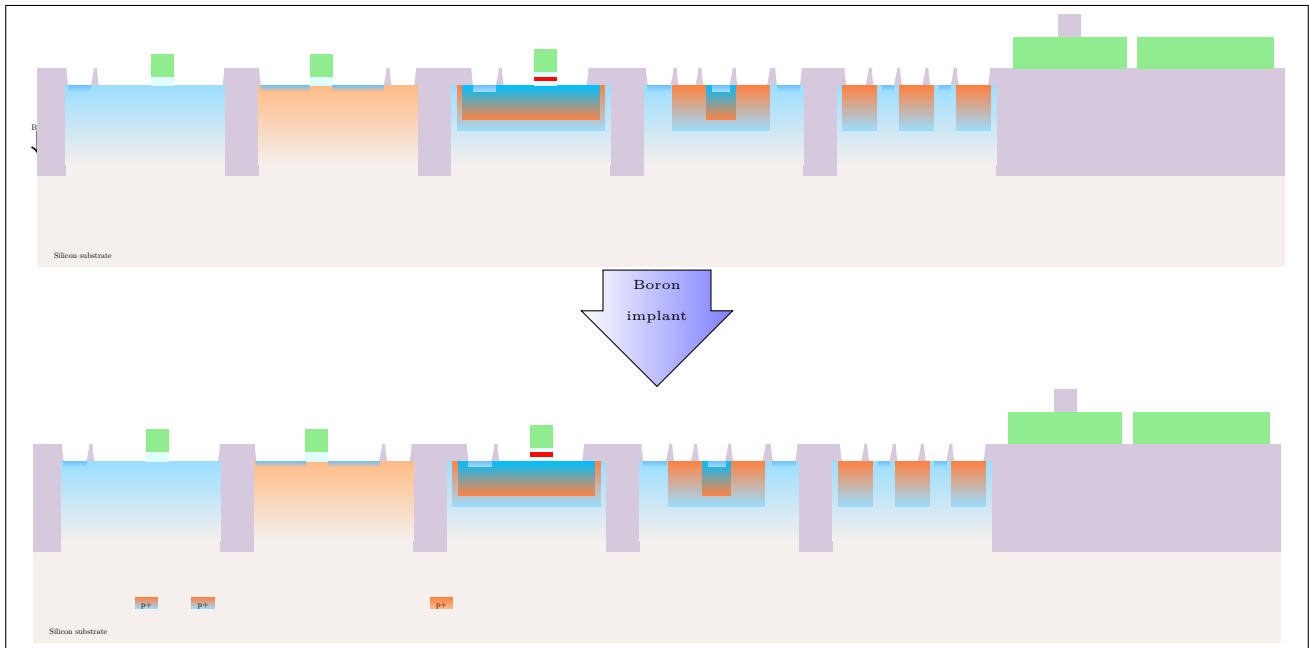


Figure 55: P+ implant process

Possible approaches:

- "CF-3000 Implanter (IMP-3000)" from HKUST

At HKUST we have an implanter which gives us better control over the initial surface concentration.

These steps are needed to arrive with the desired geometry: The pselect is implanted with a Boron (B^{11}) dose of $2.5 \times 10^{12} cm^{-2}$ at an energy of 13 keV ($43nm \pm 18nm$ deep)

10.3 Resist strip

Now we need to remove the contaminants for further processing.

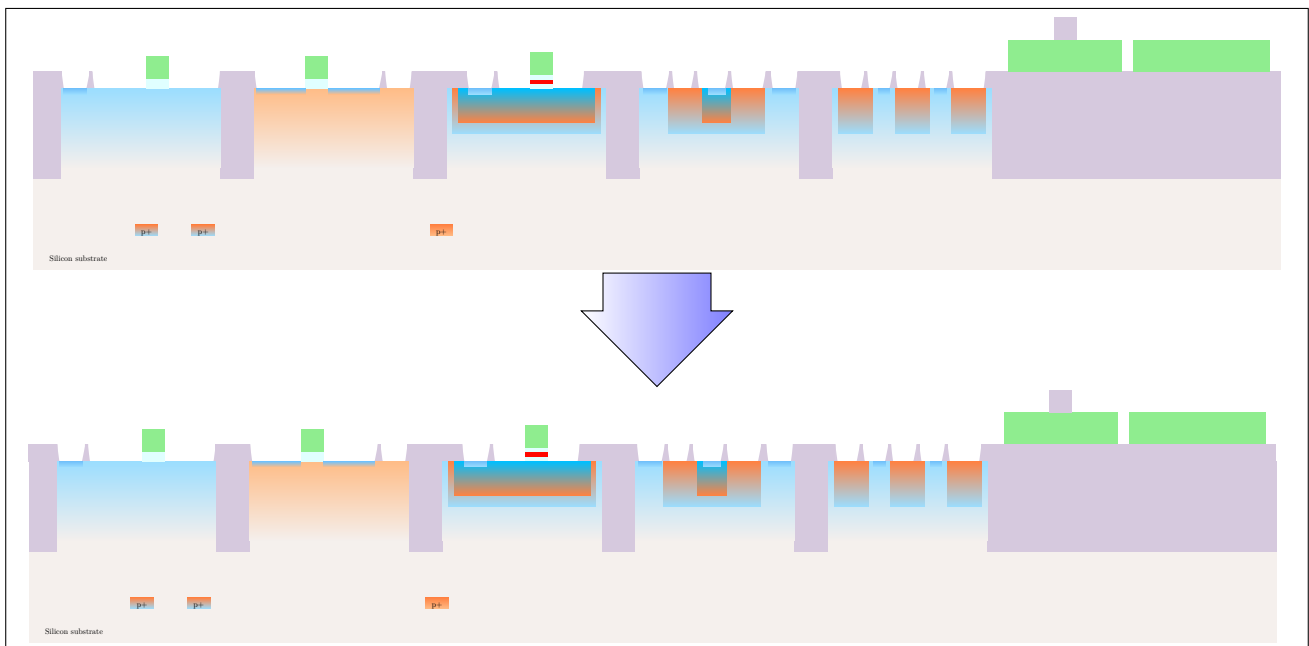


Figure 56: Resist removal

We strip the resist, rinse and perform sulfuric cleaning.

11 Silicification

Titanium silicide is one of the first SALICIDE material introduced in ULSI devices owing to its low resistivity, high thermal stability, ease in deposition and compatibility with silicon processes. Titanium has been one of the familiar materials in ULSI productions, which is also an important advantage in practical use of titanium SALICIDE.⁹

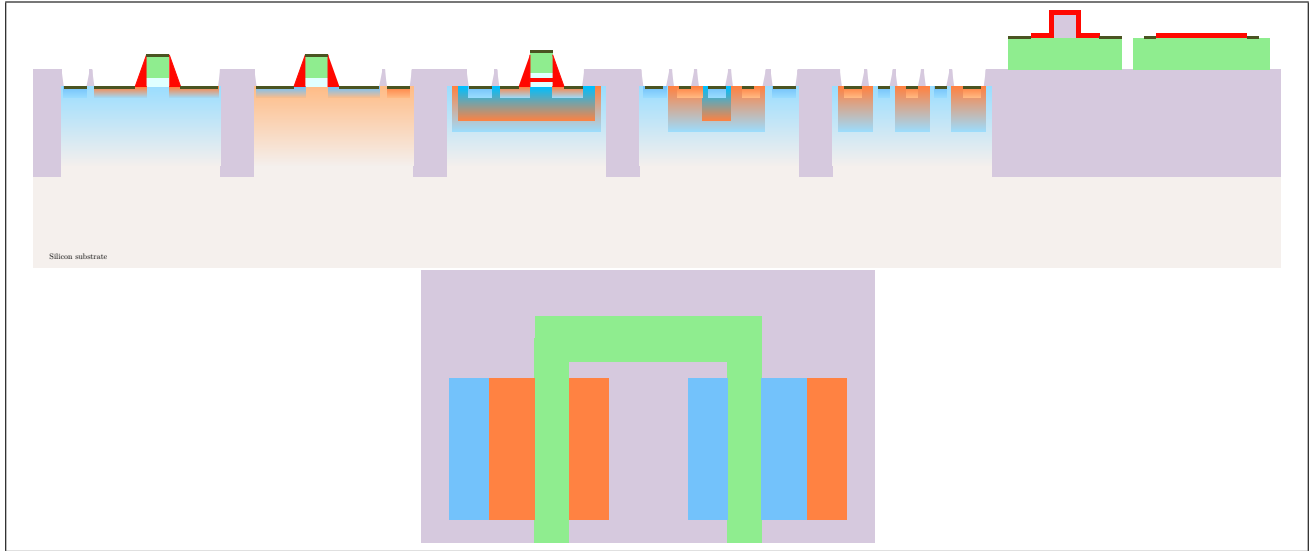


Figure 57: Silicide geometry target

In order to reduce the gate contact resistance as well as the source and drain resistance and in order to provide a more effective etch stop when plasma etching the contact windows to drain, source and gate, silicide/polycide is being added to the wafer as shown in Figure 57.

The side walls¹⁰ are required in order avoid short circuits between the junction and the gate.

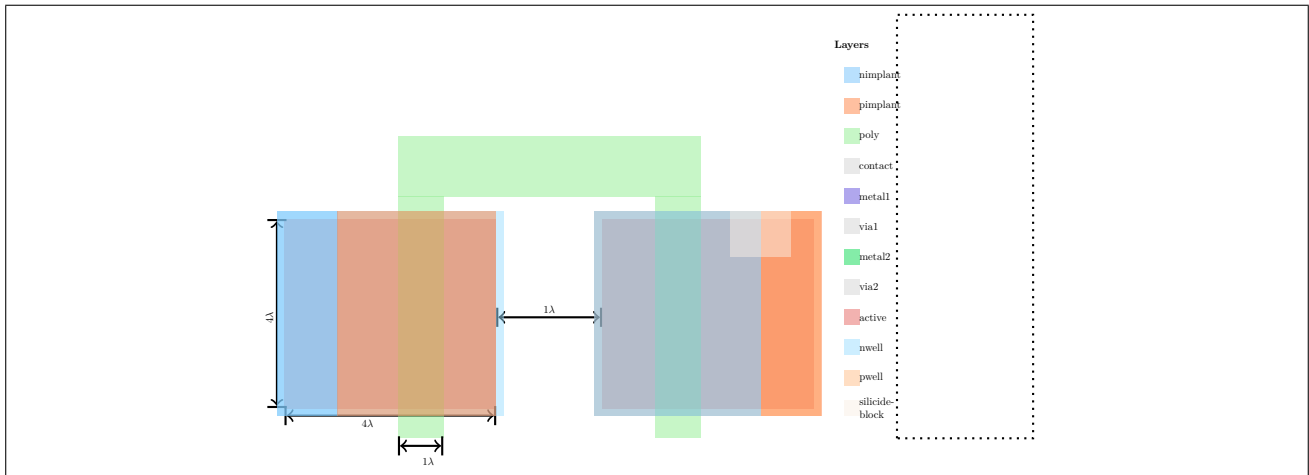


Figure 58: Silification layout

When titanium and silicon are brought into contact and heated at temperatures above 500 °C (in the presence of excess silicon) the higher-resistivity $C49-TiSi_2$ phase forms before the low-resistivity phase.

The $C49-TiSi_2$ phase has an orthorhombic base-centered structure with 12 atoms per unit cell and a resistivity of $60 - 90 \mu\Omega - cm$.

The $C54-TiSi_2$ phase has an orthorhombic face-centered structure having 24 atoms per unit cell and a significantly lower resistivity ($12 - 20 \mu\Omega - cm$) than the $C49-TiSi_2$.

The basic formation process of titanium SALICIDE is as follows:

A thin titanium film with 20-60 nm thickness is deposited on an entire wafer with MOSFETs structure. The deposited Ti film reacts with the exposed silicon areas such as the source/drain area and polysilicon gate electrodes by the first anneal at 600-700°C in N_2 ambient. In first anneal, $C49-TiSi_2$ phase is formed. Then,

⁹A Study on Formation of High Resistivity Phases of Nickel Silicide at Small Area and its Solution for Scaled CMOS Devices, 07D53437, Ryuji Tomita

¹⁰<http://www.fujitsu.com/jp/group/mifs/en/resources/news/library/tech-intro/process/side-wall.html>

the unreacted titanium film on the dielectric layer such as SiO_2 or SiN is selectively etched by APM (Ammonia and Hydrogen Peroxide Mixture) solution. The final step is second anneal at 800°C or above to transform high-resistivity C49- $TiSi_2$ phase to low-resistivity C54- $TiSi_2$ phase at the gate electrodes and source/drain areas.

11.1 Oxide deposition

The thickness of this CVD deposited oxide layer will be the width of the spacer after having used highly anisotropic etching in the next few steps, for this reason the thickness of the oxide decides over the distance between the silicide and the gate oxide.

We make the oxide layer 50nm thick.

