Enhancing IC Reverse Engineering through Inter-layer Connectivity-Aware Image Inpainting

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CNM
Centro Nacional de Microelectrónica
IMB

CSIC
Consejo Superior de Investigaciones Científicas

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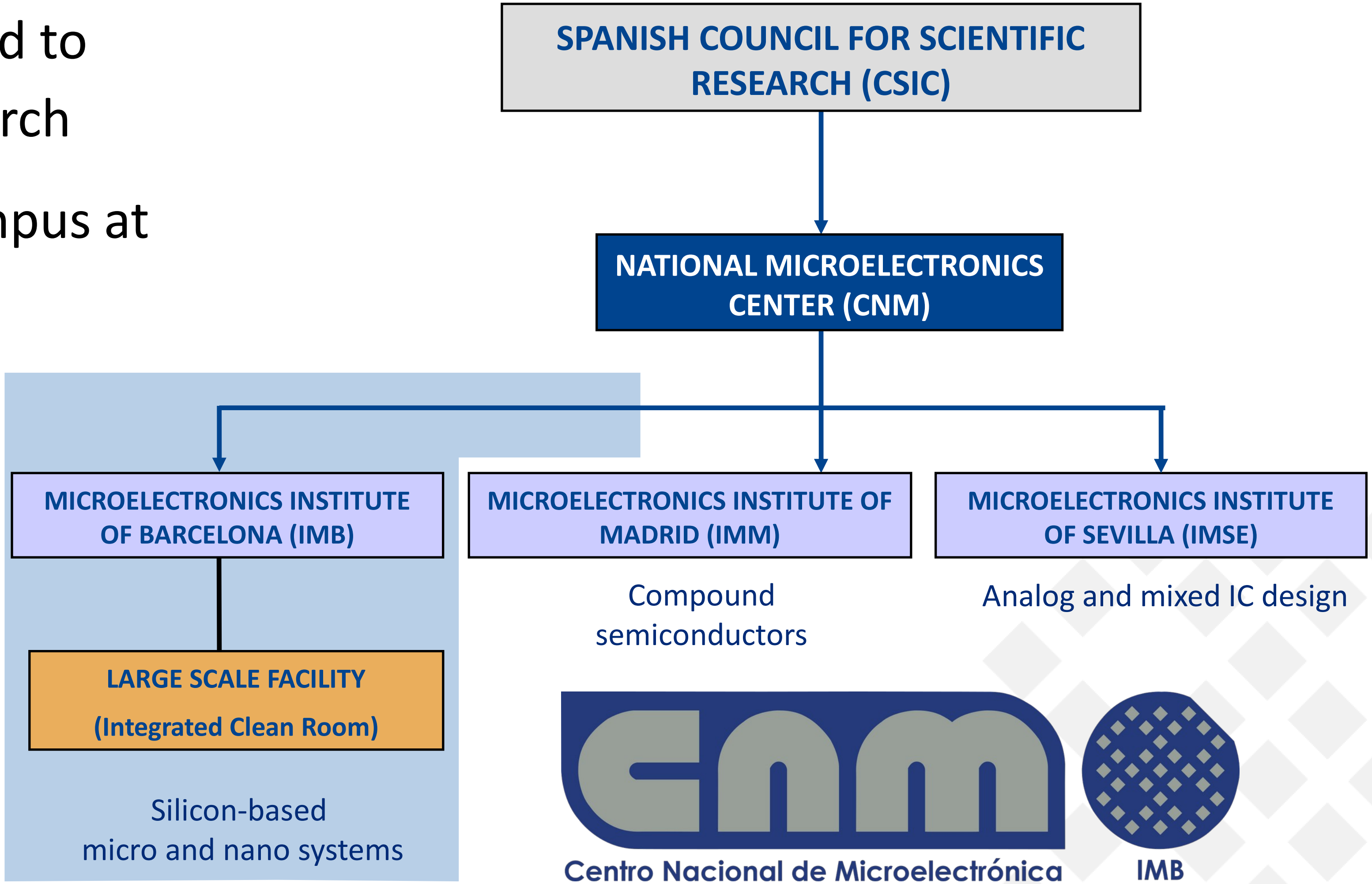
Contents

The IMB-CNM

Our institute

- The **IMB-CNM** belongs to **CSIC**, the main public research agency in Spain
- Largest institute in Spain dedicated to Micro and Nano technology research
- Located inside UAB university campus at Bellaterra, close to Barcelona
- Founded in 1985
- ~ 200 staff

Consejo Superior de Investigaciones Científicas



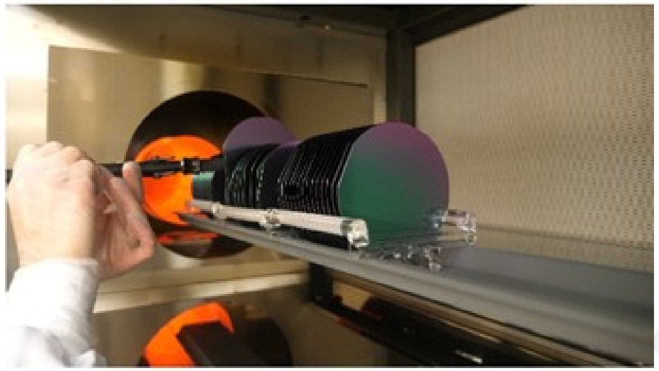
Centro Nacional de Microelectrónica IMB

IMB-CNM Clean Room

Centre Nacional de Microelectrònica IMB

CSIC Consejo Superior de Investigaciones Científicas

- 1.500 m^2
- class 100-10.000 (ISO 5-7)
- 6-inch wafer process
- >150 process tools
- CMOS and ‘free’ lines
- Staff :~40



Reverse Engineering at the IMB-CNM

Reverse Engineering Service - History

Centre Nacional de Microelectrònica IMB
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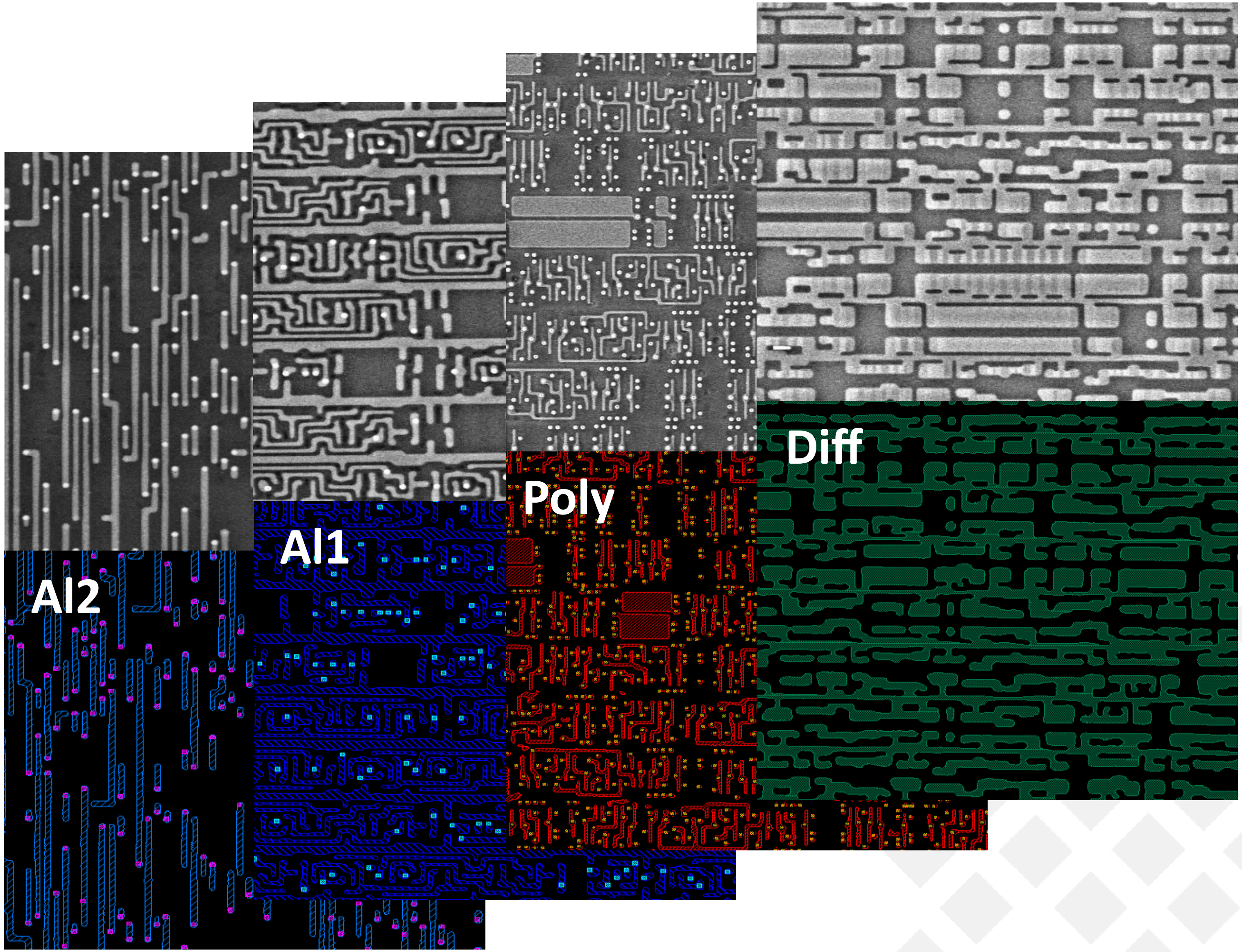
- **Late 80s**: Service starts doing physical characterization of CNM's Cleanroom process
- **~1995**: Merging with CAD services, it starts reversing other technologies, first for acquiring know-how, later as an external service
- **2003**: Starting reverse engineering of ICs (analog & digital)
  - most engineers come from design
- **2010**: Starting software automation for complex digital IC reversing process
- **2020**: First participation in a European project on security
- Current offer of external services:
  - Sample preparation for visual inspection
  - Failure Analysis
  - Patent Protection
  - Security Audits

