

Standard Cells

Open Source Tools

- yosys
- graywolf
- qrouter
- several FPGA routers

graywolf

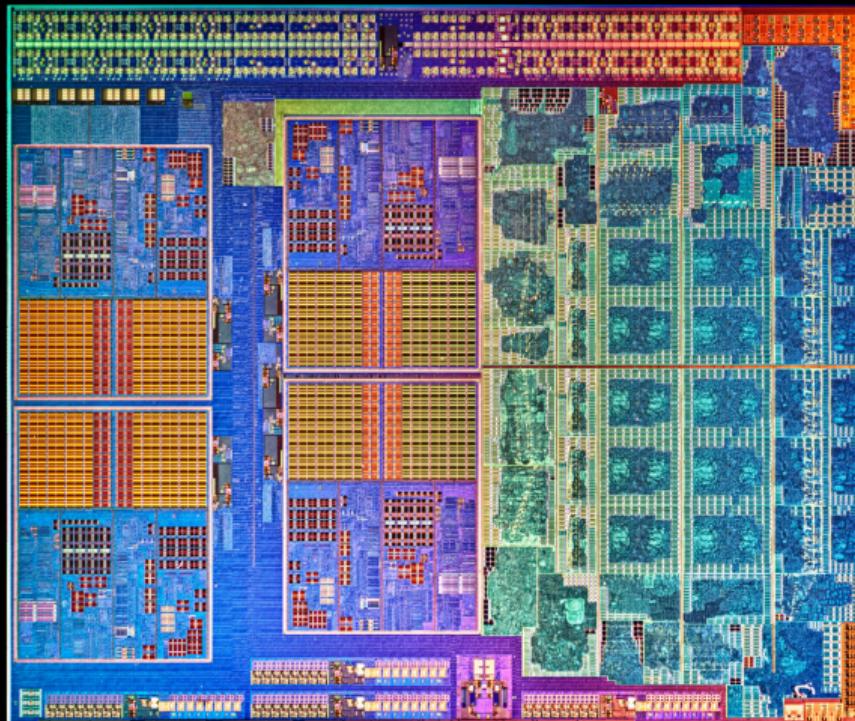
- Originates in Academia: TimberWolf
- Simulated annealing
 - Meta heuristic that is useful not only for placement
- Inline syscalls
 - This is just a bad idea

qrouter

- Started in 2011 by Tim Edwards
- Widely used for FPGA
 - Not ready for silicon
- Sequential routing
 - Parallelism not in scope
- Difficult to prove formal correctness
 - Prove that C implementation of Rip-up and Re-route is correct

Productive Tools

- Different tool sets like BonnRoute, Cadence Suite, Alliance tools, etc.
- Similar capabilities with respect to silicon
- Just throw man-power at VLSI — what is automation?



Routing: State of the Art

- Place components for a large chip
- Route wires roughly along a chessboard for a large chip
- Route detailed tracks and vias for a large chip
- Formal correctness: Rip-up and Re-route
- Formal style: Sequential/Imperative code

Routing: Proposed

- Decomposition for a large chip
- Place components and route for small chips in parallel
- Place abstract gates and route recursively
- Formal correctness: Reduction from SMT
- Formal style: Parallel/Declarative code

Divide and Conquer

Academia + Industry:

- Placement and Routing are different problems
- All components map to the same problem

LibreSilicon:

- Placement and Routing are the same problem
- Different components map to different problems

Routing Hierarchy

Academia + Industry:

- Geographical partitioning of a wafer → *cut tree*
- Based on preceding placement steps

LibreSilicon:

- Modular chip development → *subcell hierarchy*
- Subcells carry implicit and explicit subcells