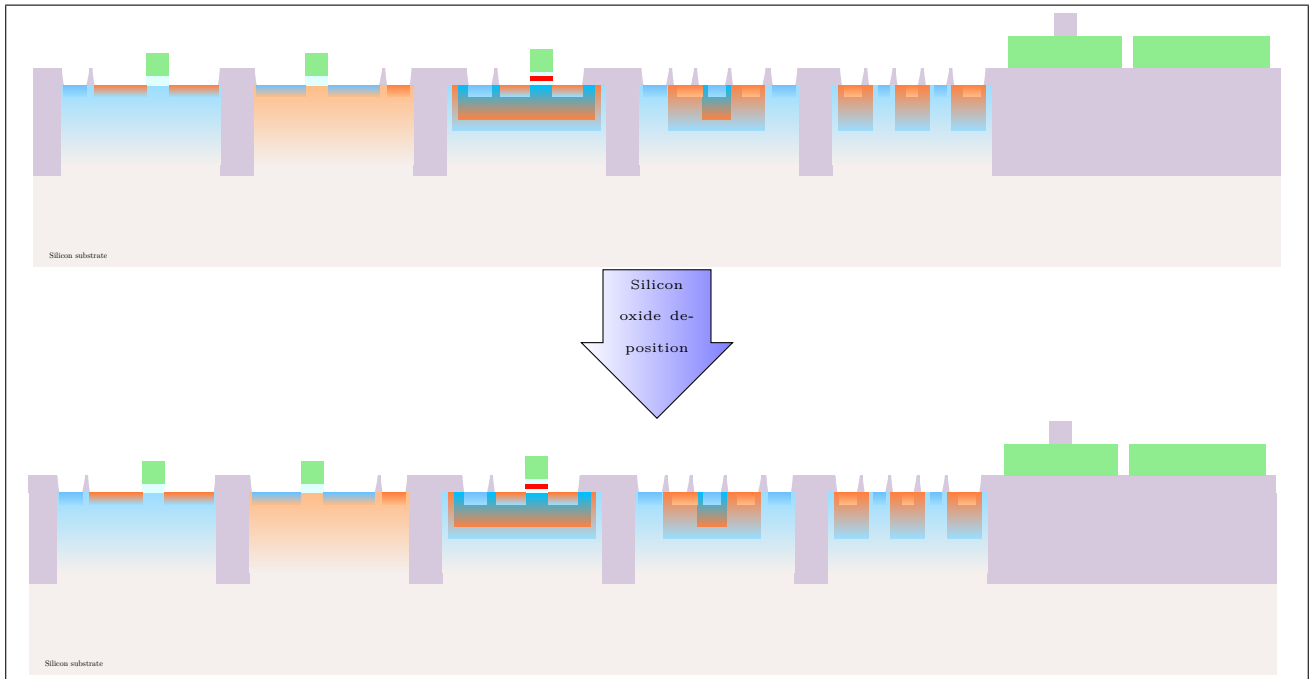


Figure 59: Oxide layer

We use the machine LPCVD machine from HKUST and deposit around 50nm of silicon dioxide with the following recipe¹¹:

- Temperature: 400 °C ($SiH_4 + O_2 = SiO_2 + 2H_2$)
- Pressure = 250 mTorr
- Silane (SiH_4) flow = 40sccm
- Oxygen (O_2) flow = 48sccm

This will give a rate of 7nm ($\pm 1nm$) per minute, so we deposit for roughly seven minutes (7 min).

11.2 Silicide block patterning

We now have to pattern the mask for the silicide block layer which will produce oxide wherever no silicide is not desired within active areas.

¹¹https://people.rit.edu/lffeee/LPCVD_Recipes.pdf

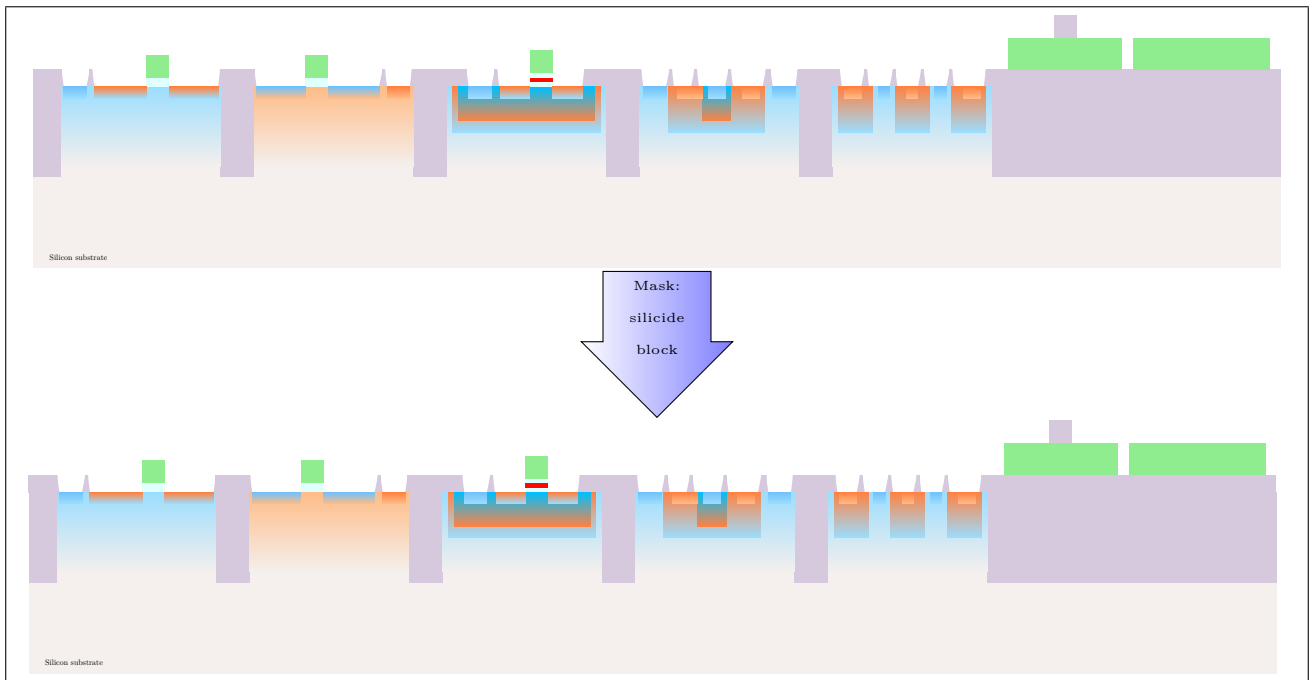


Figure 60: Patterning (silicide block)

It is not yet clear whether we will be needing this feature in the future, which means we have not yet finally decided whether we want to keep this step and layer within our process and technology.

11.3 Spacer etching

Now we have to etch our oxide as anisotropic as possible. This means that the etching mostly only comes "from above" with a few to nearly none horizontal etching. This means the etching process only "sees" the sidewall as a "thicker layer" and starts etching downward.

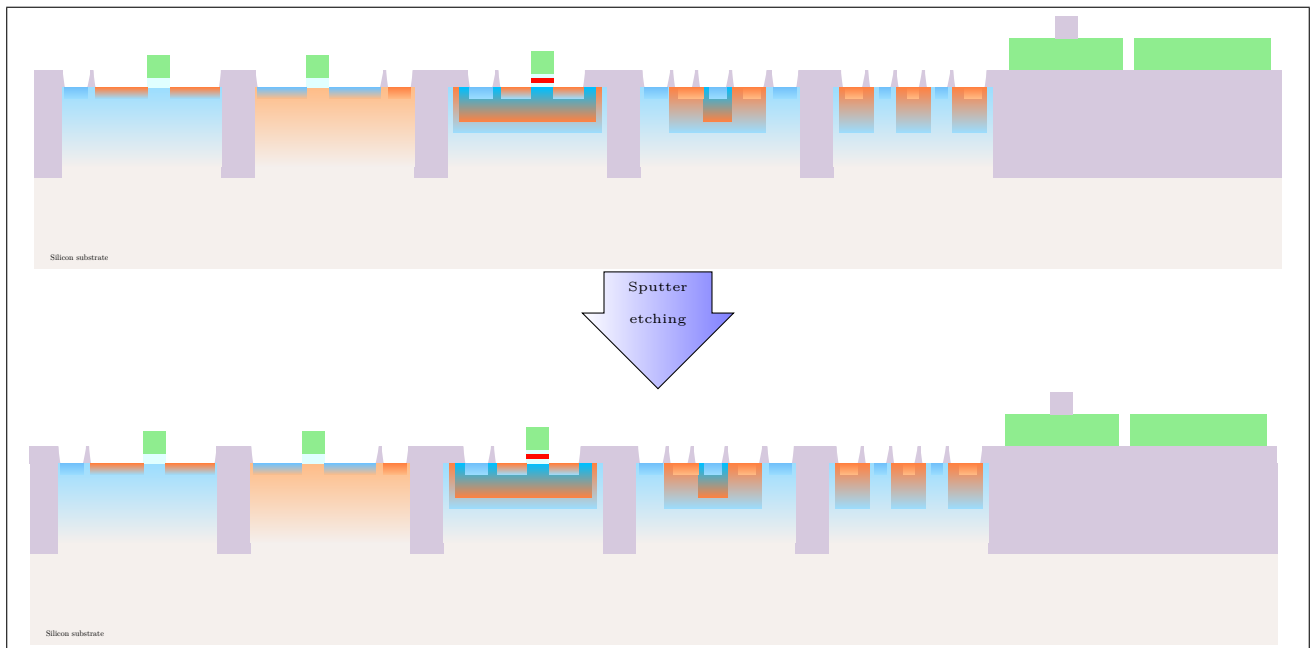


Figure 61: Anisotropic etching

Possible approaches:

- "AOE Etcher" at the NFF HKUST lab

With an etching speed of 250 nm/min for thermal oxide and an oxide thickness of around 50nm etching will take around 12 seconds.

After that we will have our desired spacer geometry forming as well as any potentially resist covered area (if silicide block is being used) with sharp etches.

11.4 Titanium deposition

We deposit a layer of titanium with a thickness of around 20-60nm which will then be reacted into titanium-silicide and titanium-polycide respectively in the further steps.

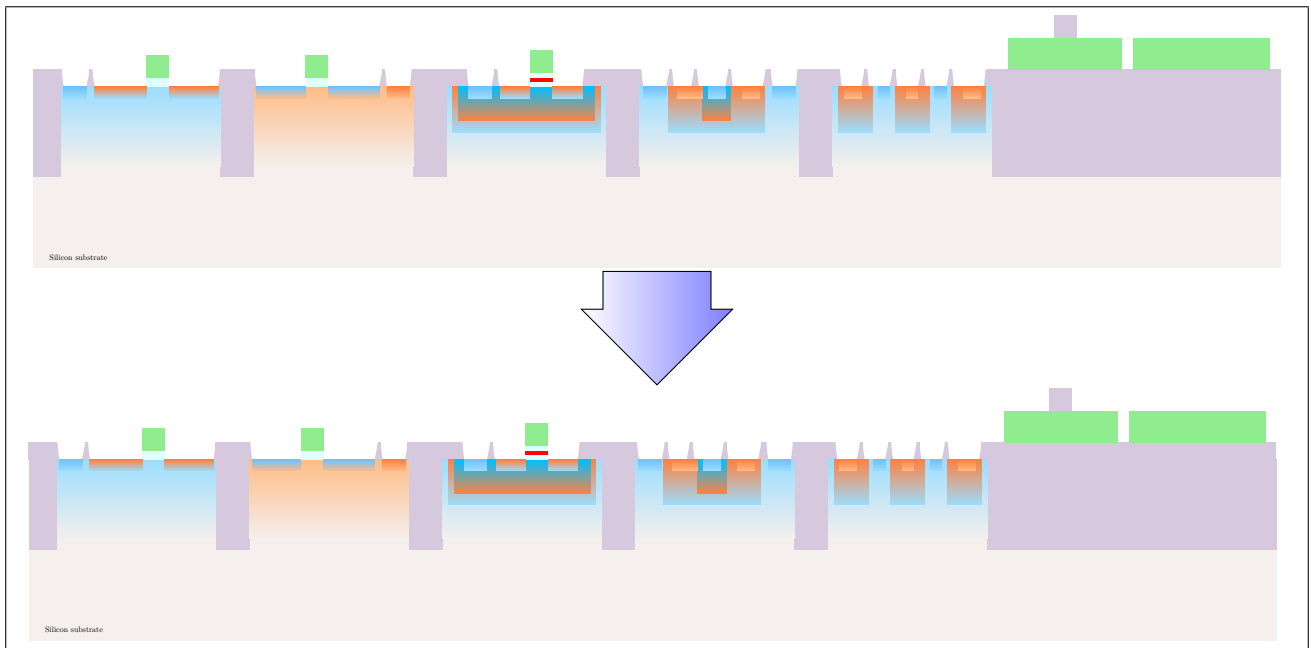


Figure 62: Titanium deposition

Possible approaches:

- **"Varian 3180 Sputter (SPT-3180)" at HKUST NFF lab:**
Has has a sputter rate of around 4 nm/s for titanium.
This means we run the deposition process for around 15 seconds.

11.5 First reaction step

The deposited Ti film reacts with the exposed silicon areas such as the source/drain area and polysilicon gate electrodes by the first anneal at 600-700°C in N_2 ambient. In this first anneal, the C49- $TiSi_2$ phase is formed.