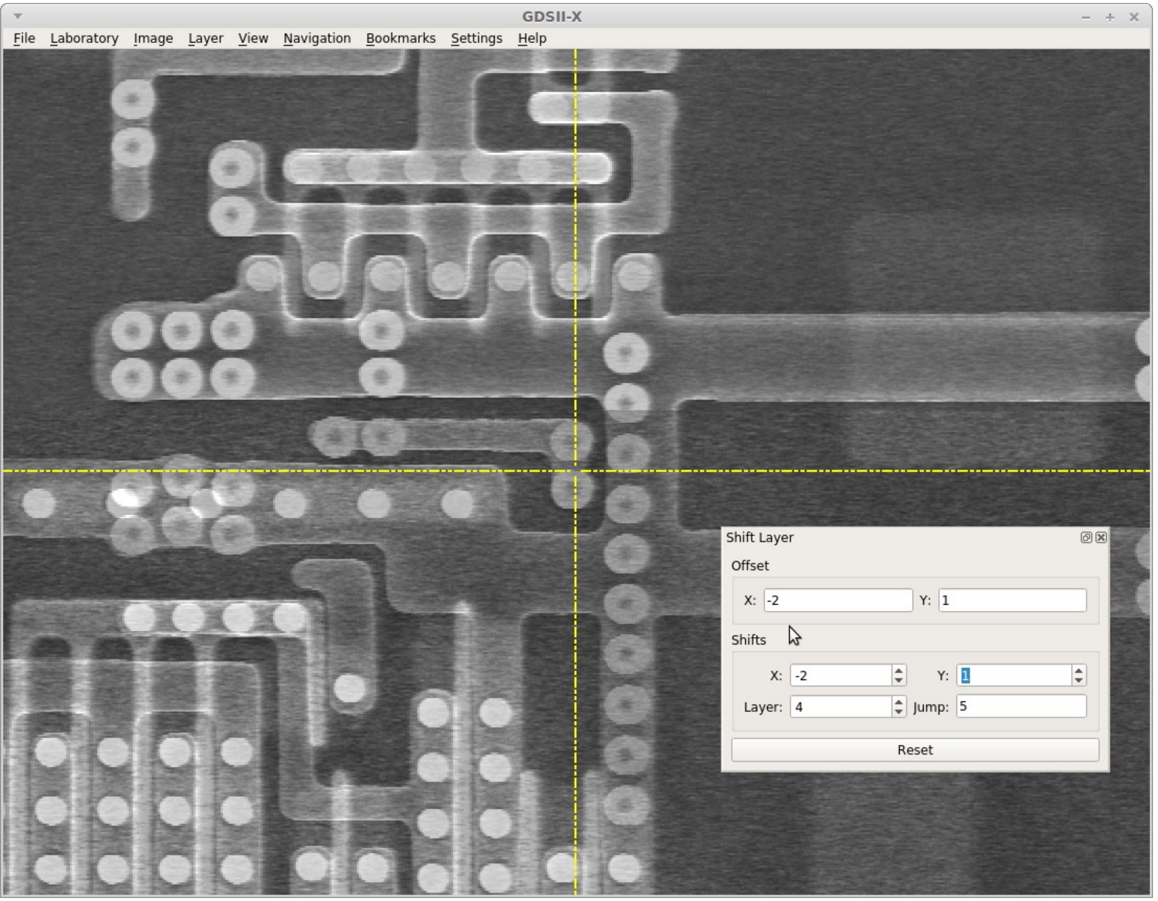
Digital IC reverse engineering

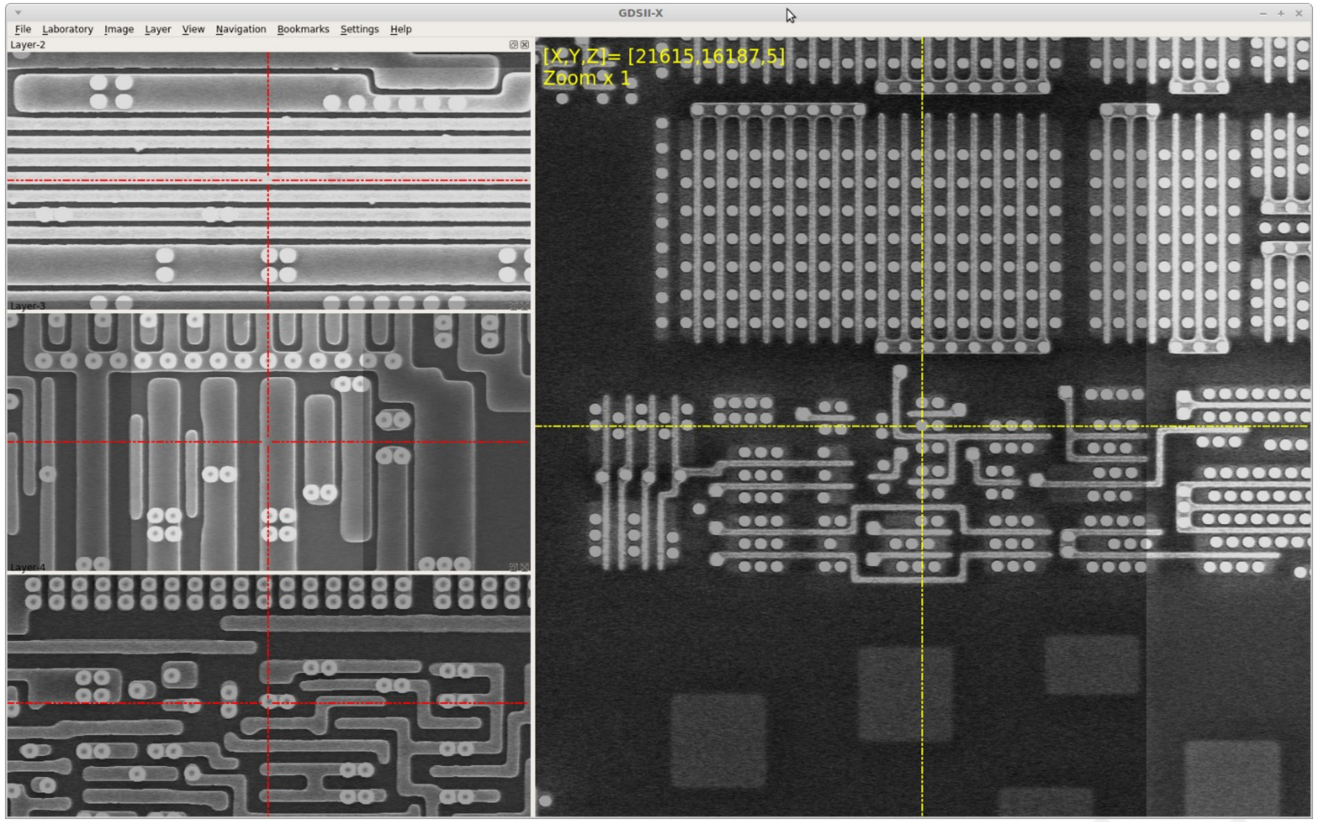
- +20 years experience in digital IC reversing
- All process steps performed at IMB-CNM
- Many steps have a high degree of automation:
  - Image acquisition
  - Image stitching
  - Layer-to-layer alignment and distortion correction
  - Image segmentation
  - Device recognition
  - Std. cell identification