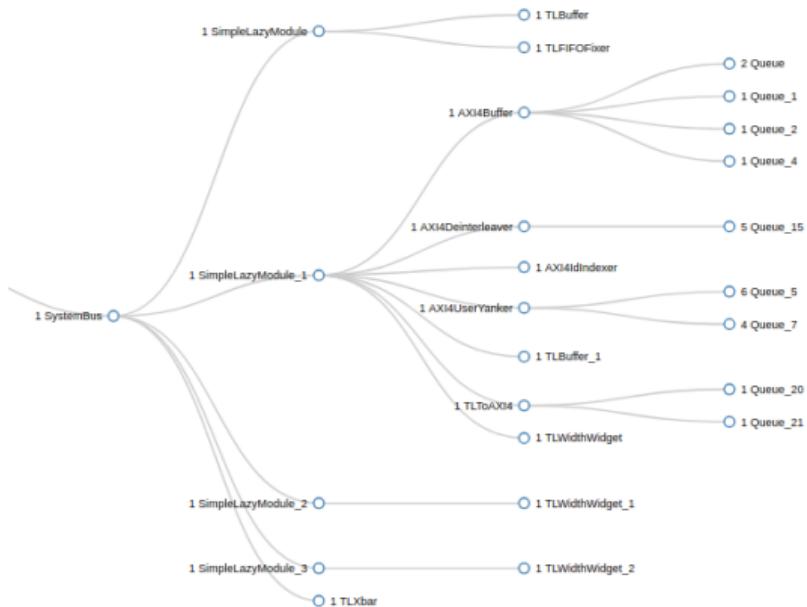
Frontier: Parallelism

- BonnRoute: concurrency + shared memory model
- qrouter: none
- lsc: map + reduce

Subcell hierarchies

- Explicit subcell hierarchies through high modularization
- Implicit subcell hierarchies through exlining
- Preserve hierarchy in compiler interfaces

High modularization



<https://murmur.libresilicon.com/lsc/rocket-chip-yosys>

Exlining

- Proof of concept: picorv

<https://murmur.libresilicon.com/lsc/rocket-chip-exline>

Unconstrained Small Unified Silicon Problem

- Components and nets → *rectilinear geometries*
- Components do not overlap
- Nets overlap with their pins on components

Minimizing Goals

- Layout area
- Maximum wire length
- Via count
- Crossing number (computational)
- Wire jogs (minor)

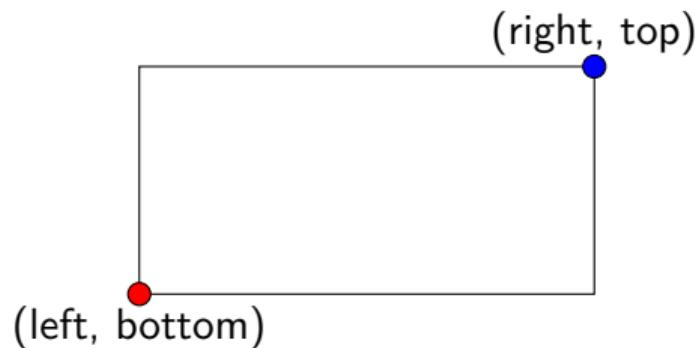
Satisfiability Modulo Theories

- Optimization problems
- Abstraction from Boolean satisfiability
- Several solvers implement smtlib2
 - ABC from University of Berkeley
 - CVC4 from Stanford
 - Boolector from Johannes Kepler University
 - MathSAT from Fondazione Bruno Kessler and DISI-University of Trento
 - Yices from SRI
 - Z3 from Microsoft

