Degate

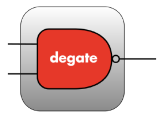
The stakes and challenges of silicon reverse engineering

https://www.degate.org

D. Bachelot[1]

[1]ESIEA
NEVERHACK

FSiC 2024,
June 20, 2024



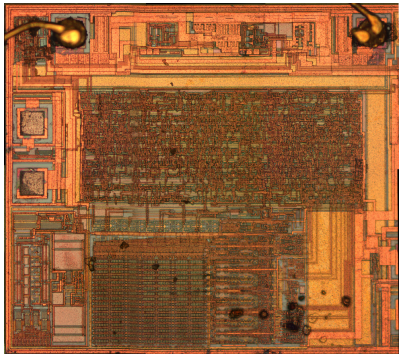
Who am I?

Dorian Bachelot[1]

- Currently a **Lead Product & Software Architect in Cybersecurity/AI** at NEVERHACK[2].
- Previously a master student doing **research on hardware reverse-engineering** at ESIEA[3]'s CNS laboratory.
- **Main maintainer** of **Degate** (since 2018).

[1] https://dorianb.net
[2] https://neverhack.com
[3] https://esiea.fr

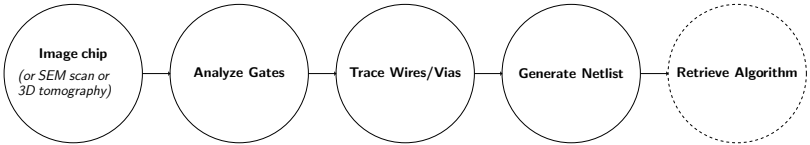
What is Silicon Chips RE?



Same idea than with software RE (from binary, to assembly and to code), chips RE go **from silicon**, **to images**, **to transistors**, **to gates**, **to netlist** and **to algorithm**.

With proper preparation and knowledge, we can go into silicon, **analyze transistors**, **retrieve gates/wires/vias** and **reconstruct implemented algorithms**. This can be used to **analyze old hardware**, build **software emulators**, search for **vulnerabilities** and **backdoors**, **break/test a protection**, **secret extraction** or **check intellectual property**.

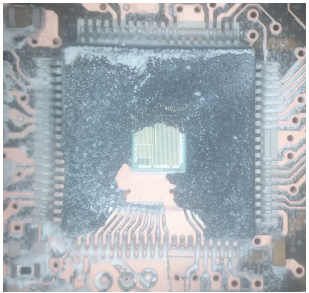
Used in IC industry for **fault/failure detection** & analysis, but **not at the same scale**.



How to Access Silicon?

Can be very costly (plasma & laser) and destructive... But also accessible with simpler methods (like chemical/mechanical). More on [4].

1. **Decapsulation** (heat, acid, mechanical, plasma, laser...)
2. **Delayering** (chemical, abrasive, laser, plasma...)
3. **Cleaning** (ultrasound, acid...)



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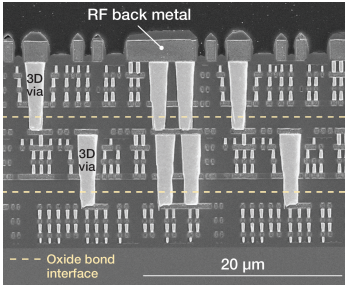
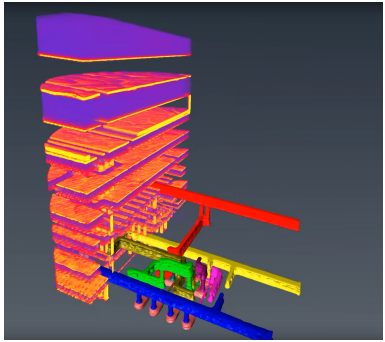


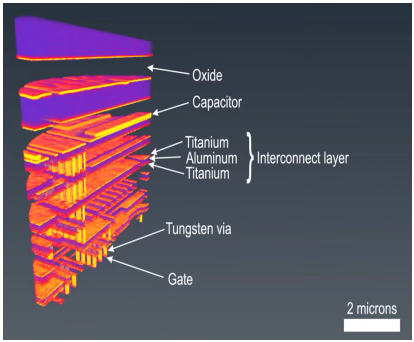
MIT

How to Retrieve Images?