GDSII-X: Our software tool

- +10 years of development but in constant evolution

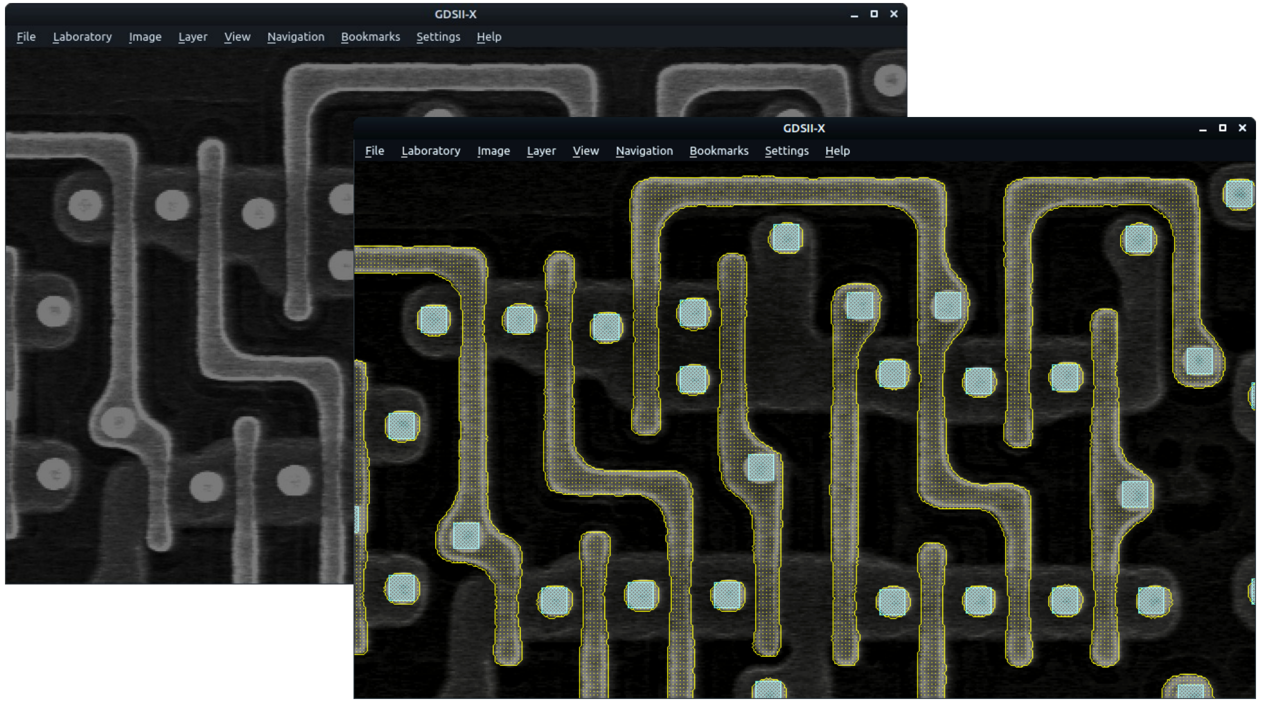


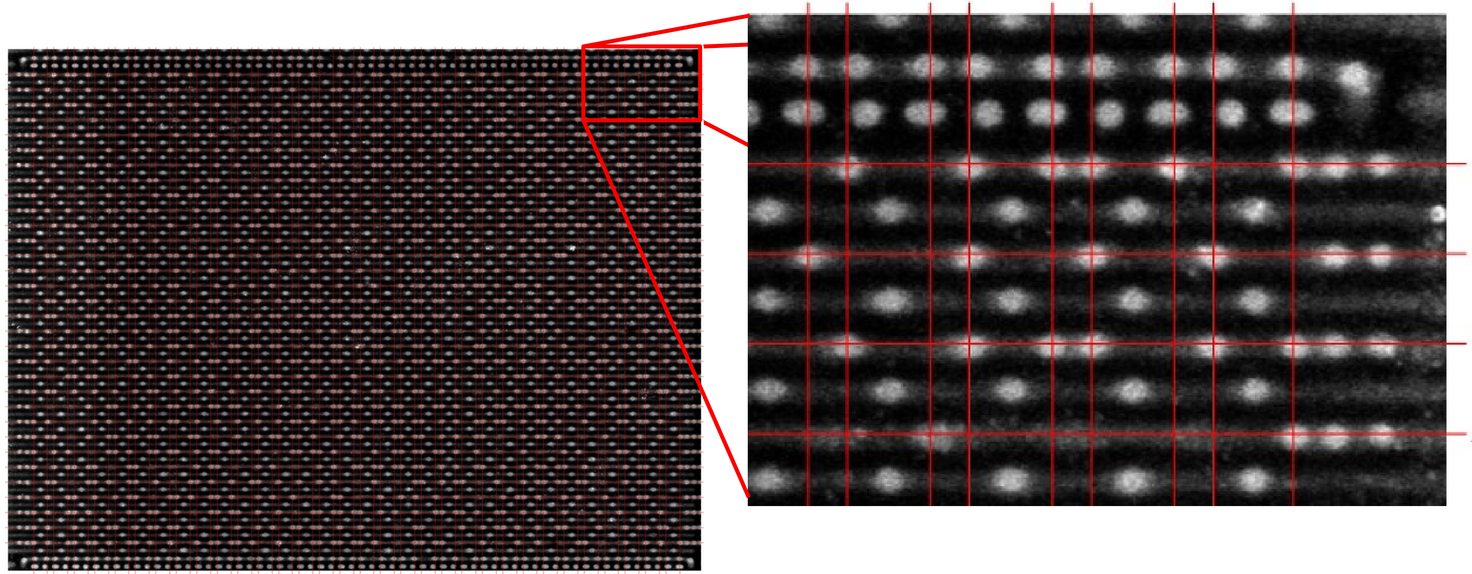


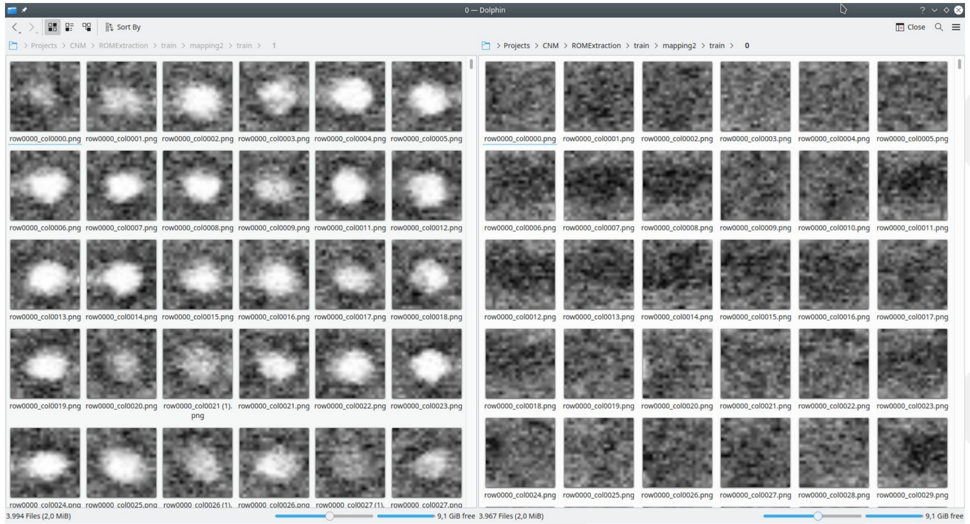
- Versatile tool
  - Image stitching
  - Layer-to-layer alignment
  - Distortion correction