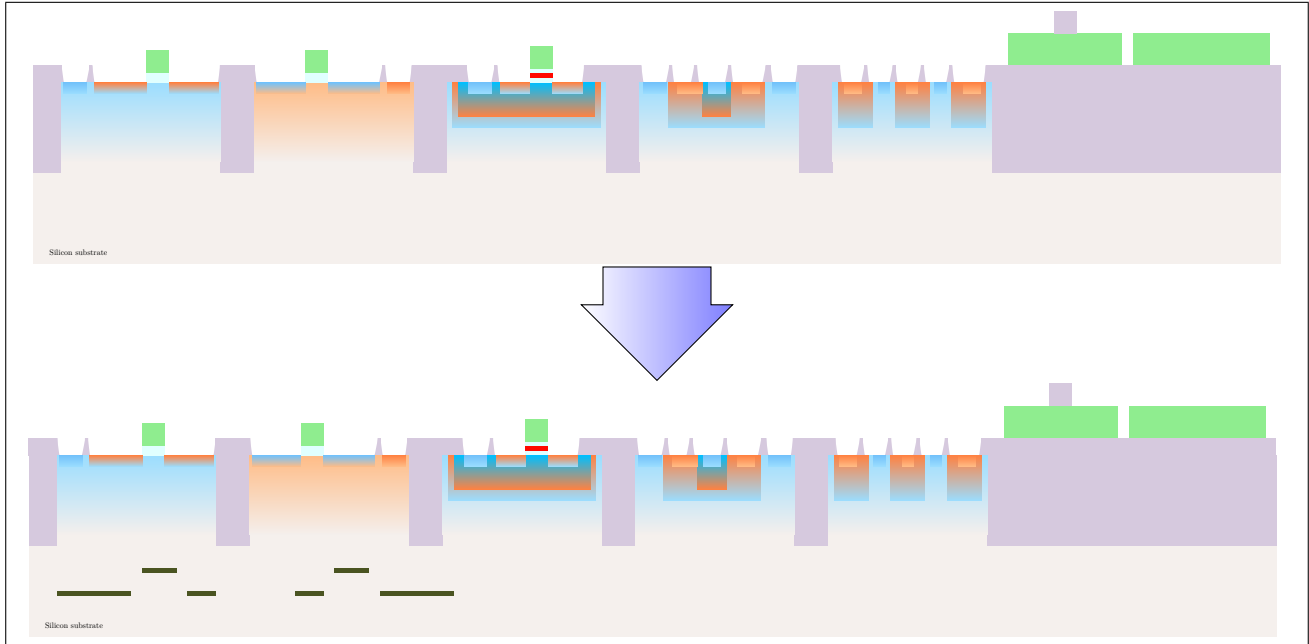


Figure 63: Reaction 1

We use the "AG610 RTP (DIF-R2)" from the HKUST at 700°C for 240 seconds.

11.6 Metal removal

The unreacted titanium film on the dielectric layer such as SiO_2 or SiN is selectively etched by APM (Ammonia and Hydrogen Peroxide Mixture) solution.

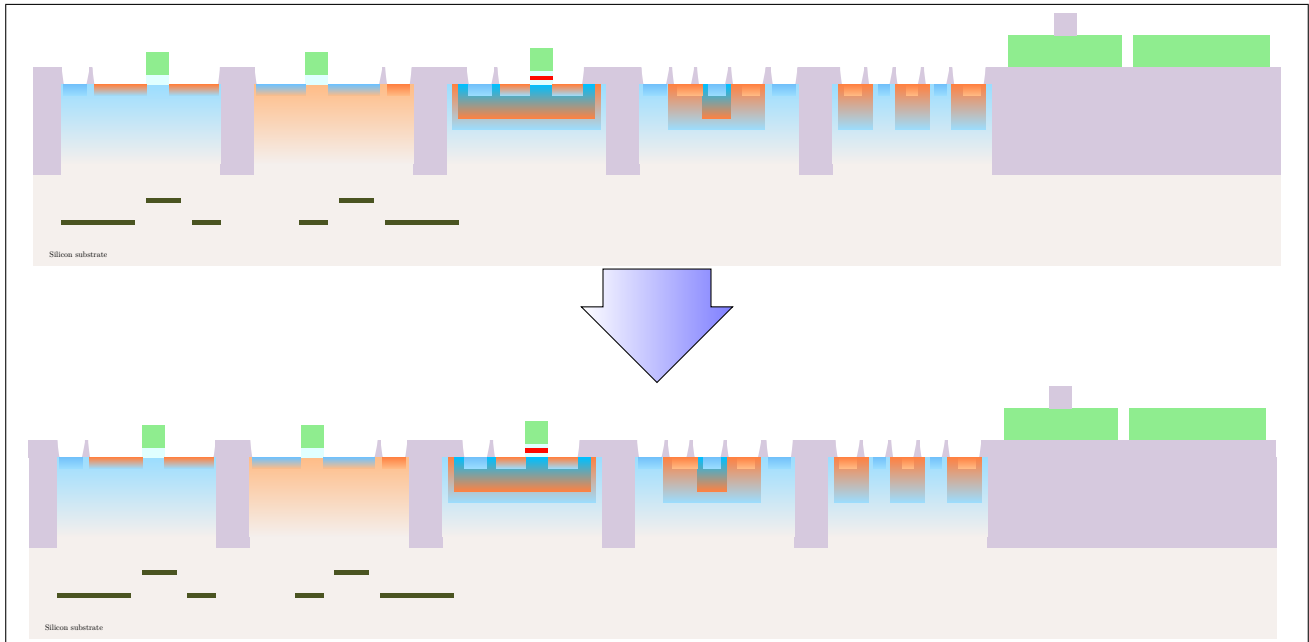


Figure 64: Titanium etch

11.7 Second reaction step

The final step is a second anneal at 800 °C or above to transform the high-resistivity C49- $TiSi_2$ phase to the low-resistivity C54- $TiSi_2$ phase at the gate electrodes and source/drain areas.

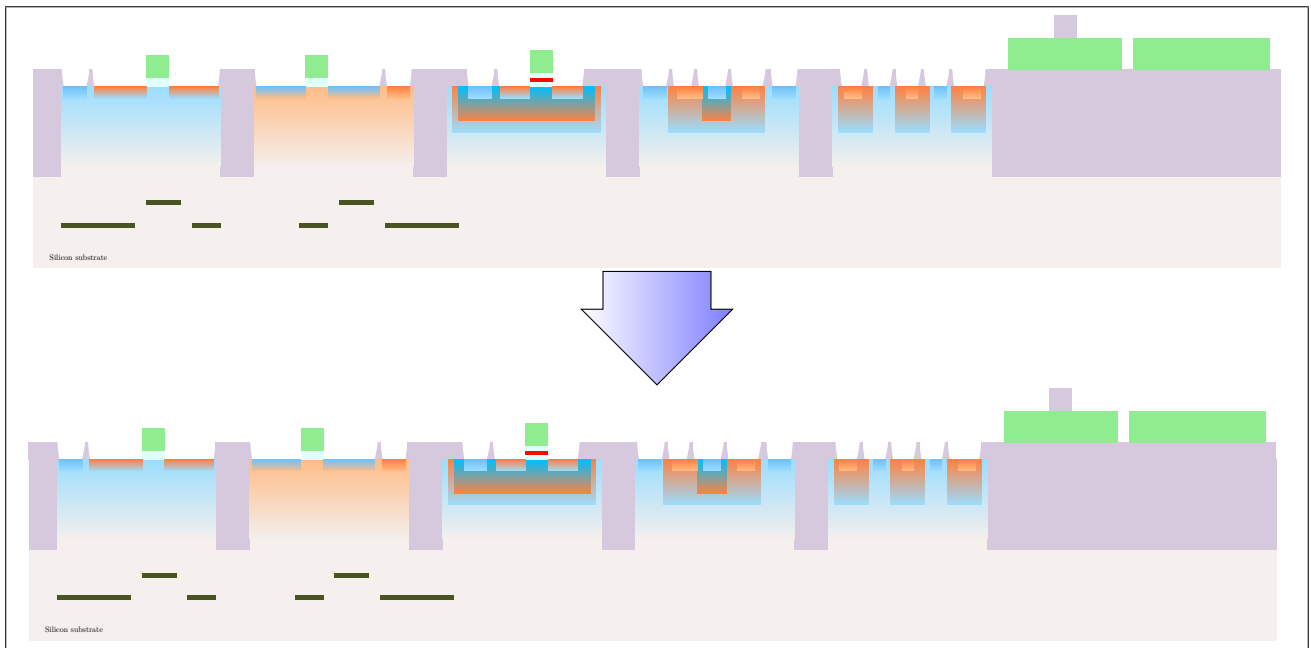


Figure 65: Reaction 2

We use the "AG610 RTP (DIF-R2)" again at 800°C for 240 seconds.

12 Contacts to active area

Now we have to build the first set of vias connecting the first metal layer to the active area. These vias are in the fringe between front-end and back-end process.

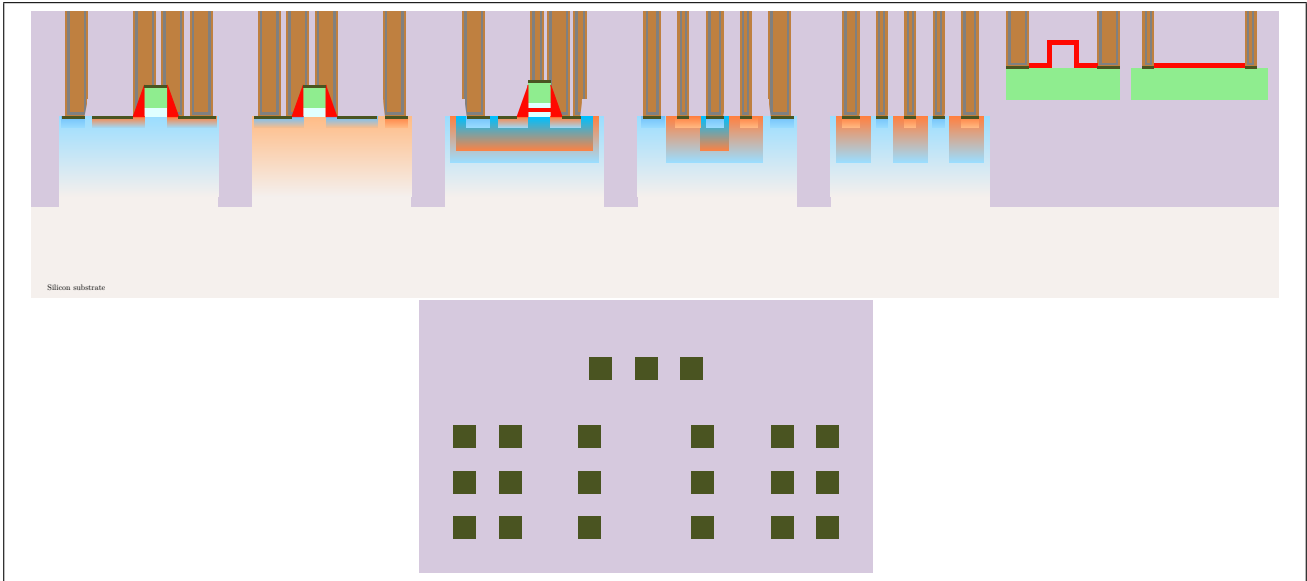


Figure 66: Contact geometry target

As can be seen in [Figure 66](#), the goal of this step is purely to deposit a layer of isolation oxide, get the holes into it, down to the silicide and polyside in order to form wires later on. We do not want to etch down anywhere else than the silicide/polyside areas because these function as etch stoppers, while everywhere else we might etch further than desired with small variations in etching time which might result in a drastic variation in sheet resistance of the junctions and gate.

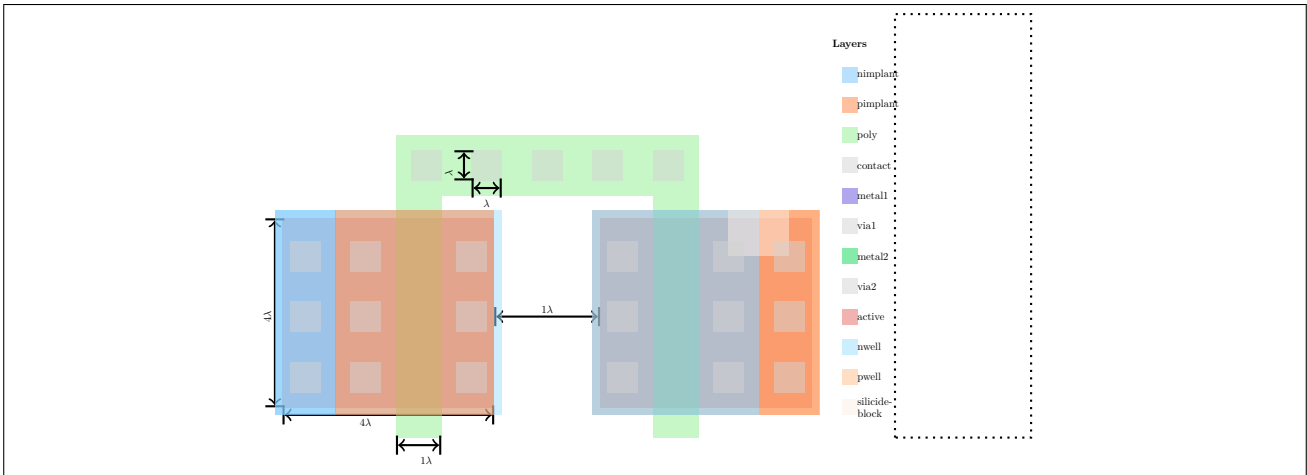


Figure 67: First via layout

It should be noted again that the via placement and dimensions in [Figure 67](#) are solely for demonstration purposes for the process and are in no way the actual standard cell design for the final standard cell lib.

In later iterations of this process we might be switching to Tungsten as the metal material for this step.

12.1 Isolation dioxide layer

We now need to grow a layer of thick oxide in order to isolate the Aluminum interconnect layer from the active area. We can't use oxide grown in from the silicon itself inside a furnace, because of the polysilicon and silicide covering the wafer. For that reason we resort to deposited LTO (low temperature oxide), which has a lower density which is even better, because of the spacing between the isolation between the metal layers is even better.