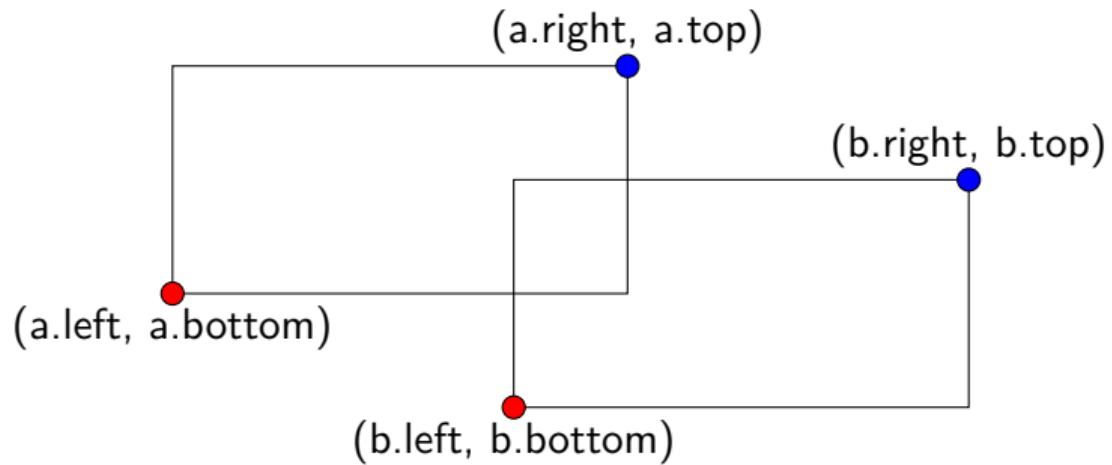
Boolean Satisfiability

$$(\alpha_1 \vee \alpha_2 \vee \alpha_3) \wedge (\neg\alpha_4 \vee \alpha_5 \vee \alpha_6)$$