GDSII-X: Our software tool

- AI-based segmentation
- Design layout segmentation
  - U-Net based
  - polygon simplification
- Memory extraction
  - fuse & ROM
  - grid distortion compensation







Gate extraction

- Gate identification procedure:
    1. Transistor identification using GDS data and standard EDA tools
    2. Computation of a custom topological descriptor
        - Each gate topology has its unique descriptor!
    3. Fast comparison to an extensive gate topology descriptor database
- Insensitive to technology scaling or device sizing and multiplicity
- Only have to deal with new unknown topologies
    - New topologies found decrease, while database increases

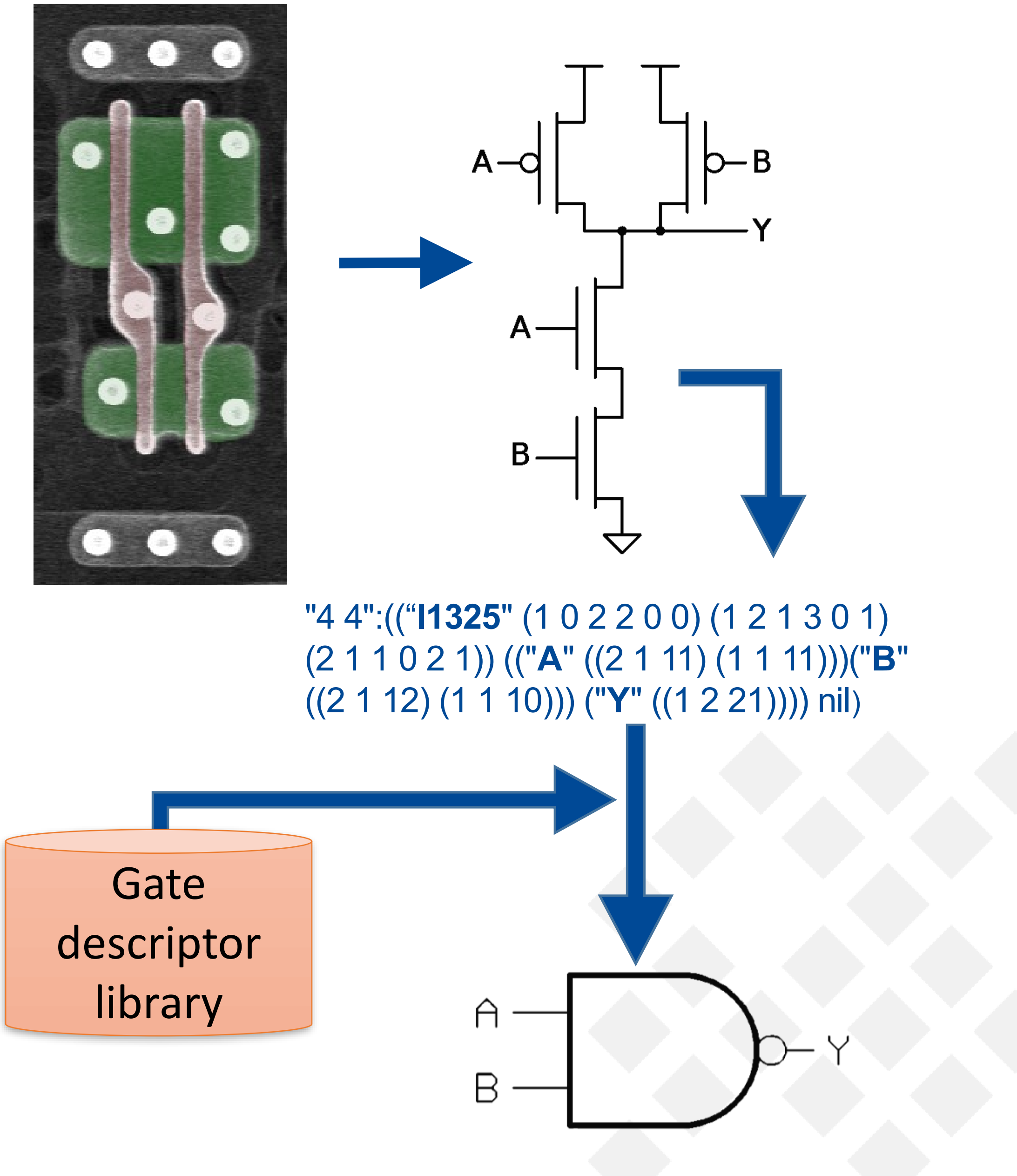
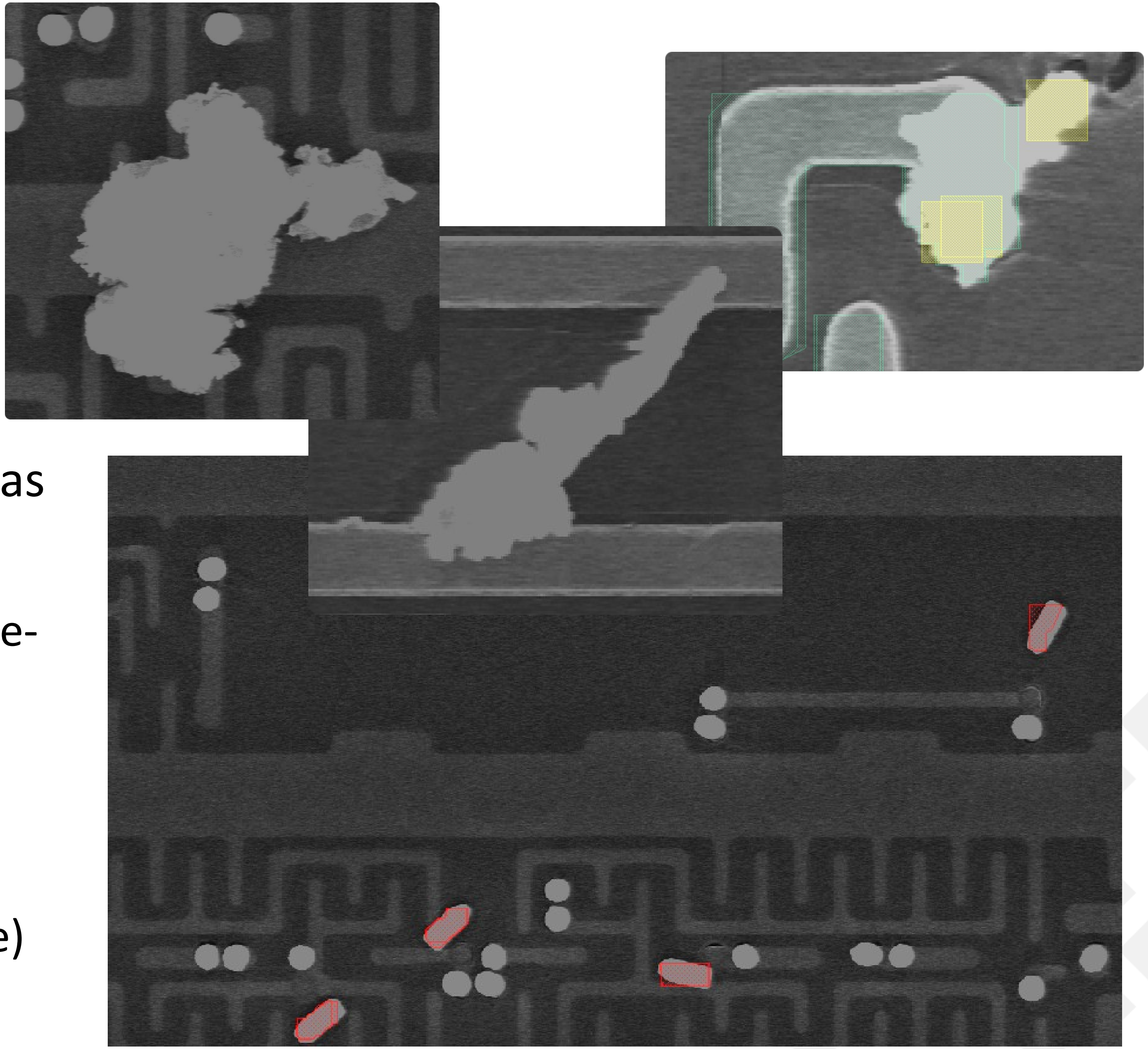


Image Inpainting in RE

Design Reconstruction Errors

- Multiple sources of errors:
  - sample preparation
  - SEM artifacts
  - stitching errors
  - dust
- Design extraction errors should be fixed as soon as possible
  - error correction is one of the most time-consuming tasks in IC RE
- **Dust** errors are very difficult to detect
  - ERC and DRC-like checks
  - IA models (dataset difficult to generate)



Nice solution from last HARRIS edition!