Using each layer (invasive) or directly using the chip (non-invasive):

- Take very-high resolution images from **optical microscope** (basic, confocal) ;
- Scan from an **electron microscope** (SEM, TEM...) ;
- Generate a 3D model using **electron tomography** ;



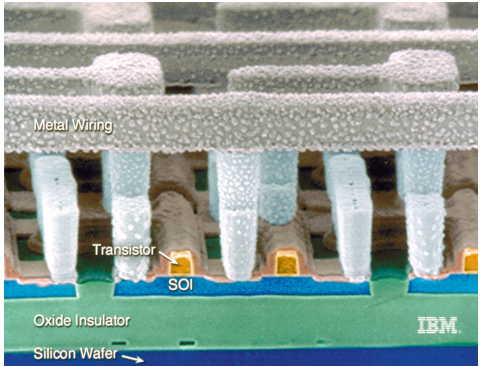


[1]

How to Perform the Analysis?

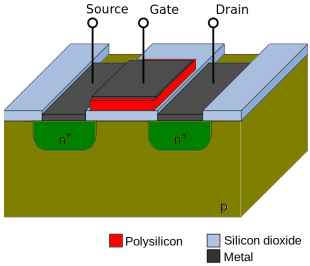
Overview:

1. Choose a **zone of interest**,
2. Identify each **gate type**, annotate, and place in a **"gate library"**,
3. Find other **gates instance** from gate library,
4. Link gates by tracing **wires and vias**,
5. Export to **netlist** (e.g. by translating each gate to VHDL/Verilog code).

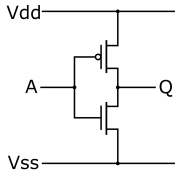


How to identify a transistor?

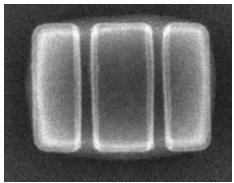
1. Search, at transistor layer, for **doped zones**.
2. Spot the **zebras**.
3. Use logic to identify the **type of each transistor** (e.g. PMOS are bigger to compensate with lower hole mobility).
4. Search for **wires** (to identify inputs and outputs).



(NMOS, *Wikipedia*)



(Inverter, *Wikipedia*)



(PMOS [10])

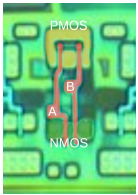
How to Identify a Gate?

Transistor layer

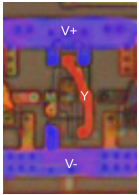
Logic layer

Metal layer

⇓

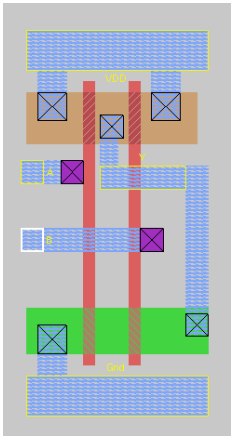


P & N zones and 2 inputs



V+ & V-, and output

⇒



[7] ⇒

NAND gate!

A	B	Y
0	0	1
1	0	1
0	1	1
1	1	0

How to Retrieve the Netlist from Analyzed Gates?

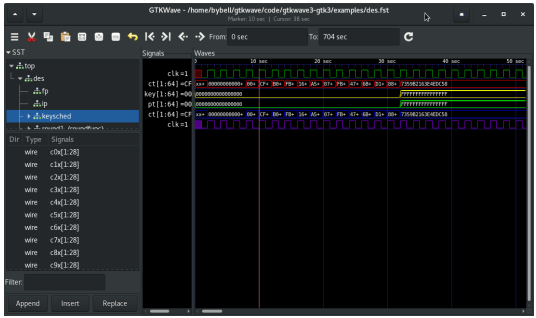
```
module jsrflipflop(q,qbar,clk,rst,sr);
    output reg q;
    output qbar;
    input clk, rst;
    input [1:0] sr;

    assign qbar = ~q;

    always @(posedge clk)
    begin
        if (rst)
            q <= 0;
        else
            case(sr)
                2'b00: q <= q;
                2'b01: q <= 0;
                2'b10: q <= 1;
                2'b11: q <= 1'bx;
            endcase
    end
endmodule
```

- Each gate can be described with **hardware description language (HDL)**, like **Verilog** or **VHDL**.
- **Wires & vias** can also be described.
- That's all we need to **obtain the netlist**!