Defining rectangular components



Overlaps



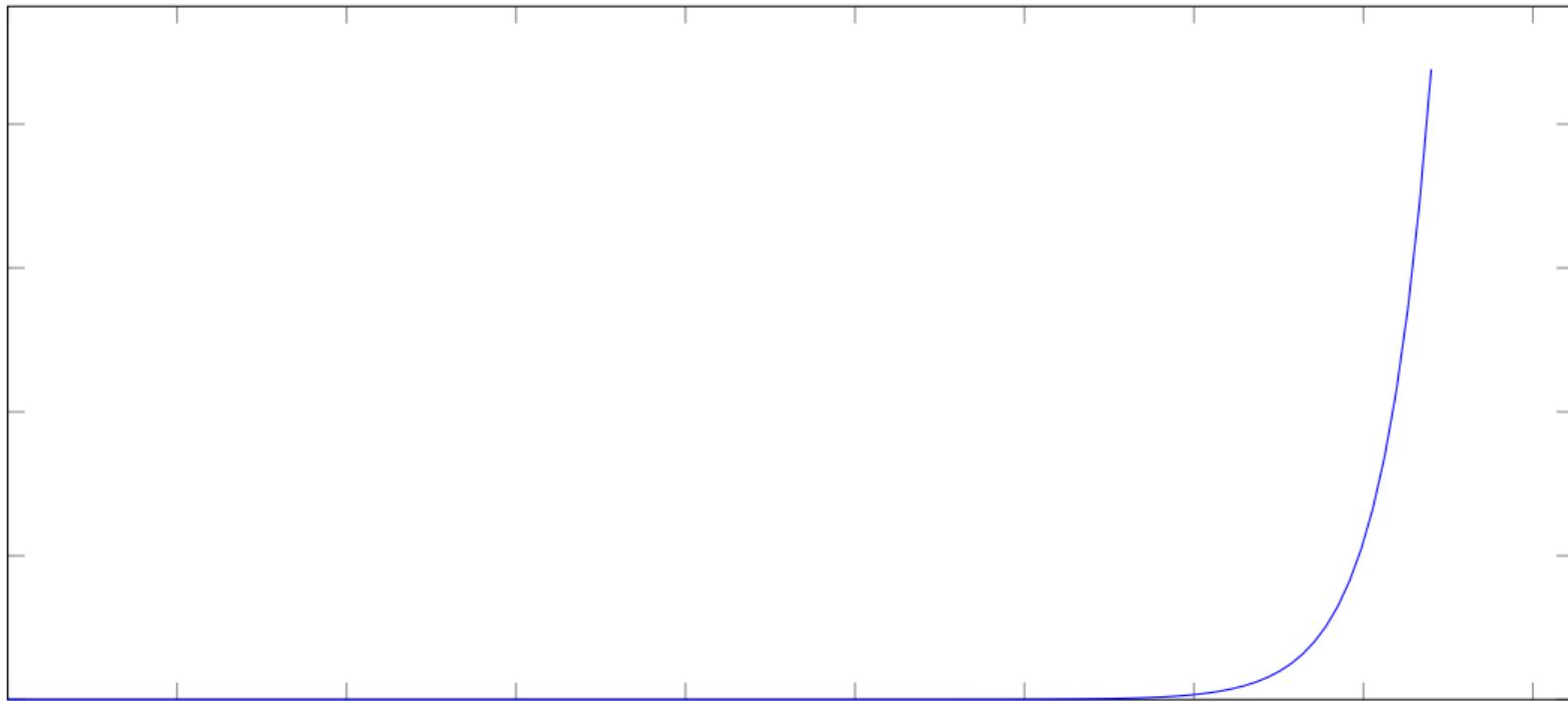
Reduction from SMT

$$b.\text{left} > a.\text{right} \parallel a.\text{bottom} > b.\text{top}$$

Combining in the LSC Semigroup

overlap + net connect + another constraint

Stay low



Maximize yield

- Minimize area of a chip → *silicon compiler*
- Minimize physical errors → **silicon process**

Features

- MOSFETs
- LDMOSFETs (High voltage)
- BJTs
- Zener polysilicon diodes
- SONOS flash cells
- Polysilicon resistors
- Metal caps

Process design considerations

- Should be portable
- Robust
- Low amount of layers
- KISS (Keep it simple and stupid)
- Avoid expensive machines (can be manufactured in a home lab)

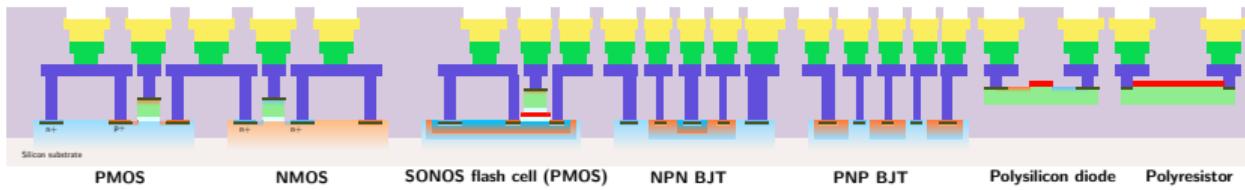
Process design considerations



Process design considerations



Cross section



PearlRiver (珠江芯片一号)

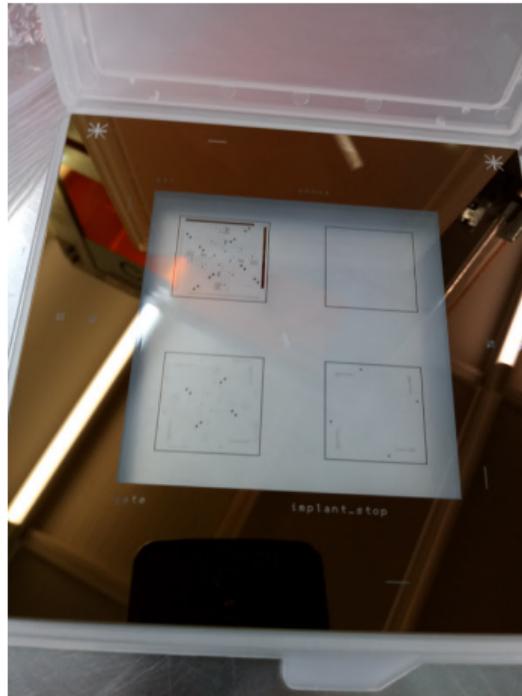


PearlRiver (珠江芯片一号)

Fulfills following functions:

- Debugging
- Calibration of new equipment to LibreSilicon
- Research of new features
- Syncing process features between fabs

Photomask



Photomask

- Is stepper/aligner brand specific
- ASML stepper masks contain 4 layers each
- The NFF stepper has a reduction value of 5:1
- A 5 micron gate on the mask is 1 micron on the wafer

Photo resist (HKUST)