- HARRIS 2023: Very Interesting presentation (Kudos to **Cheng Deruo** et al.)

JOINT ANOMALY DETECTION AND INPAINTING FOR MICROSCOPY IMAGES VIA DEEP SELF-SUPERVISED LEARNING

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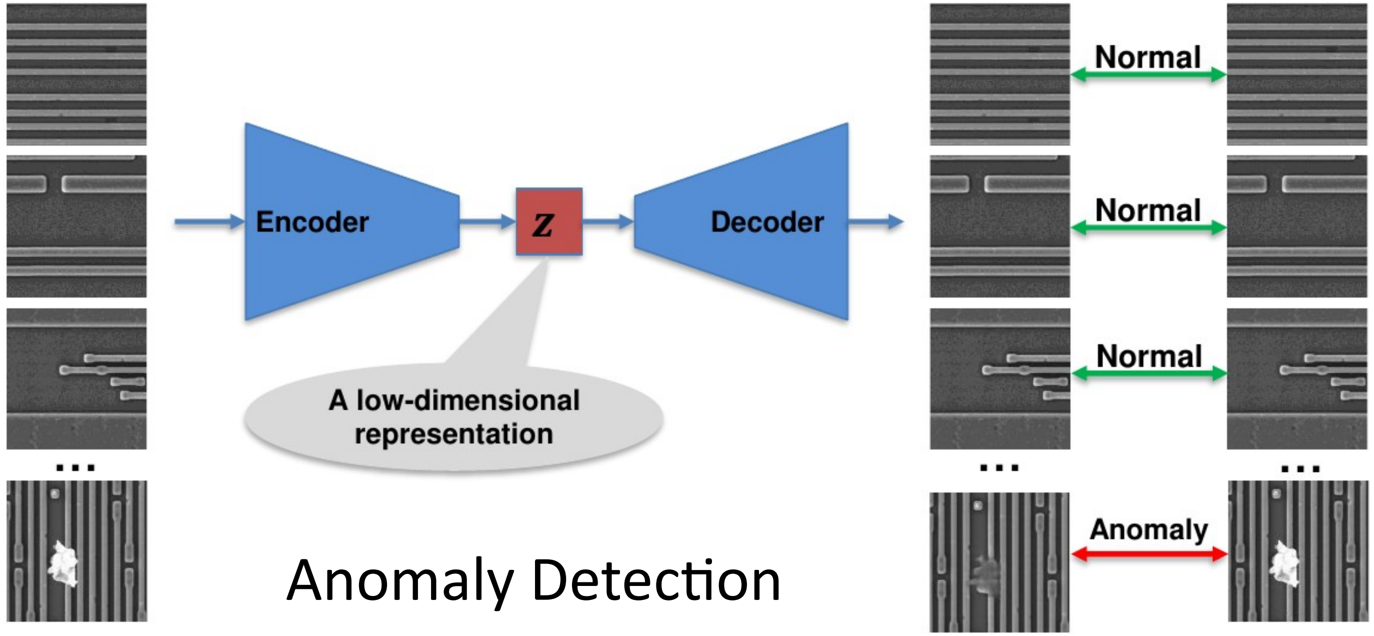
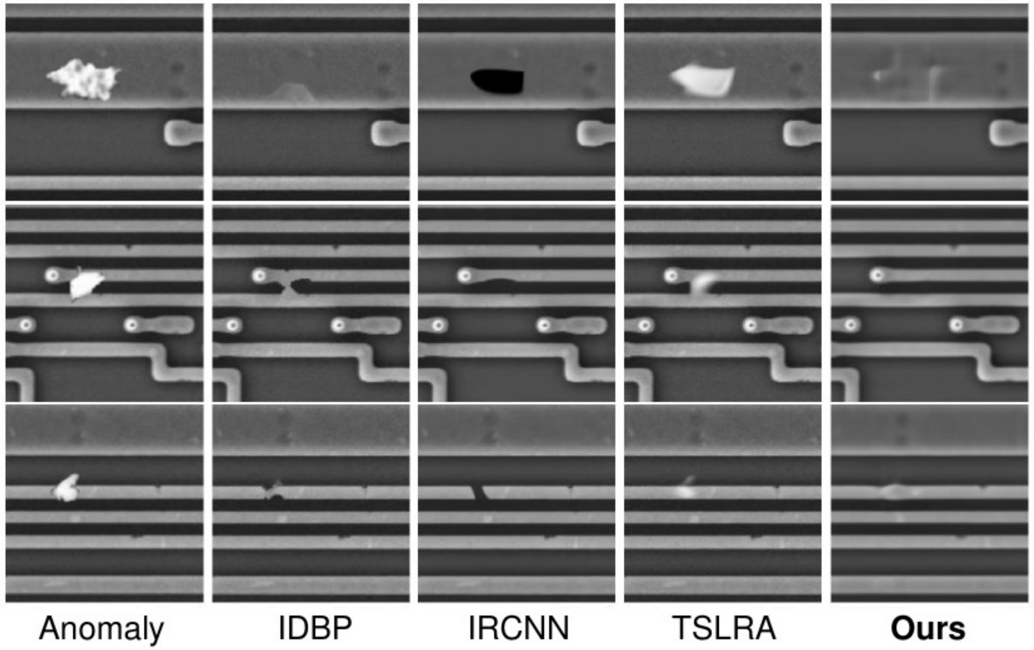