We can, from HDL, **simulate the extracted netlist** and **find incoherence** (*example with gtkwave below*):



How to Get the Algorithm/Specification from Netlist? [3]

After retrieving the **netlist**, we are left with a **huge and "unorganized" number of gates**. The **specification discovery** phase aims to **retrieve IC's algorithm/functionality** from the extracted netlist.

Using specific algorithms you can **automate some phase**:

- **Partitioning** of the netlist (*to retrieve a semblance of "code" structure*).
- **Recovery** of the registers (*if applicable*).
- **Identification** of the extracted "groups" (*partitions*) of the netlist.
- **Construction** of a library of netlist components from the identified "groups".

These algorithms **need to allow some degrees of error** from the netlist extraction. This phase is ∼analogous with **duplicated, standard & library functions identification** for **software engineering**. A nice open source tool for this is **HAL**[4] (compatible with Degate's outputs!).

[4] https://github.com/emsec/hal

To Summarize

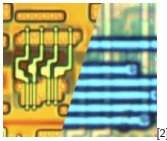
Image chip
(or SEM or 3D tomography)

- **Decapsulate**,
- Select **area of interest**,
- **Delayer**,
- Clean,
- Stitch.


[2]

Analyze Gates

- Analyze transistors,
- **Identify each type of gates**,
- Retrieve all instances of each gate (**pattern matching**).


[2]

Trace Wires/Vias

- Identify **wires**,
- Identify **vias**,
- **Connect gates**.


[2]

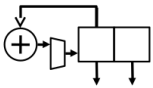
Generate Netlist

- **Export netlist**,
- Gate simulation,
- Try to identify errors.

```
<?xml version="1.0"
<gate-library>
 <gate description=
  <ports>
   <port id="0" nam
   <port id="1" nam
```
[2]

Retrieve Algorithm

- Extract algorithm,
- **Discover specification**,
- Perform functional analysis[3],
- Build a **software emulator**,
- Try to **identify errors**.


[2]

Importance for Cybersecurity

How can we **trust software** if we **can't trust hardware** (e.g. "specialized" ASIC)?

- Is there any **vulnerability in the hardware implementation** of an algorithm (e.g. crypto standard with predictable initialization, bad randomness...)?
- Is there any **hardware Trojan** (e.g. placed by the foundry)?
- If there is a vulnerability/backdoor, **patching is impossible**, far **more impactful** than software vulnerabilities.

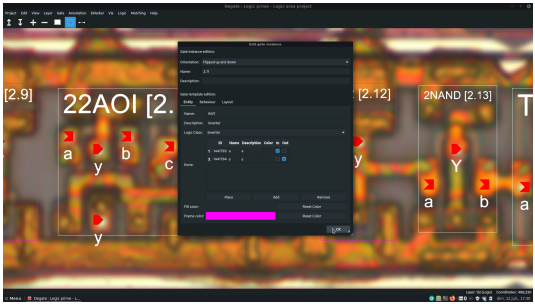
Some examples of vulnerabilities found thanks to silicon RE:

- *Legic Prime*, *NXP Hitag2*, *DECT DSC*, *CryptoRF*, *Atmel CryptoMemory* & *NXP Mifare Crypto-1* (∼2008, Nohl et al): **weak (or potentially weak) cryptographic ciphers**.
- Undisclosed ones?