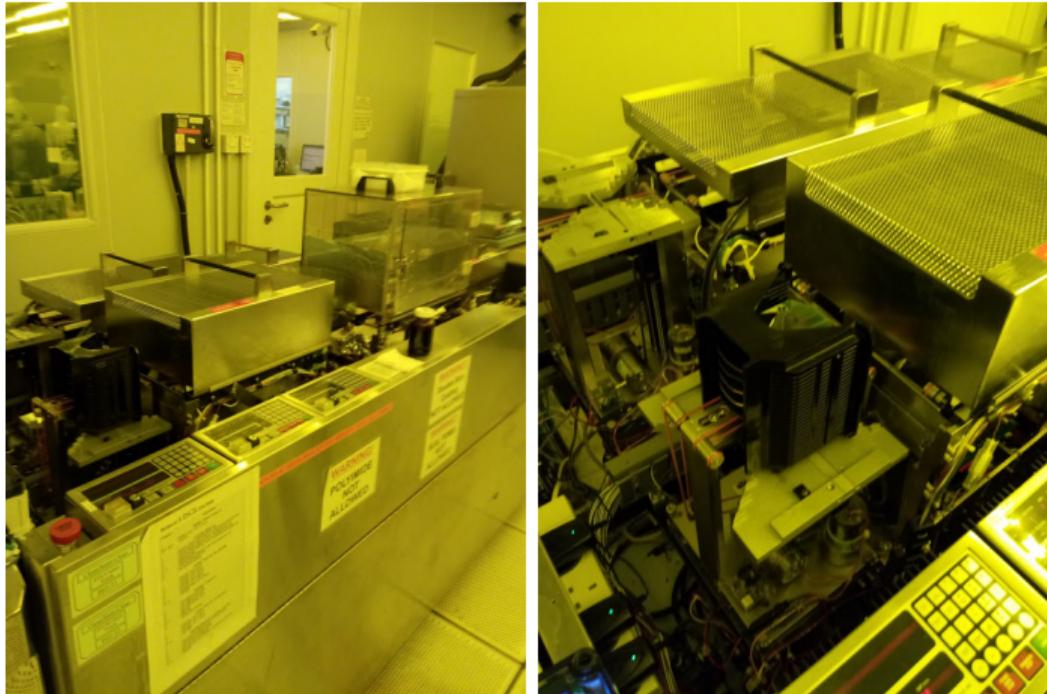


Photo resist (HKUST)

Two types of photo resist:

- FH 6400L (implantation)
- HPR 504 (normal etch)

Factors to consider:

- Thickness of FH 6400L and implantation energy are interlinked
- Thickness of HPR 504 and etching time are interlinked (selectivity)