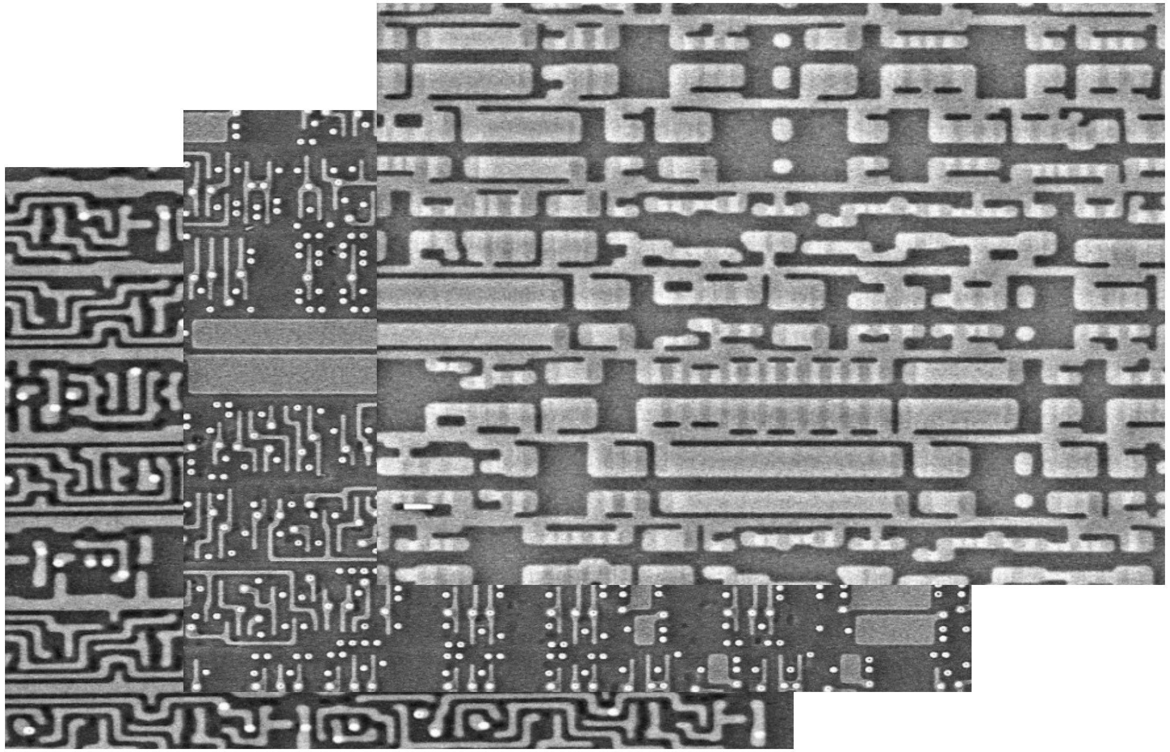
Image inpainting

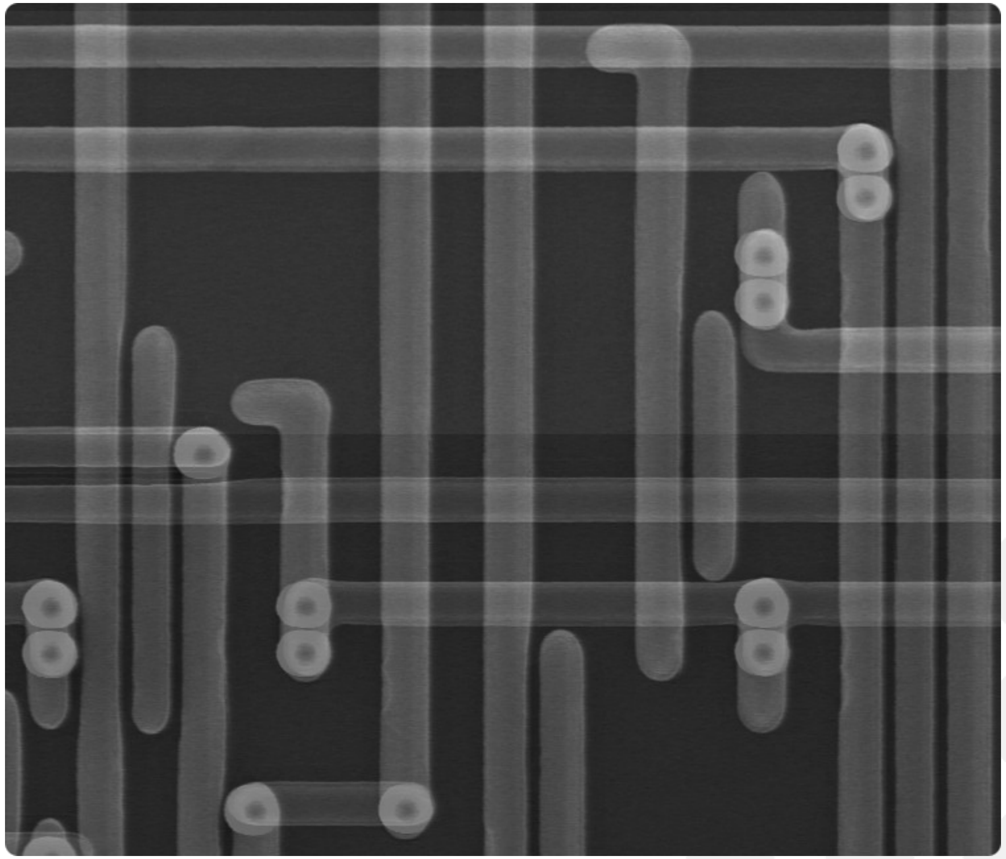


Inter-layer Connectivity-Aware Image Inpainting

Inter-layer Connectivity-Aware Image Inpainting

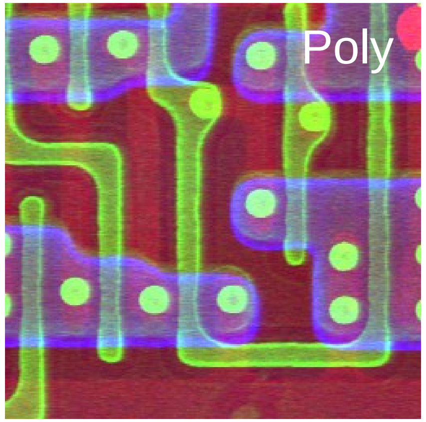
- IDEA: Use inter-layer information to perform the inpainting!
  - **Information recovery** through node-vias inter-connections
- **Triplet Images** for dataset generation
  - Upper-Mid-Lower Layers

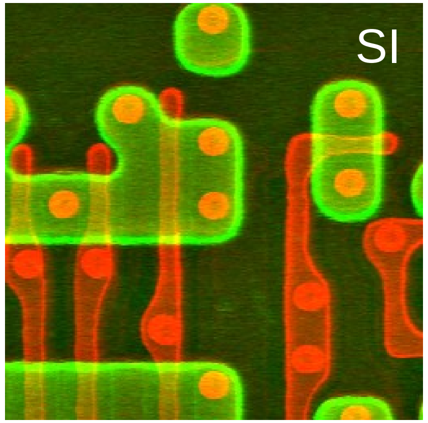


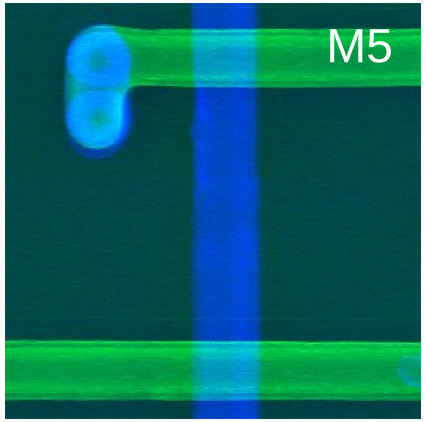


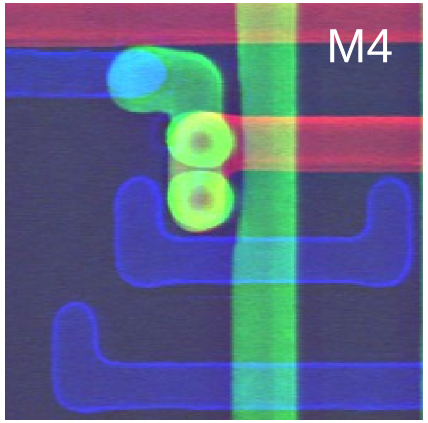
Dataset Generation

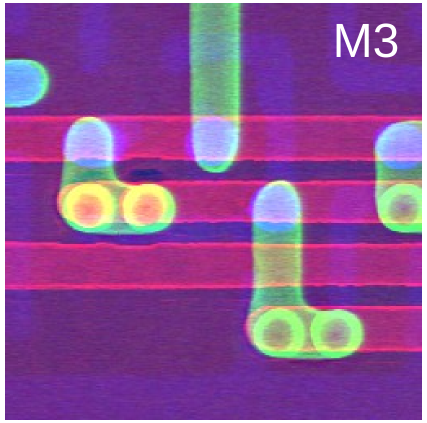
- Triplet Images
  - IDEA: SWAP RGB Images channels gray-scale images from different layer levels.
    - For instance:
      - Si-Poly-M1, M2-M3-M4, Empty-Si-M1
      - Empty → Black Images
  - It is required a precise inter-layer alignment
    - Layer Stitching & Distortion Correction
    - Inter-layer alignment → Mosaic Warping
  - Path Image Size → **256 x 256 pixels** (Architecture Input)