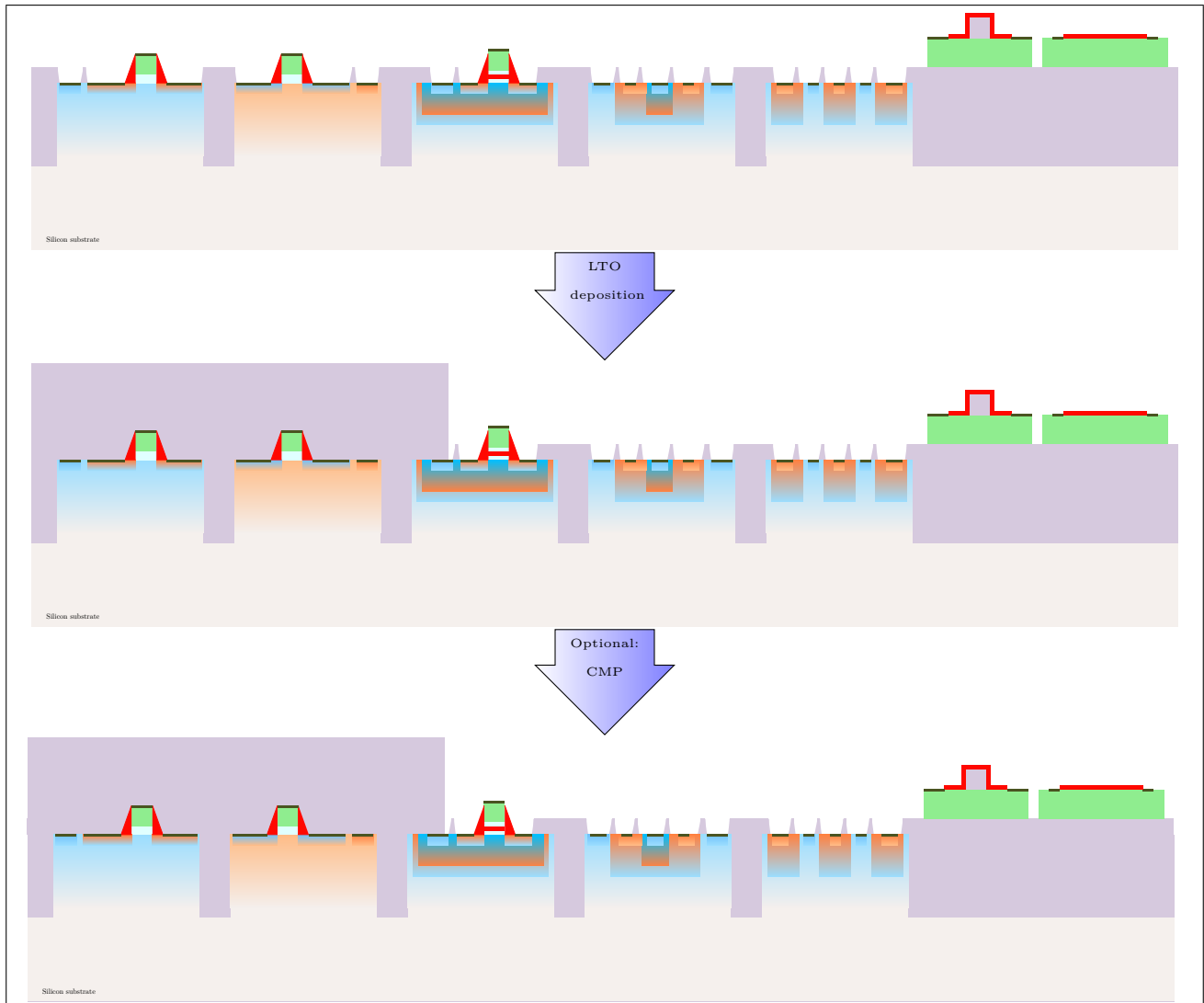


Figure 68: Oxide layer

We target a isolation layer thickness to $2\mu m$ in order to be sure that we have covered the polysilicon gate everywhere.

Possible approaches:

- **"LPCVD-B3 LTO (CVD-B3)" from HKUST**

At HKUST we have a chemical vapor deposition unit which gives us better control over the layer thickness. These steps are needed to arrive with the desired geometry¹²

1. Set the growth rate to 14 nm/min
2. Run for 140 minutes

- **In a furnace ("a hack around")**

In case of a lack of LPCVD equipment one might also resort to "hack together" a solution for LTO deposition using a furnace¹³

1. Deposit tetraethyl orthosilicate ($SiC_8H_{20}O_4$)

¹²<http://memslab.blogspot.com/2013/01/lto-lpcvd.html>

¹³<https://www.sciencedirect.com/science/article/pii/S0167577X89900062>

2. React for 20 minutes at 1050°C in N_2 environment in a furnace

After depositing the oxide, one might wanna perform a CMP step in order to planarize the oxide surface for a more uniform deposition of metal in [subsection 13.1](#)

12.2 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 "contact" layer within the GDS2 file onto a **bright field** mask. The requirement is a **negative** tone resist.

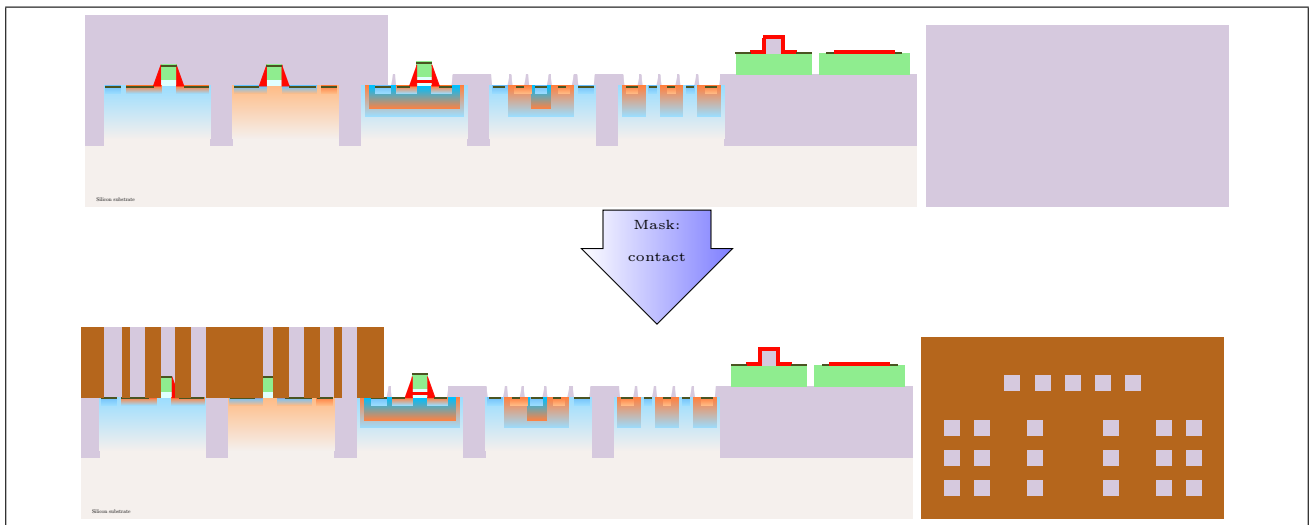


Figure 69: Patterning contact vias

The thickness of the resist layer and the baking duration will vary depending on the specific equipment for which this process will be implemented with. Also after the exposure and development, the hard baking shouldn't be forgotten!

12.3 Etching

We now need to open a window in the dioxide layer, through which the later on deposited Aluminum will touch down onto the silicide/polyside contacts of the active area.

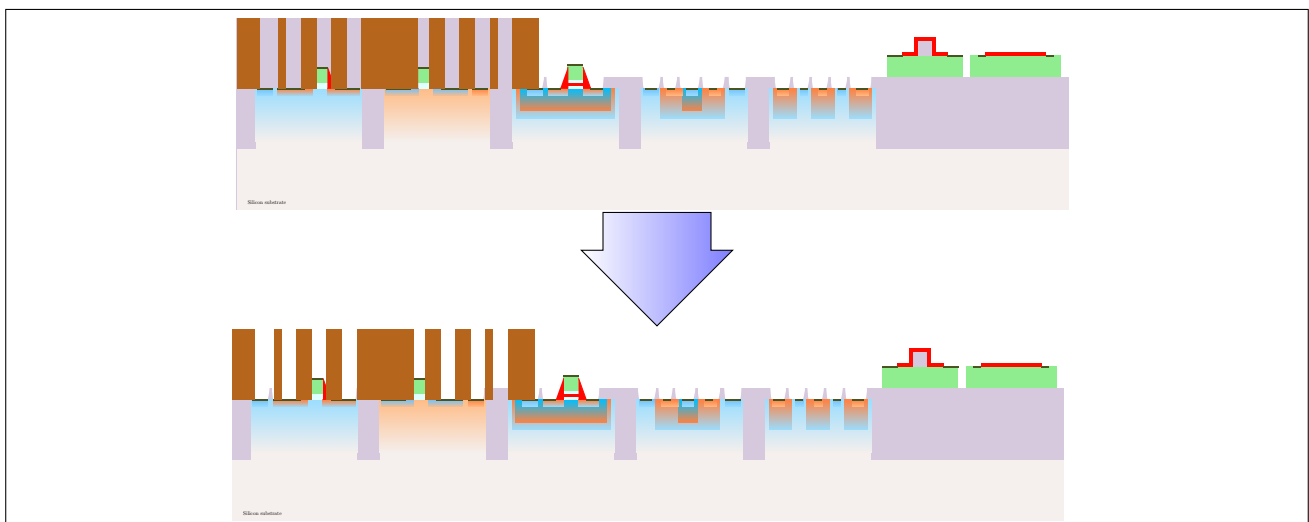


Figure 70: Etching contact holes

Since the silicon dioxide layer is $2\mu\text{m}$ thick and we want to reach the silicon below we can use wet etching as described in the chemistry chapter.

Possible approaches:

- **"AOE Etcher (DRY-AOE)" from HKUST**
We can use anisotropic plasma etching for sharper borders.
- **Chemical solution**
We can use buffered hydrofluoric acid (BOE (1:6)) at room temperature ($\approx 508 \text{ nm/min}$) for around 4

minutes in order to get through the $2\mu m$ of oxide.
Too long over 4 minutes might cause under-etch however!

12.4 Resist strip

Now we need to remove the contaminants for further processing.

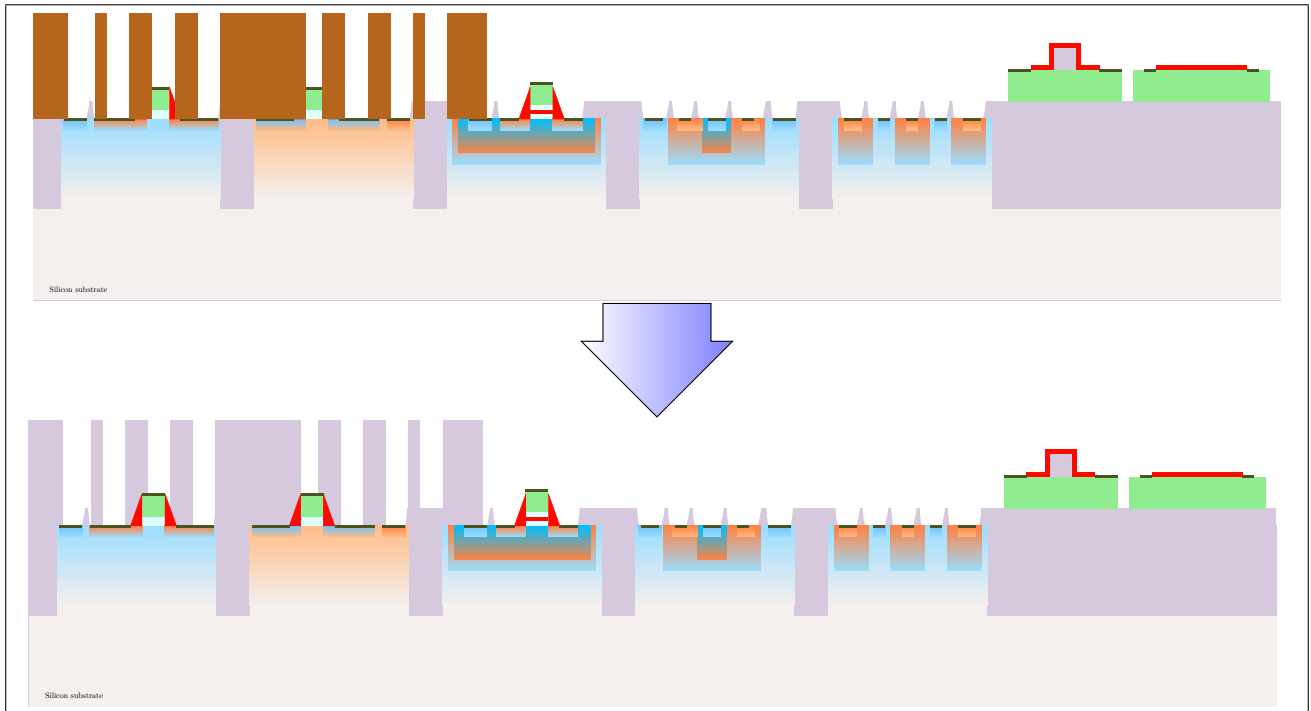


Figure 71: Resist removal

We strip the resist, rinse and perform sulfuric cleaning.