Introduction

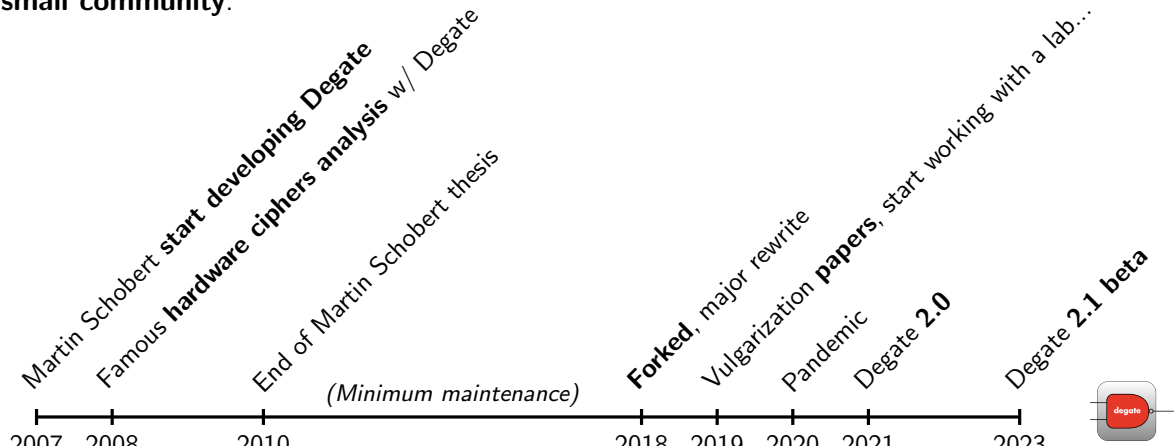
Degate is a multi-platform software for semi-automatic **Very-Large-Scale Integration (VLSI) chips reverse engineering** of digital logic in chips.

- ~70k LoC
- Supports Mac, Linux & Windows,
- Qt based,
- Multi-language support,
- Gate definition,
- Gate template, via & wire matching,
- Rule checks,
- ...



History

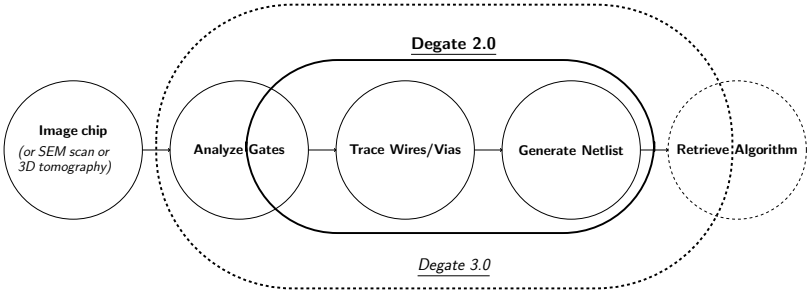
A long story, with **technical debt** and **major IC evolution** (in transistor count), along with a **small community**.



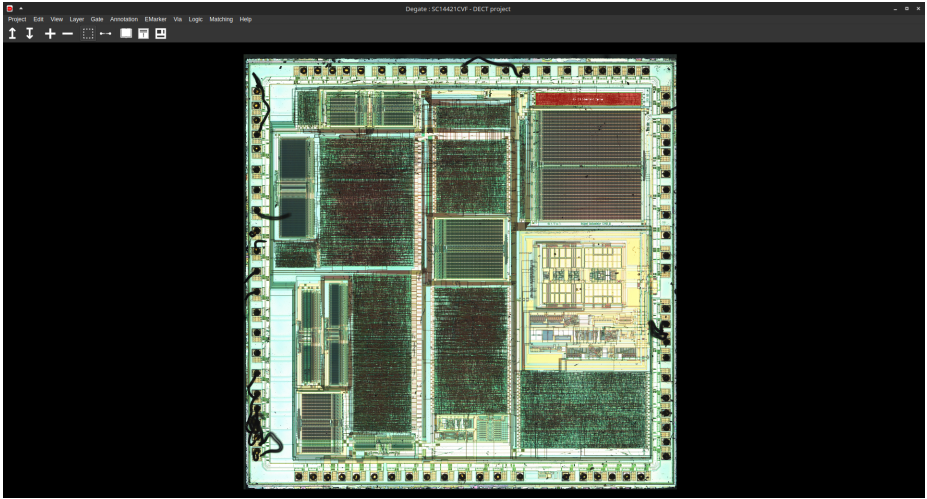
Usage

Degate help to reverse **VLSI chips** by creating an analyzed **gate library**, doing **template matching** to find gates instances from this library, **matching wires & vias**, **exporting netlist** and **navigating really huge images**.