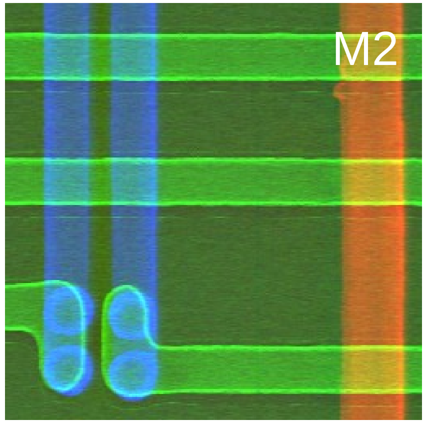


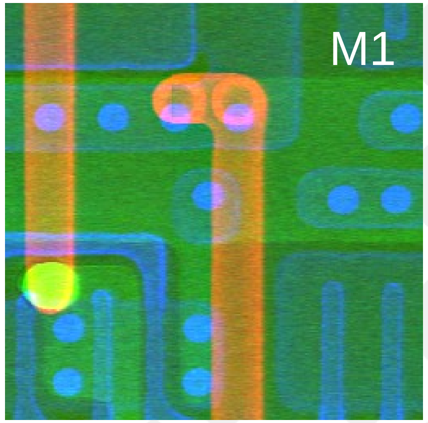






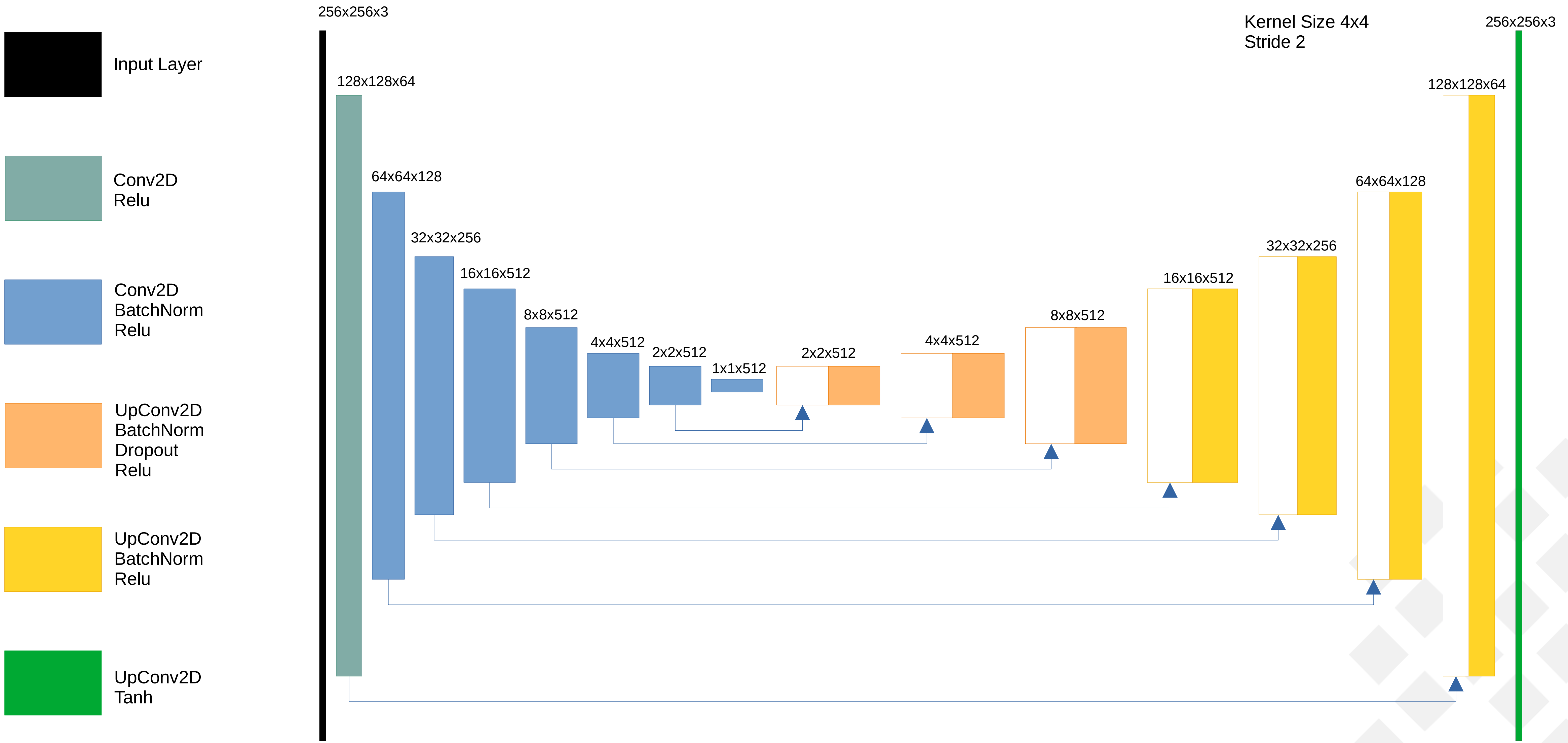






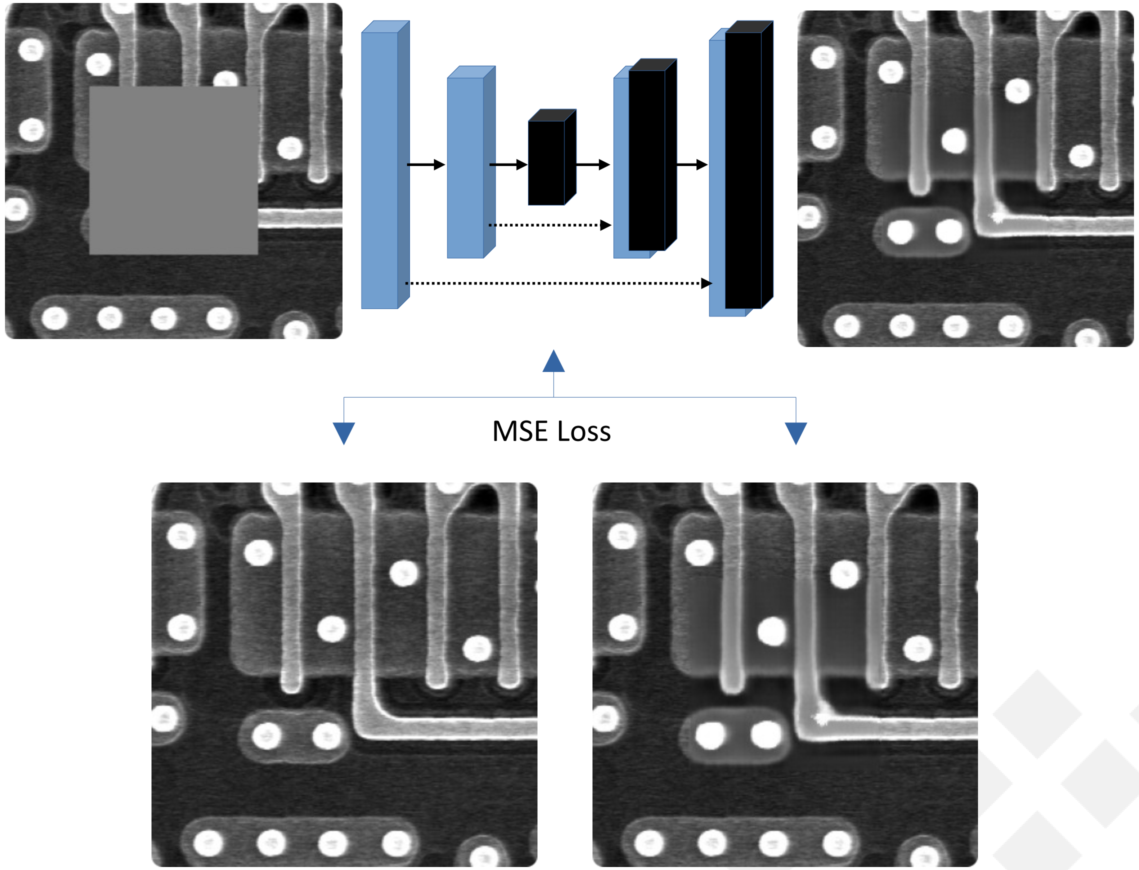
Deep Learning Architecture

- Based on Pix2Pix Generator → Baseline U-Net (Encoder-Decoder with skip connections)



Training Procedure

- Self-Supervised Learning Task
  - Given an image, mask a region
    - 128x128px mask
  - Network must reconstruct it
    - It uses current layer spatial information
    - Inter-layer information
  - Evaluate the reconstruction
    - Use the original image (without masking)
    - Compute Mean Square Error Loss
    - Update network’s weights
  - Continue with the next iteration