13 First metal layer

Now we've got to build the first interconnect wires, connecting the contact vias to the "metal1" wires, which will provide a way to contact to them with the via1 contact layout.

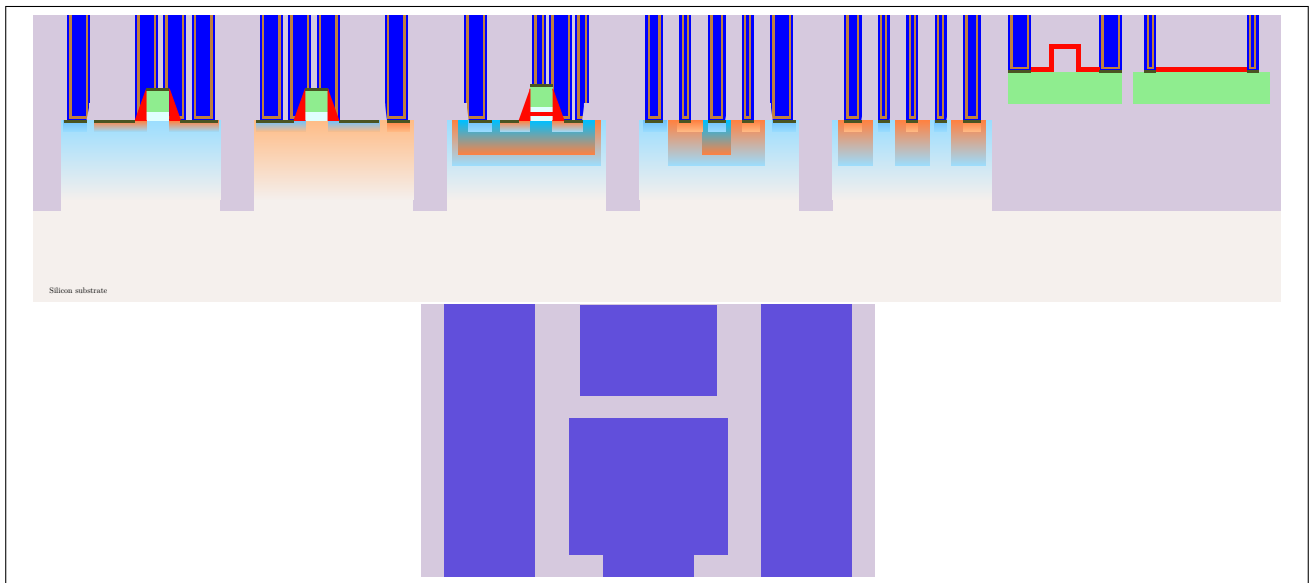


Figure 72: Metal geometry target

As can be seen in [Figure 72](#), the goal of this step is purely to etch the wire structure for the first metal layer into the in [subsection 13.1](#) deposited metal layer, and form wires by doing so.

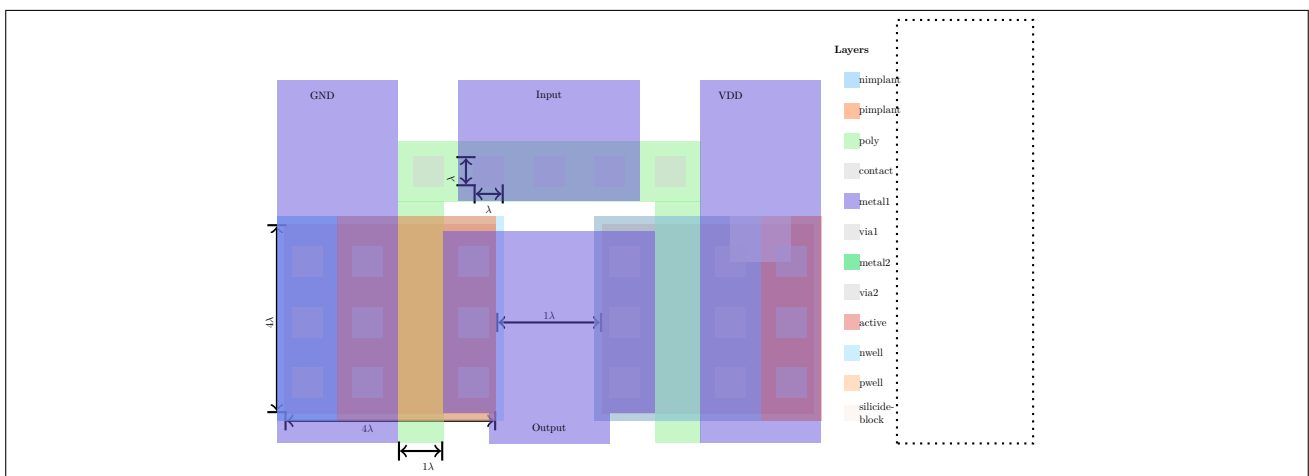


Figure 73: First metal layout

It should be noted again that the via placement and dimensions in [Figure 73](#) are solely for demonstration purposes for the process and are in no way the actual standard cell design for the final standard cell lib.

In later iterations of this process we might be switching to Tungsten as the metal material for this step so the etching method might change in further releases.

13.1 Metal deposition

Now we somehow have got to get the metal onto our silicon oxide in a fashion so that it fills the holes we've etched in [subsection 12.3](#) and touches down onto the silicide/polycide, thus making a contact to the active area.

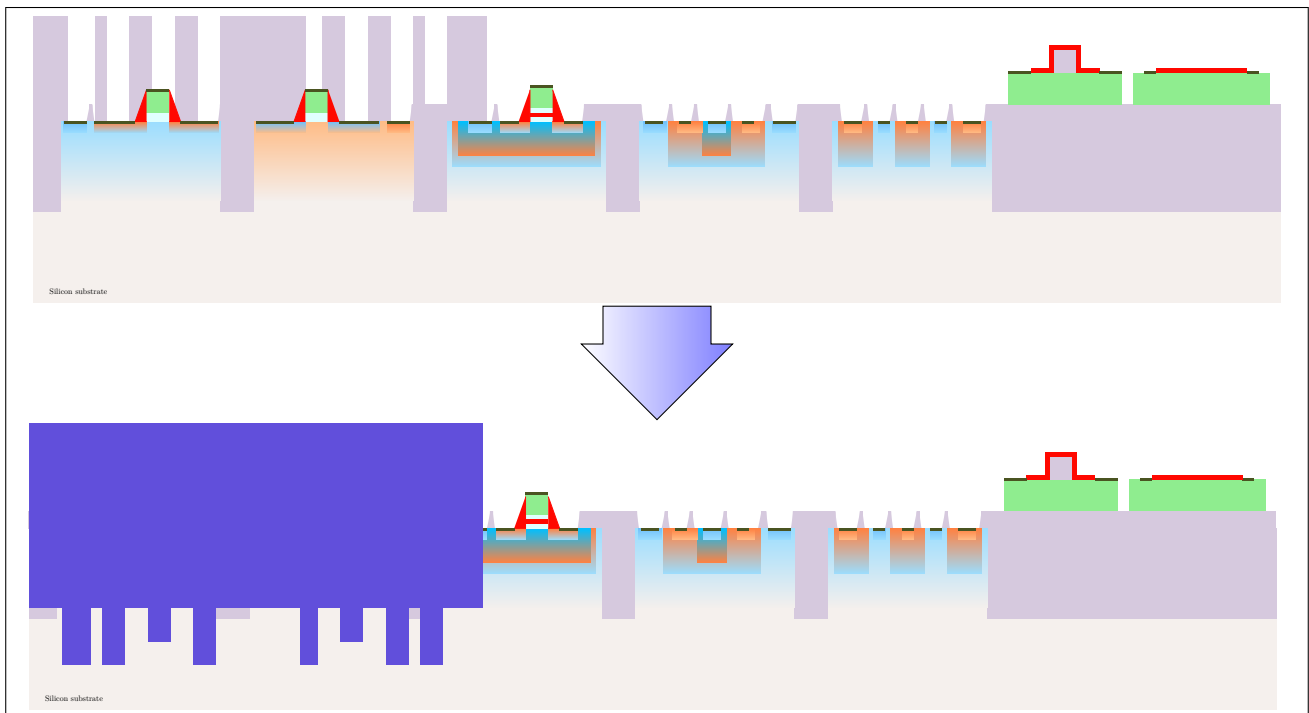


Figure 74: Metal deposition

In order to reach the target of filling the holes in the oxide and having at least another depth worth of space in order to have an enough low resistance of the wire interconnect. We end up with a target thickness of $4\mu m$.

Possible approaches:

- "Varian 3180 Sputter (SPT-3180)" from HKUST
The deposition speed is $16nm/s$ which gives us a required deposition time of 250 seconds for $4\mu m$.
- Add your solution here!

13.2 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 "metal1" layer within the GDS2 file onto a **bright field** mask. The requirement is a **positive** tone resist.

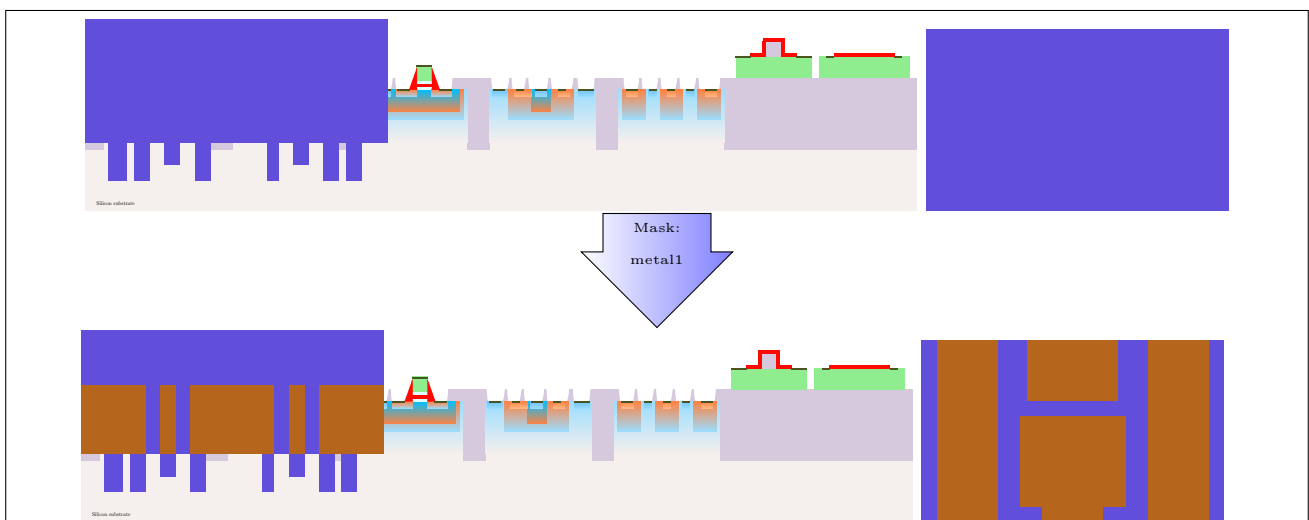


Figure 75: Patterning first wires

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. Also after the exposure and development, the hard baking shouldn't be forgotten!

13.3 Etching

Now we've got to etch the Aluminum which hasn't been covered yet by the resist in order to get the desired wire structures.

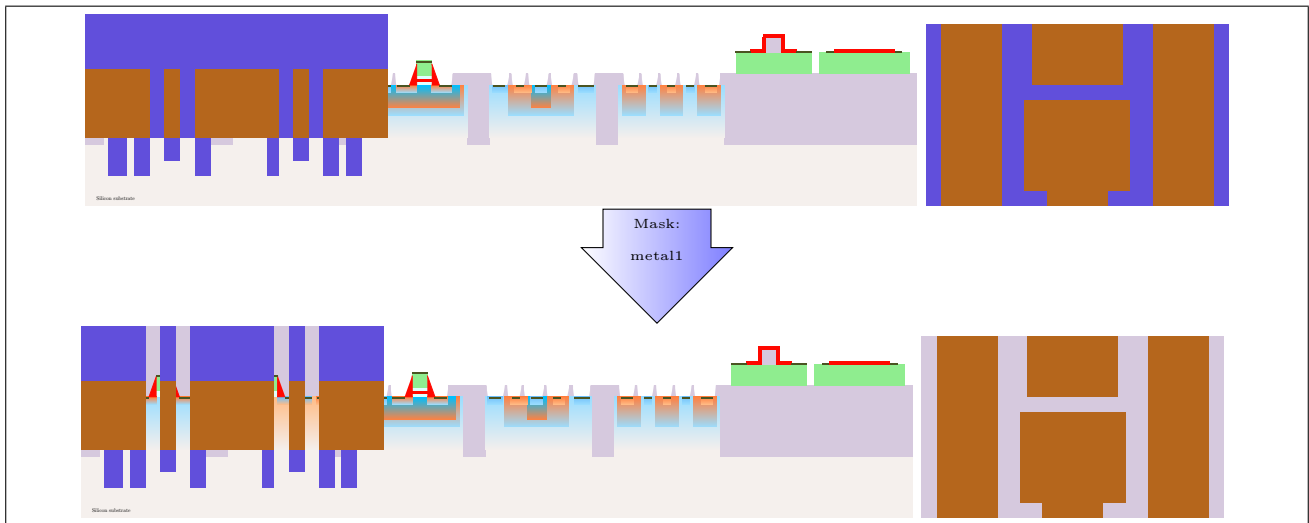


Figure 76: Etching first wires

Possible approaches:

- **"Oxford Aluminum Etcher (DRY-Metal-2)" from HKUST**
The normal etch rate for Aluminum is 180 nm/min with this machines
We've deposited $4\mu\text{m}$ Aluminum in [subsection 13.1](#) which means we've got to etch for around 22 minutes and 13 seconds
- **Chemical solution**
Please specify here!