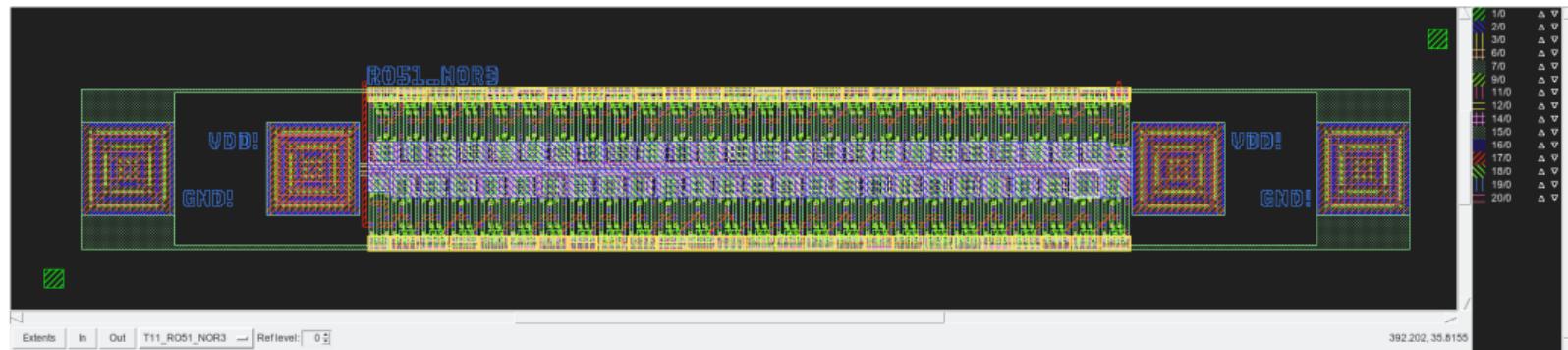
After exposure



Alignment

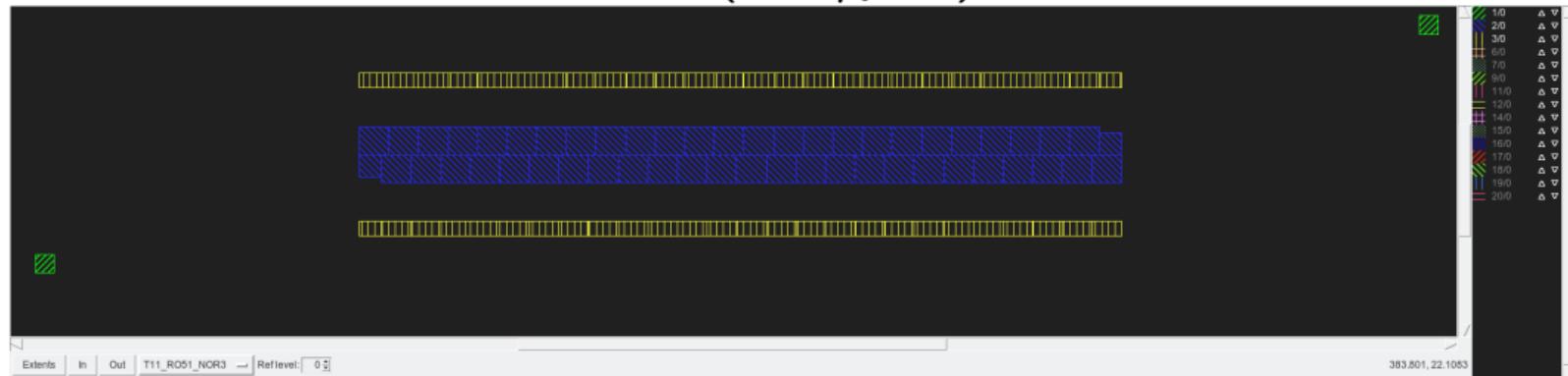


Example: NOR3 ring oscillator



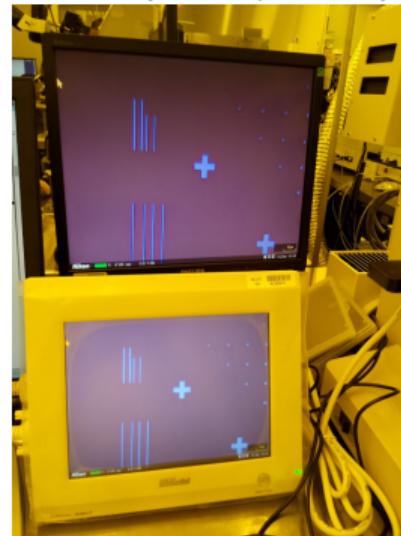
Example: NOR3 ring oscillator

Wells (nwell/pwell):



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Example: NOR3 ring oscillator

Recipe for nwell:

- Coat with implant resist (soft bake 60 seconds, 110°C)
- Expose nwell-mask
- Puddle develop 69 seconds and hard bake 60 seconds at 120°C
- Implant Phosphorus, $2.33 \times 10^{12} cm^{-2}$ @ 70keV
- Strip resist with plasma ash or 20 minutes in 120°C hot sulfuric acid

Note: Alternatively predisposition can be used

Example: NOR3 ring oscillator

Recipe for pwell:

- Coat with implant resist (soft bake 60 seconds, 110°C)
- Expose pwell-mask
- Puddle develop 69 seconds and hard bake 60 seconds at 120°C
- Implant Boron, $1.93 \times 10^{12} cm^{-2}$ @ 40keV
- Strip resist with plasma ash or 20 minutes in 120°C hot sulfuric acid
- Diffuse both wells together for 4 hours at 1050°C in inert atmosphere (N_2)

Note: Alternatively predisposition can be used

The Fick's equation

$$\frac{\partial N}{\partial t} = D \cdot \frac{\partial^2 N}{\partial x^2}$$

The Fick's equation

$$x_I(t) = 2 \cdot \sqrt{D_e \cdot t} = 2 \cdot \sqrt{D_0 \cdot \exp\left(-\frac{E_a}{k \cdot T}\right) \cdot t}$$

Element	D_0 $\frac{cm^2}{s}$	E_a [eV]
P	10.50	3.69
As	0.32	3.56
Sb	5.60	3.95
B	10.50	3.69
Al	8.00	3.47
Ga	3.60	3.51
Cu	0.0025	0.65