Focus on **modern ICs** with **standard cells**, and supports **any 2D capture/imaging method** (SEM, optical...).



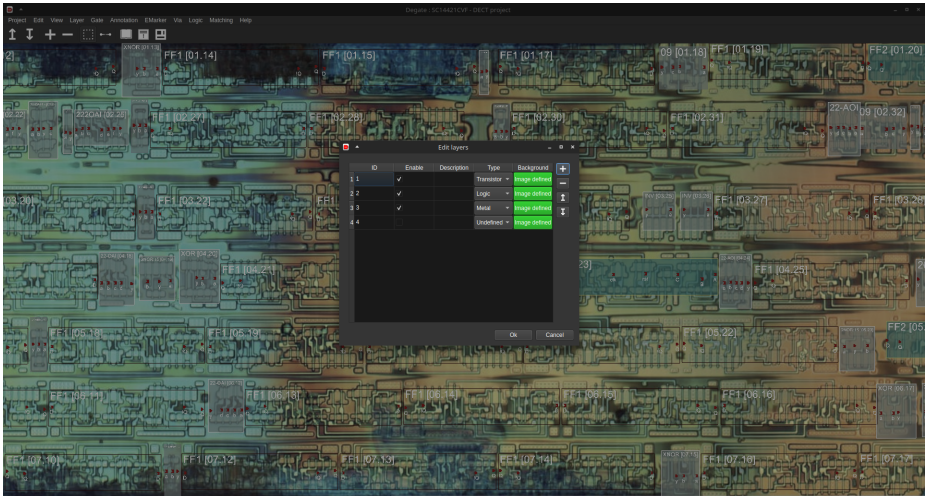
Small Demonstration



Overview of the chip, for zone of interest selection.

A sub-project can then be created on the zone of interest, and specific layers can be added (independent from the rest).

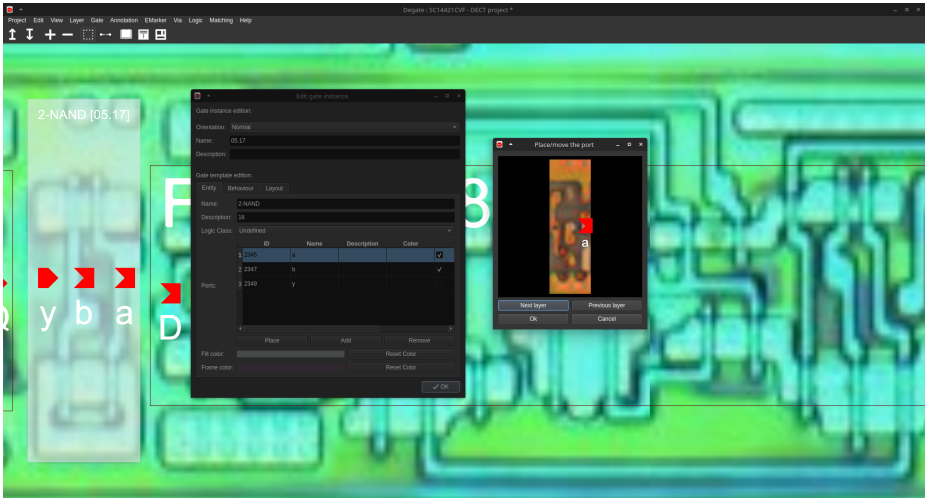
Small Demonstration



Each sub-project can contains multiple layers (pre-aligned images).