13.4 Resist strip

Now we need to remove the photo resist for further processing because it would contaminate the equipment.

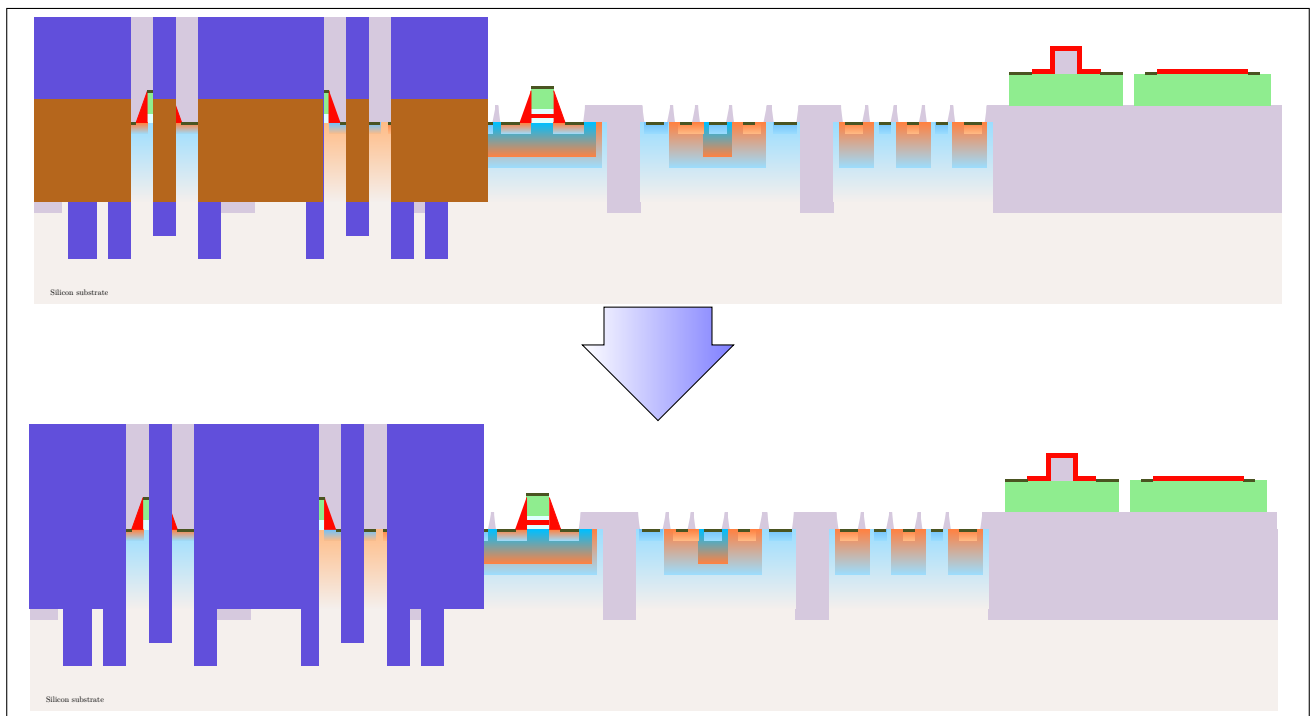


Figure 77: Resist removal

Because we now have a metal layer we can't use sulfuric acids because this would dissolve/attack the Aluminum as well as the photo resist. Instead we have got to use an organic solvent which does not react with Aluminum.

Possible approaches:

- **"MS2001 resist stripper" from HKUST**

It can be found at the wet stations: Wetstation W, X, Y and Z (WET-W1 to WET-W2, WET-X1 to WET-X2, WET-Y1to WET-Y2, WET-Z1 to WET-Z2)

- **Another chemical solution**

Please specify here!

14 Via

Now we have to build an additional set of vias connecting the first metal layer to the next metal layer. These vias are already part of the front-end process.

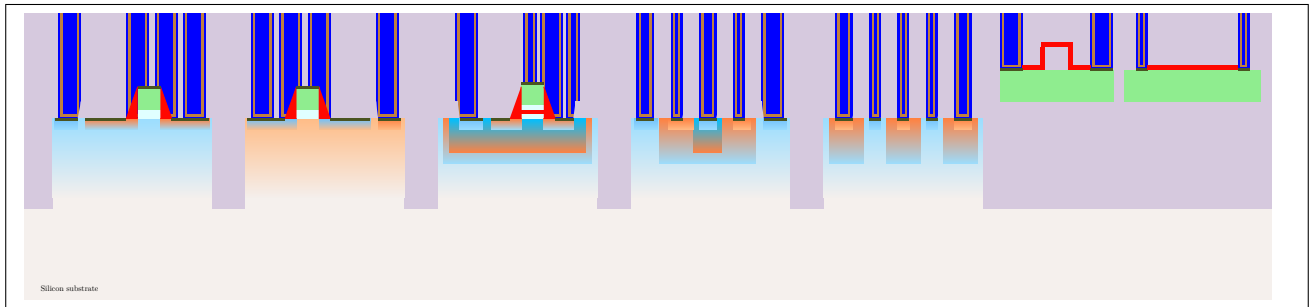


Figure 78: Contact geometry target

As can be seen in [Figure 78](#), the goal of this step is purely to deposit a layer of isolation oxide, get the holes into it, down to the metal layer below in order to form wires later on.

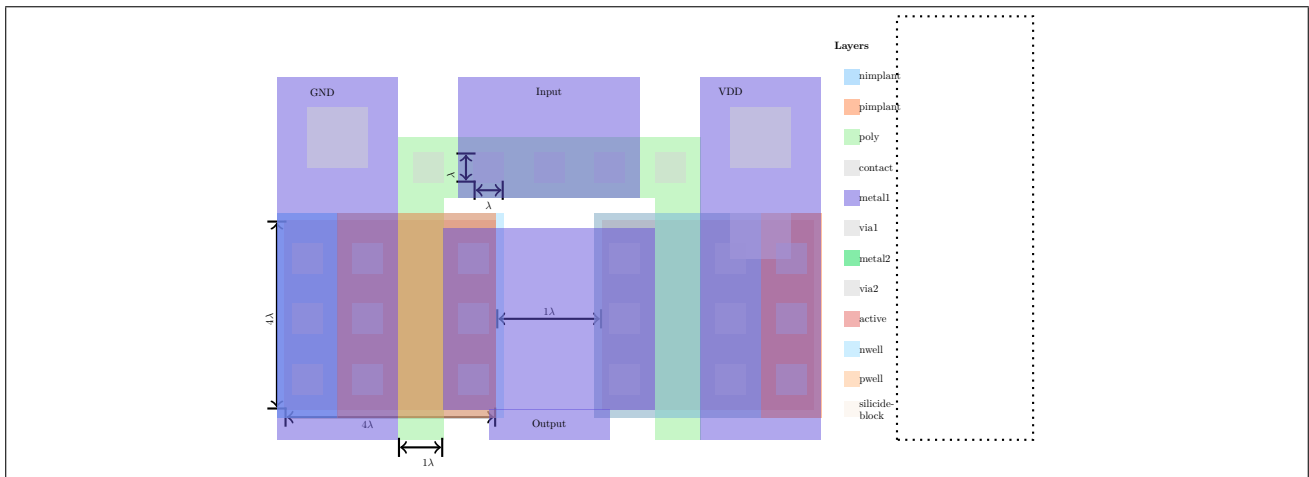


Figure 79: First via layout

It should be noted again that the via placement and dimensions in [Figure 79](#) are solely for demonstration purposes for the process and are in no way the actual standard cell design for the final standard cell lib.

In a later iterations of this process we might be switching to Copper as the metal material for this step which will result in a variation of this step because the usage of damascene method.

14.1 Isolation dioxide layer

We now need to grow a layer of thick oxide in order to isolate the Aluminum interconnect layer from the active area.

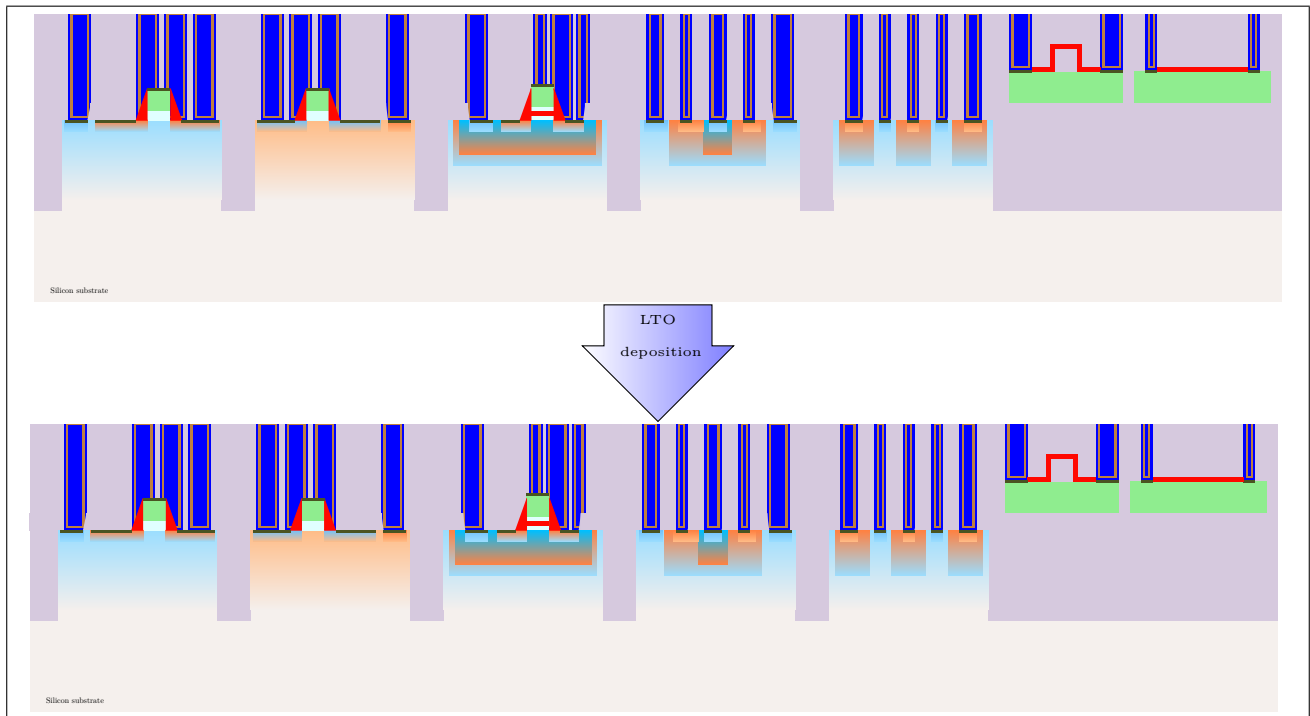


Figure 80: Oxide layer

Possible approaches:

- **"LPCVD-B3 LTO (CVD-B3)" from HKUST**

At HKUST we have a chemical vapor deposition unit which gives us better control over the layer thickness. These steps are needed to arrive with the desired geometry¹⁴

1. Set the growth rate to 14 nm/min
2. Run for 140 minutes

- **In a furnace ("a hack around")**

In case of a lack of LPCVD equipment one might also resort to "hack together" a solution for LTO deposition using a furnace¹⁵

1. Deposit tetraethyl orthosilicate ($SiC_8H_{20}O_4$)
2. React for 20 minutes at 1050°C in N_2 environment in a furnace

¹⁴<http://memslab.blogspot.com/2013/01/lto-lpcvd.html>

¹⁵<https://www.sciencedirect.com/science/article/pii/0167577X89900062>

14.2 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 "contact" layer within the GDS2 file onto a **bright field** mask. The requirement is a **negative** tone resist.

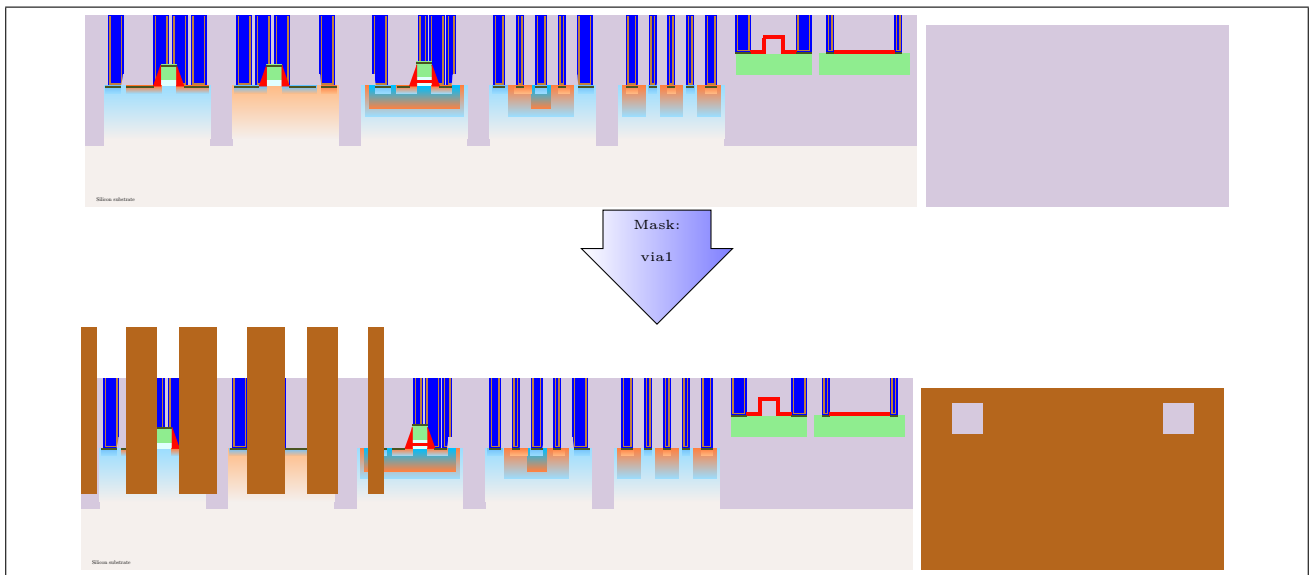


Figure 81: N+ region resist mask

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. Also after the exposure and development, the hard baking shouldn't be forgotten!