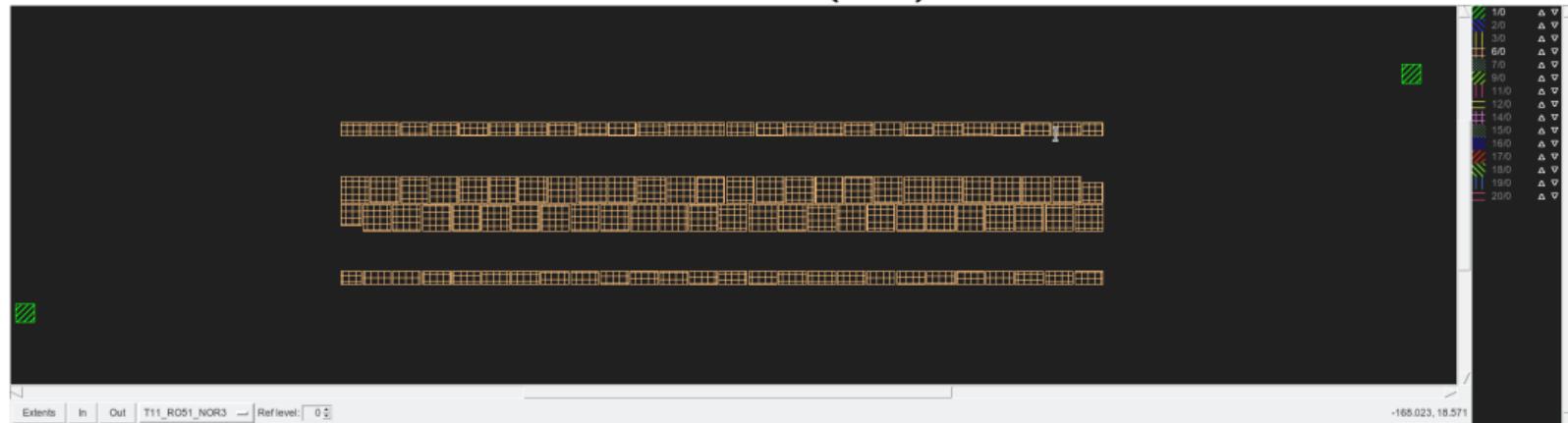
The Fick's equation

$$N(x, t) = \frac{Q}{\sqrt{\pi \cdot D_e \cdot t}} \cdot \exp \left(\frac{-x^2}{4 \cdot D_e \cdot t} \right)$$

The Fick's equation

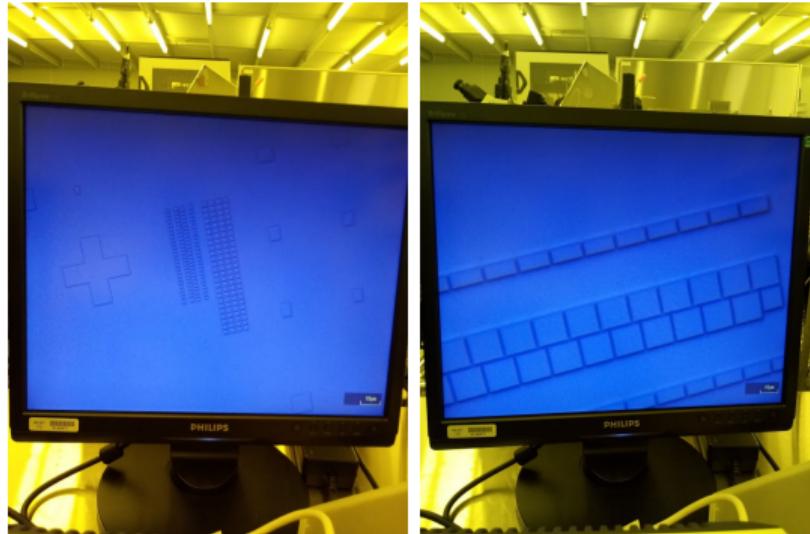
Example: NOR3 ring oscillator

Isolation (STI):



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Example: NOR3 ring oscillator

Recipe for STI:

- **Dry**

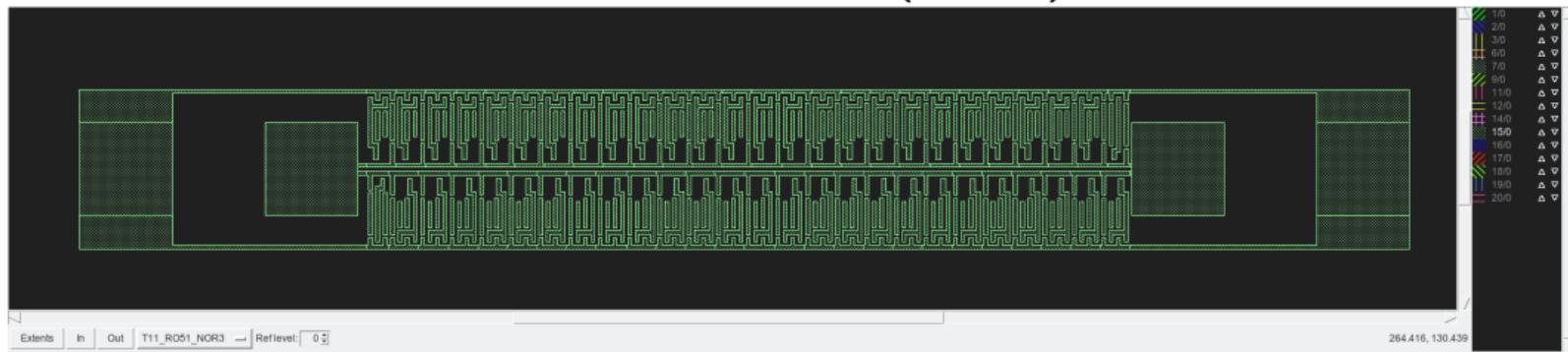
- Plasma etching recipes are machine specific
- Variate the cycles for your recipe to match 2 microns

- **Wet**

- Take TMAH: $N(CH_3)_4^+ OH^-$ (Tetramethylammonium hydroxide)
- Dilute with deionized water with DI:TMAH (3:1)
- Heat TMAH (25%) to 80°C
- Dip wafer into the solution for around 6 minutes and 15 seconds (320nm/min, 2 microns)

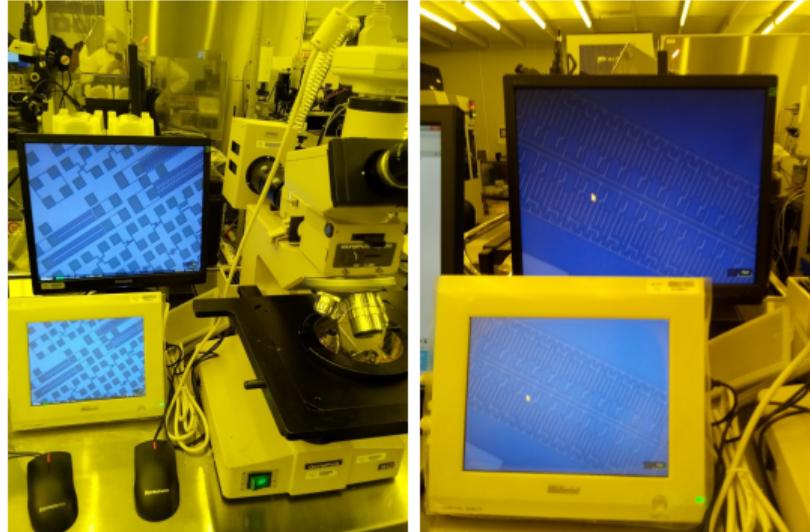
Example: NOR3 ring oscillator

Metal interconnect (metal1):



Example: NOR3 ring oscillator

Metal interconnect (metal1):



Example: NOR3 ring oscillator

Recipe for metal interconnects:

- Make a vacuum (low pressure)
- Deposit 100nm Aluminum
- Deposit 30nm Titanium over the Aluminum
- Take out of vacuum
- Dip into HF:DI (1:10) water solution for a few seconds until Titanium is gone
- Dip into FeCl₃ or other suitable Aluminum etchant for around 30 seconds until Aluminum is gone