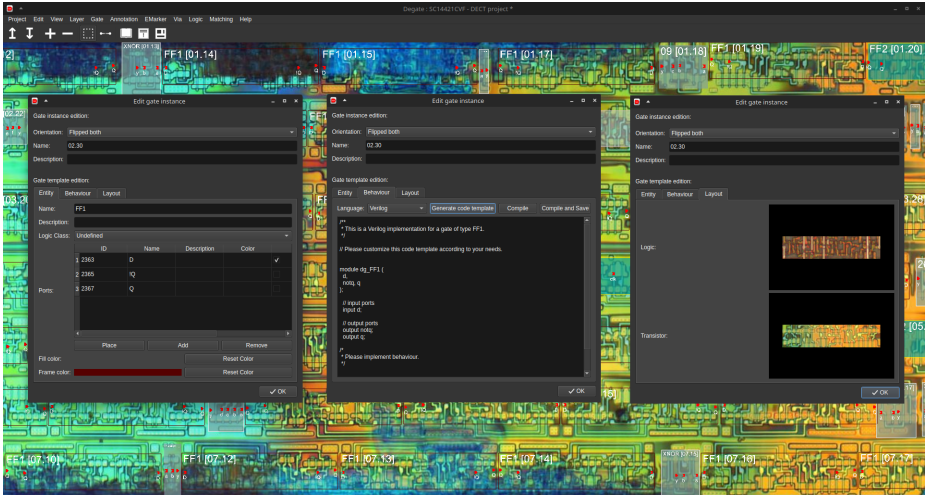
Two project mode: 1. For smaller images, will convert each images in Degate's format (for fast access) and 2. New (WIP, beta) mode for huge images (load only partial tiles in RAM, and doesn't change/import initial file).

Small Demonstration



Each gate can be described with VHDL/Verilog, have a list of port (placed on image), a type associated etc.

Small Demonstration



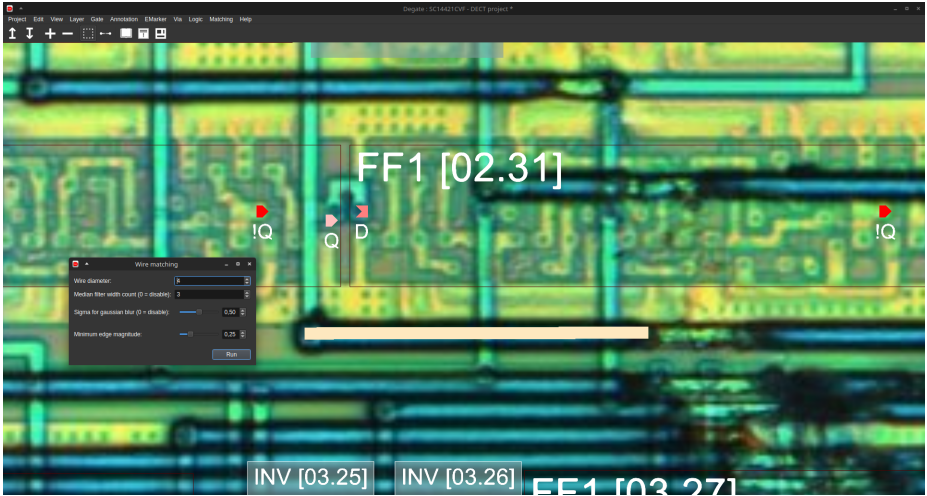
Each identified gate (from the gate library) can be matched manually or using template matching algorithms.

Small Demonstration

Template matching (will soon be ported to OpenCV) will use gate library to automate gate identification.

Currently it uses normalized cross-correlation (with some more steps).