14.3 Etching

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

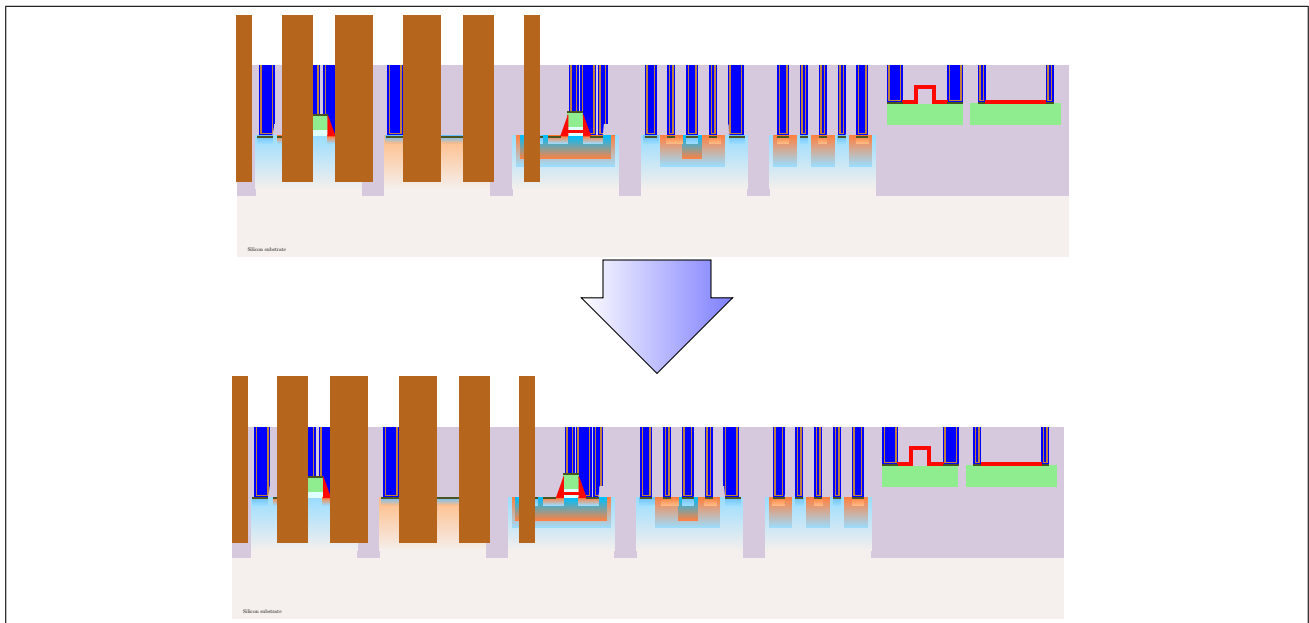


Figure 82: N+ region opened

Since the silicon dioxide layer is 100nm thick and we wanna reach the silicon below we can use wet etching as described in the chemistry chapter.

Possible approaches:

- **"AOE Etcher (DRY-AOE)" from HKUST**
We can use anisotropic plasma etching for sharper borders.
- **Chemical solution**
We can use buffered hydrofluoric acid (BOE (1:6)) at room temperature (≈ 508 nm/min) for around 4 minutes in order to get through the $2\mu\text{m}$ of oxide.
Too long over 4 minutes might cause under-etch however!

14.4 Resist strip

Now we need to remove the photo resist for further processing because it would contaminate the equipment.

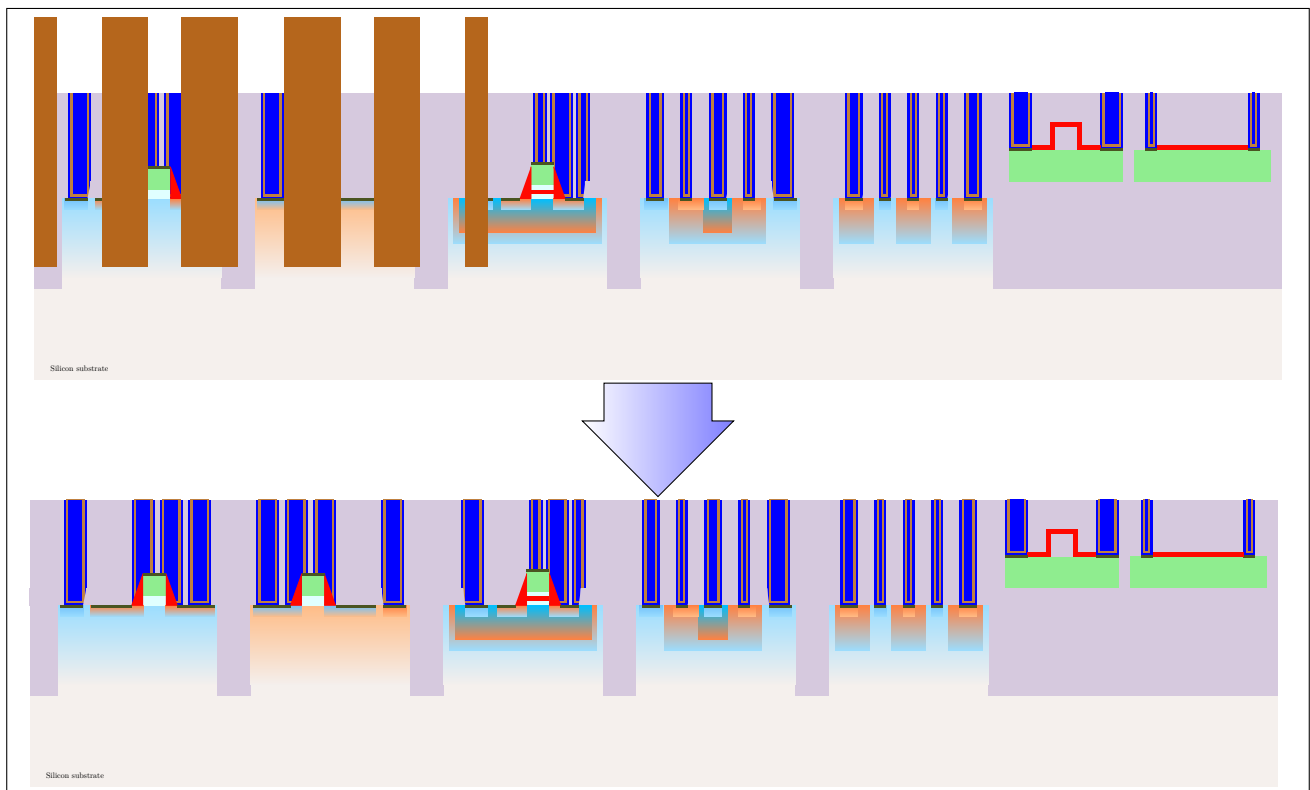


Figure 83: Resist removal

Because we now have a metal layer we can't use sulfuric acids because this would dissolve/attack the Aluminum as well as the photo resist. Instead we have got to use an organic solvent which does not react with Aluminum.

Possible approaches:

- **"MS2001 resist stripper" from HKUST**

It can be found at the wet stations: Wetstation W, X, Y and Z (WET-W1 to WET-W2, WET-X1 to WET-X2, WET-Y1to WET-Y2, WET-Z1 to WET-Z2)

- **Another chemical solution**

Please specify here!

15 Additional metal layer

Now we've got to build the more interconnect wires, connecting the contact vias to the "metal2" wires, which will provide a way to contact to them with the via2 contact layout.

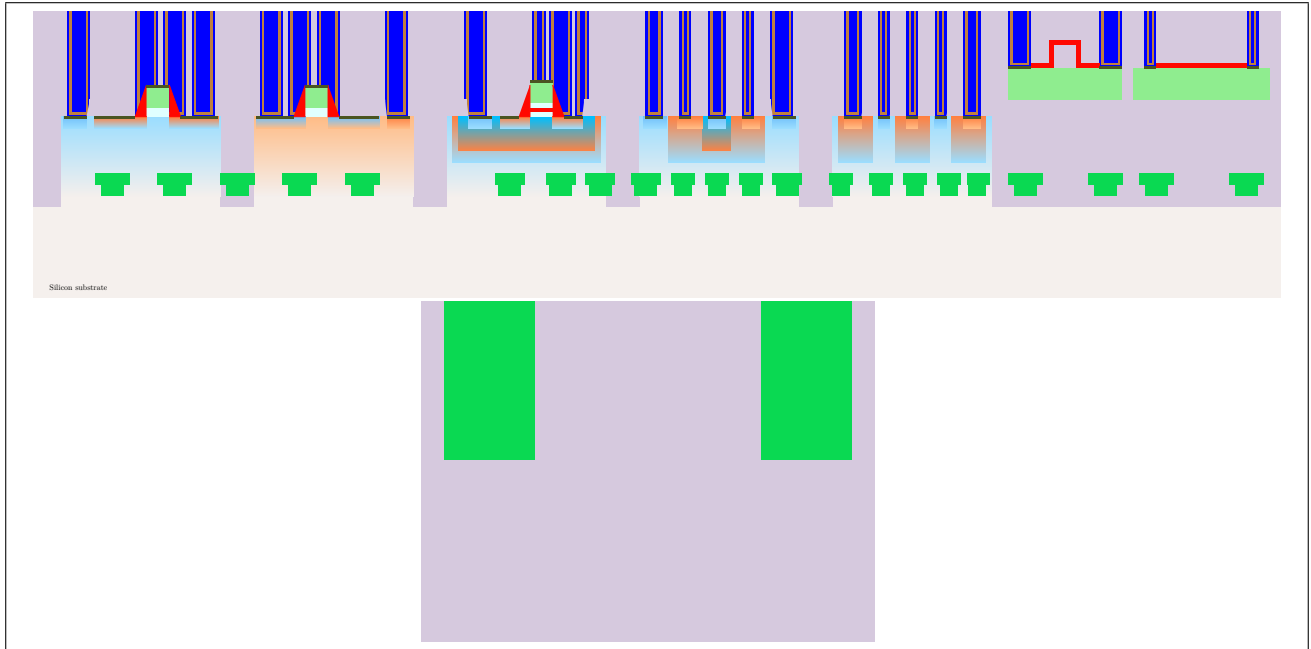


Figure 84: Metal geometry target

As can be seen in [Figure 84](#), the goal of this step is purely to etch the wire structure for the additional metal layer into the in [subsection 15.1](#) deposited metal layer, and form wires by doing so.

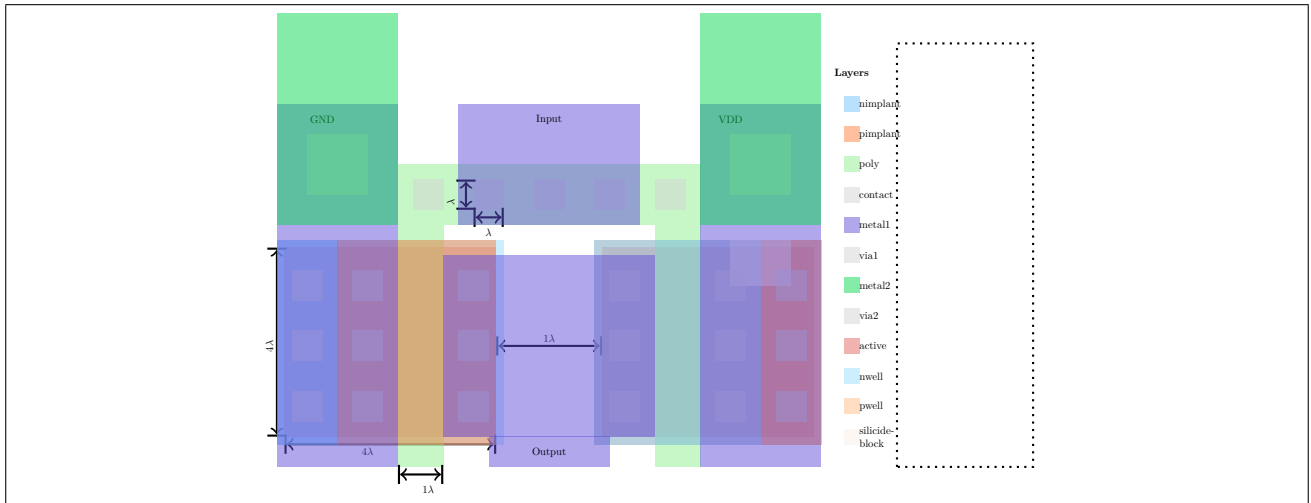


Figure 85: Second metal layout

It should be noted again that the via placement and dimensions in [Figure 85](#) are solely for demonstration purposes for the process and are in no way the actual standard cell design for the final standard cell lib.

In later iterations of this process we might be switching to Tungsten as the metal material for this step so the etching method might change in further releases.

15.1 Metal deposition

Now we somehow have got to get the metal onto our silicon oxide in a fashion so that it fills the holes we've etched in [subsection 14.3](#) and touches down onto the last metal layer, thus making a contact to the plane below.

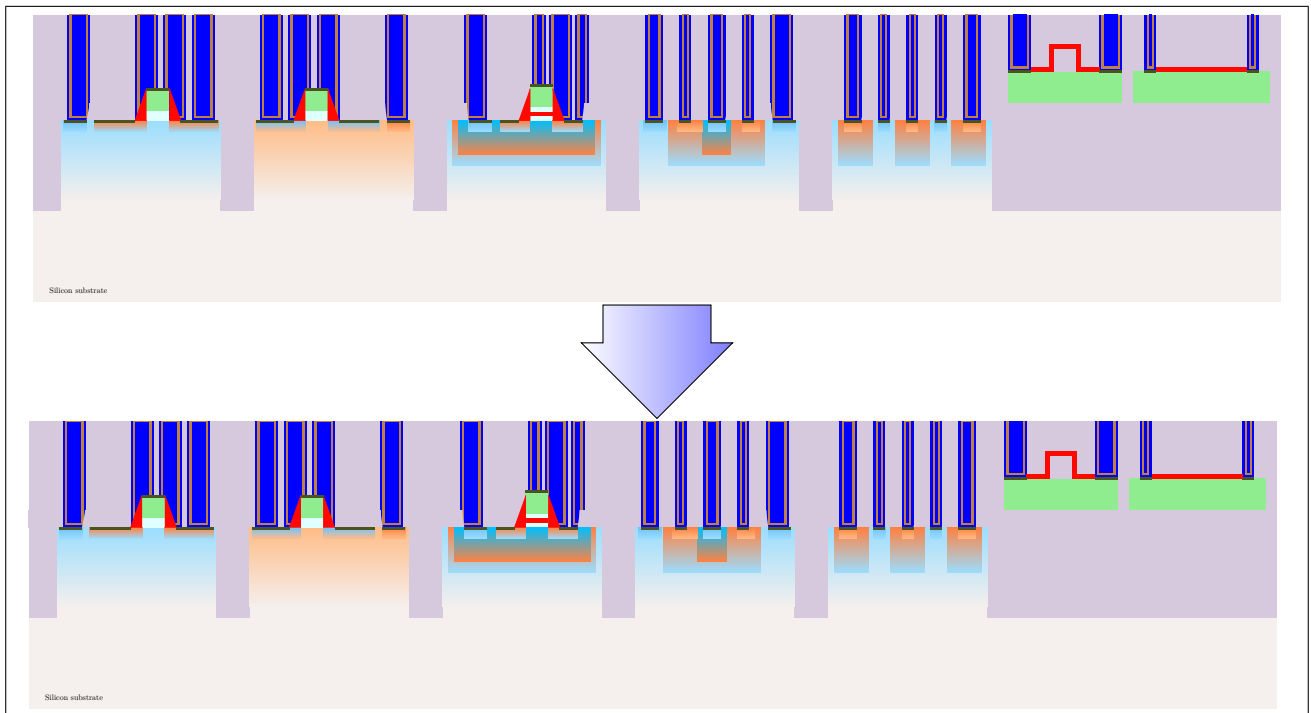


Figure 86: Metal deposition

In order to reach the target of filling the holes in the oxide and having at least another depth worth of space in order to have an enough low resistance of the wire interconnect. We end up with a target thickness of $4\mu m$.

Possible approaches:

- **"Varian 3180 Sputter (SPT-3180)" from HKUST**
The deposition speed is 16nm/s which gives us a required deposition time of 250 seconds for $4\mu m$.
- **Add your solution here!**

15.2 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 "more1" layer within the GDS2 file onto a **bright field** mask. The requirement is a **positive** tone resist.

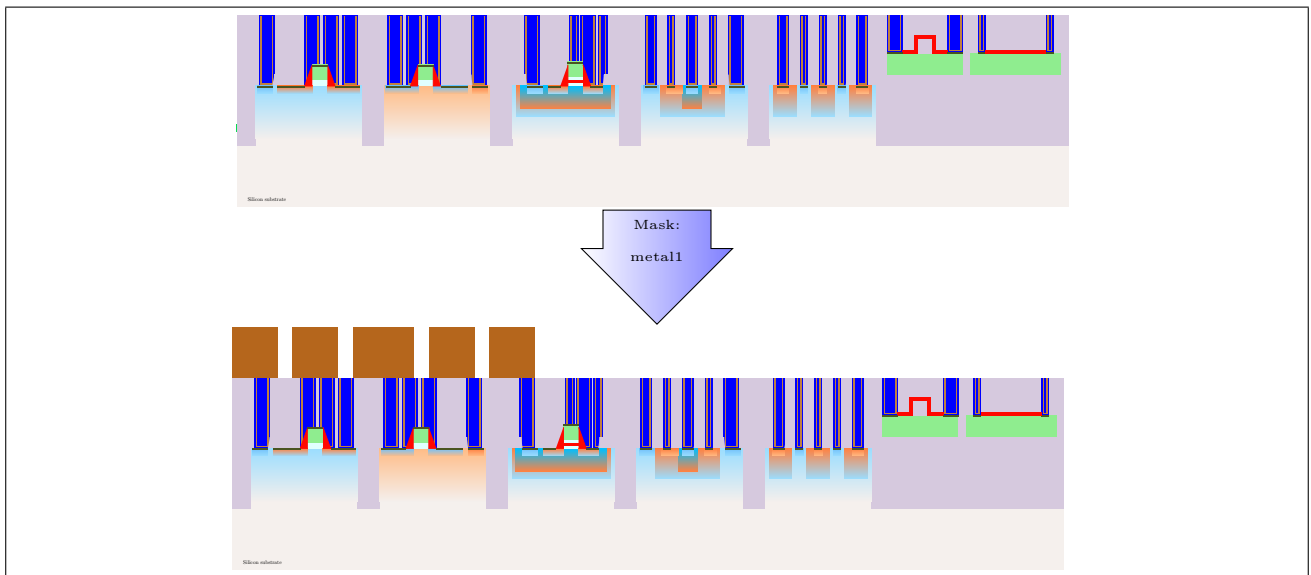


Figure 87: Patterning first wires

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. Also after the exposure and development, the hard baking shouldn't be forgotten!

15.3 Etching

Now we've got to etch the Aluminum which hasn't been covered yet by the resist in order to get the desired wire structures.

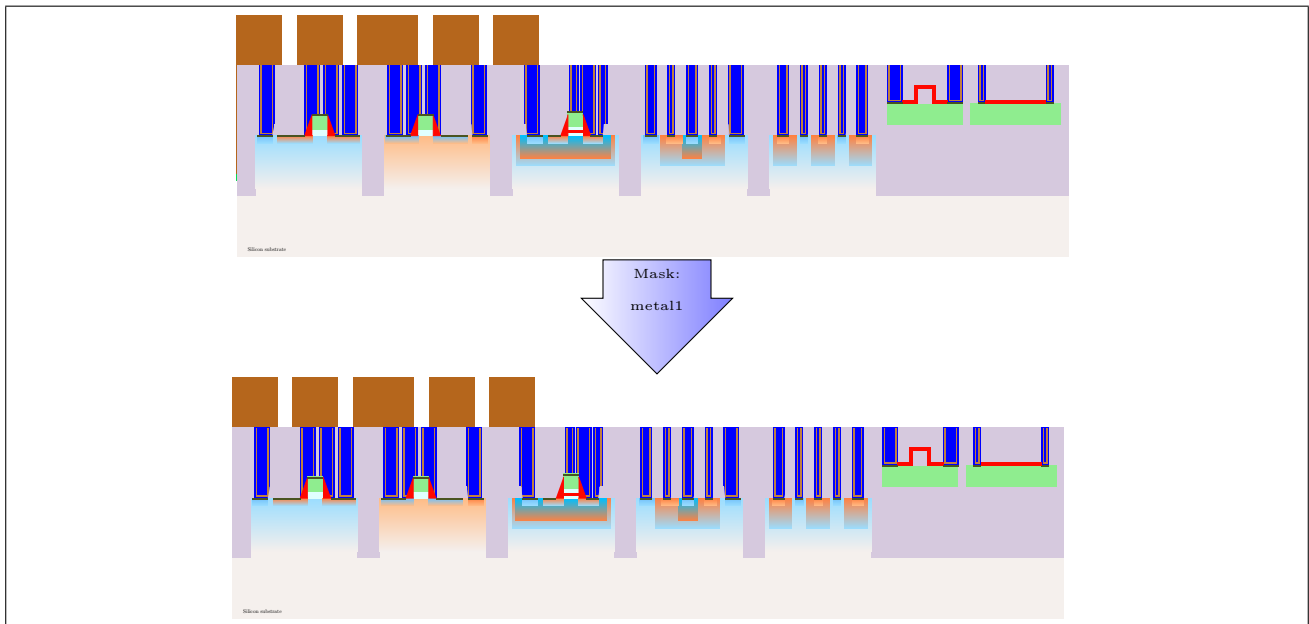


Figure 88: Etching first wires

Possible approaches:

- **"Oxford Aluminum Etcher (DRY-Metal-2)" from HKUST**
The normal etch rate for Aluminum is 180 nm/min with this machines
We've deposited $4\mu\text{m}$ Aluminum in [subsection 15.1](#) which means we've got to etch for around 22 minutes and 13 seconds
- **Chemical solution**
Please specify here!

15.4 Resist strip

Now we need to remove the photo resist for further processing because it would contaminate the equipment.

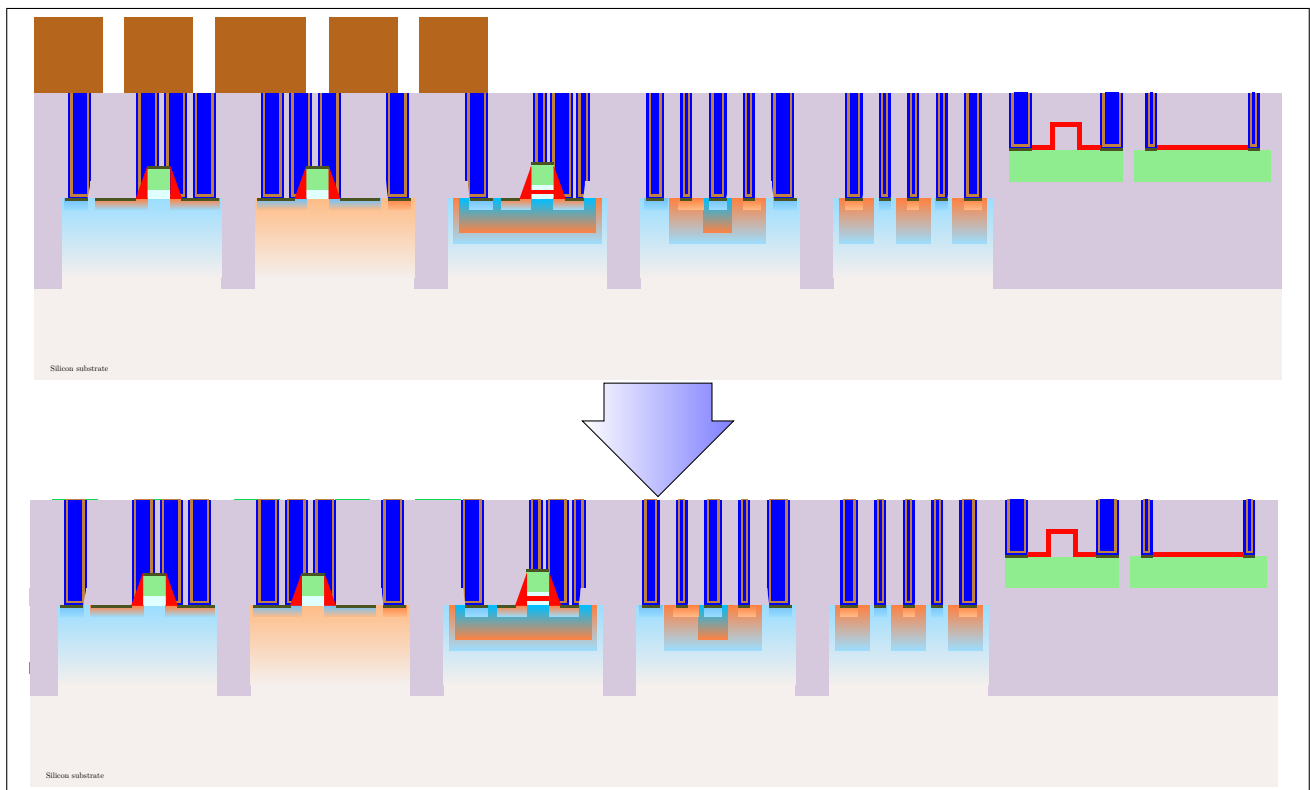


Figure 89: Resist removal

Because we now have a metal layer we can't use sulfuric acids because this would dissolve/attack the Aluminum as well as the photo resist. Instead we have got to use an organic solvent which does not react with Aluminum.

Possible approaches:

- **"MS2001 resist stripper" from HKUST**

It can be found at the wet stations: Wetstation W, X, Y and Z (WET-W1 to WET-W2, WET-X1 to WET-X2, WET-Y1to WET-Y2, WET-Z1 to WET-Z2)

- **Another chemical solution**

Please specify here!