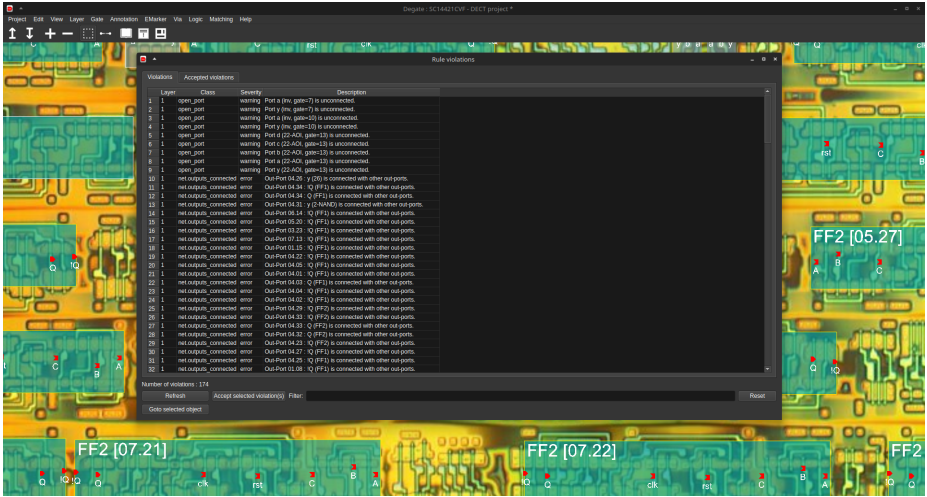
Small Demonstration



Wire matching, and specifically port interconnection, is the real challenge (and very error prone).

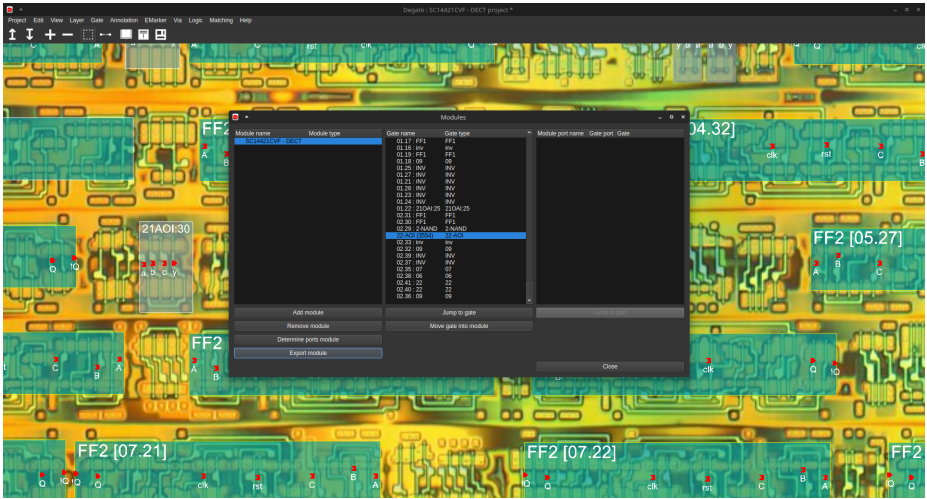
Currently it uses zero crossing edge detection.

Small Demonstration



Helpers are available, like rudimentary (but to be improved) rule checking (e.g. for coherency).

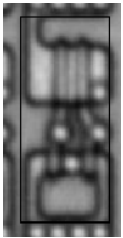
Small Demonstration

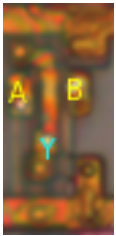


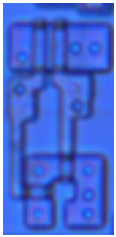
Everything can be organized in "module", exported individually (in Verilog/VHDL), etc... "Divide et impera".

Engineering Challenges

- Gate template, wires & vias **matching**.
- Very **huge images** handling.
- **Error** recovery/acceptance/identification.
- Multiple possible **image format** (e.g. .tiff, .png...) & **image source** (e.g. SEM, confocal...).
- 10+ years **old software** (mix of old & new C++).
- **Collaborative** analysis.
- Integrated **gate analyzer**.
- Explicit full **netlist exporter**.







MIFARE NAND[2] LEGIC NAND[2]

Research Challenges

- **3D capture**, imply rethinking Degate (New 3D mode? New software? Really accessible?), and **new algorithms** (e.g. for matching, tracing and gate identification).
- **Machine learning**/better algorithms for:
  - Auto-**vectorization** ;
  - Gate auto **identification** (from vectorized analysis) ;
  - Gate auto **wiring** ;
  - Auto vias & wires **identification**.
- Take advantage of certain capture methods such as **SEM** which makes **automation easier**.
- Making the **field more accessible** (more automation, new abstractions for analysis, communication...).
- Use Degate for **advanced analysis** and **published results**.

References I

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