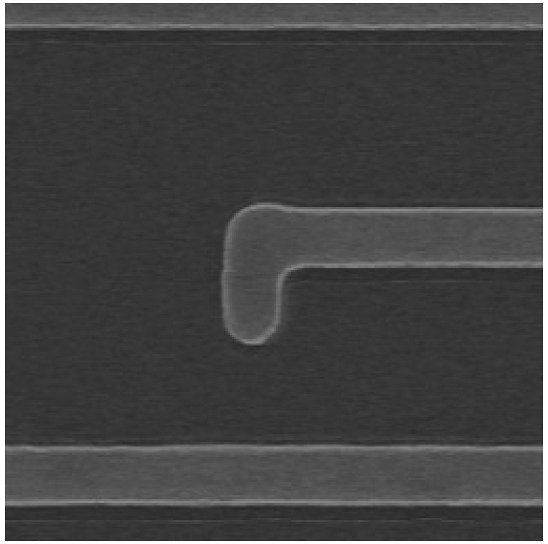


Training Details

- Dataset distribution:
  - Training 90% - Validation 5% - Test 5%
  - M3 Layer: 5688, 315 and 315 patch images (from only 90 original 4Mpx SEM images)
- Computational cost:
  - NVIDIA GeForce RTX 4060Ti
  - 12 hours approx.
  - 60 epochs approx.
- Architecture summary:
  - Total params: 54,425,859
  - Trainable params: 54,414,979
  - Non-trainable params: 10,880

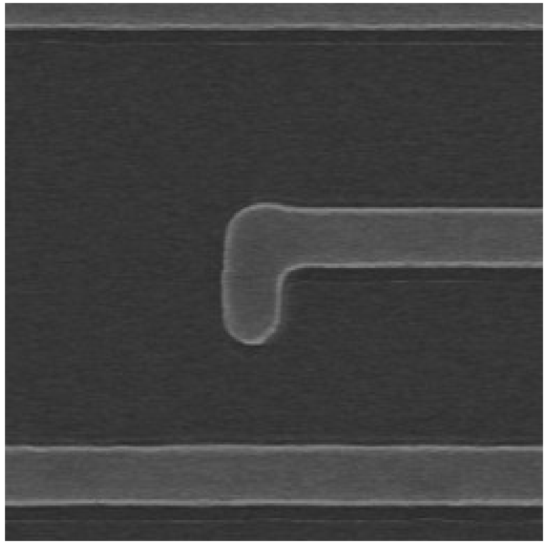
How reconstruction works

original

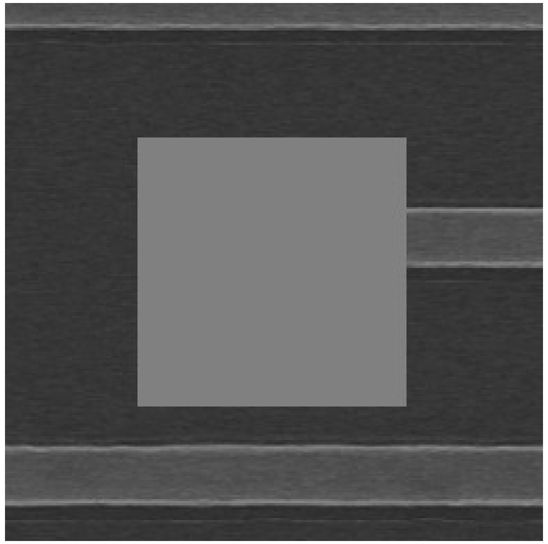


How it works

original

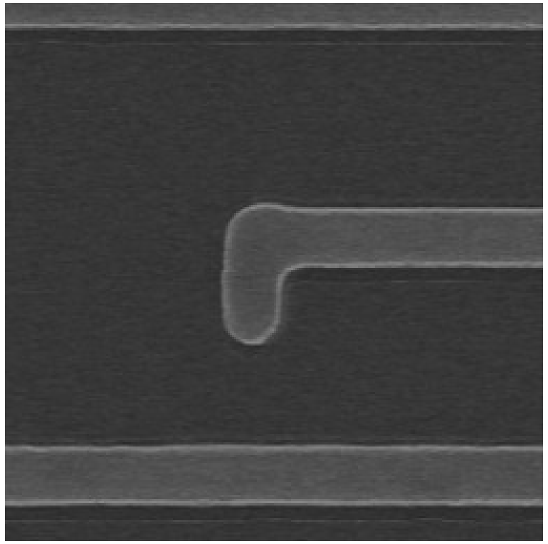


inpainting mask



How it works

original



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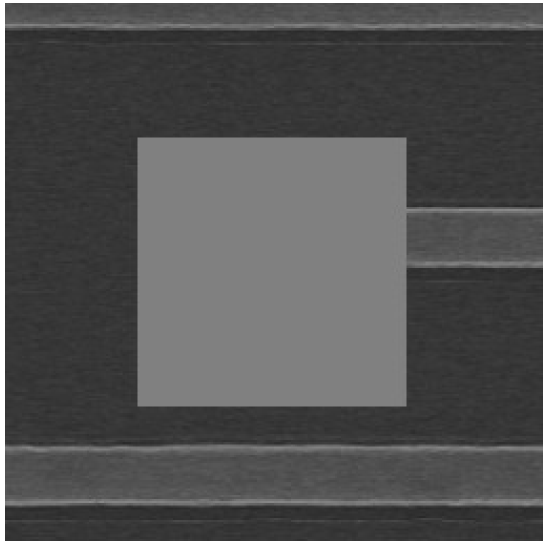
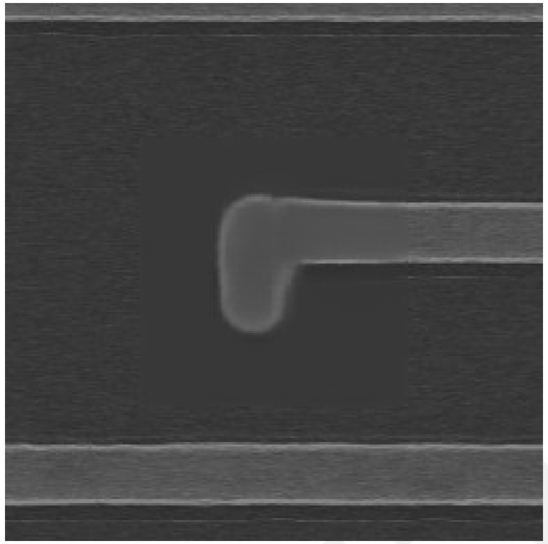
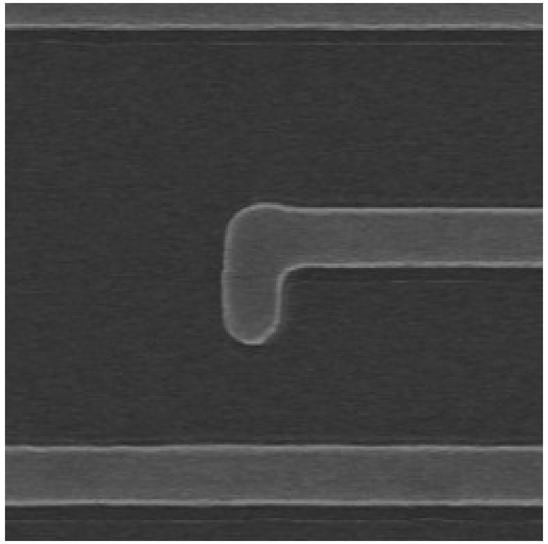


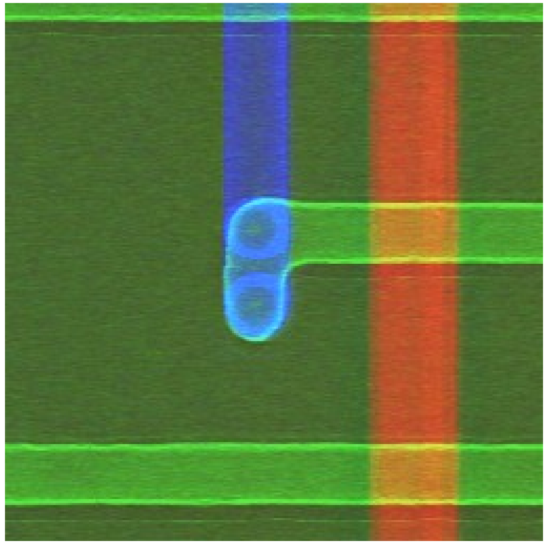
predicted



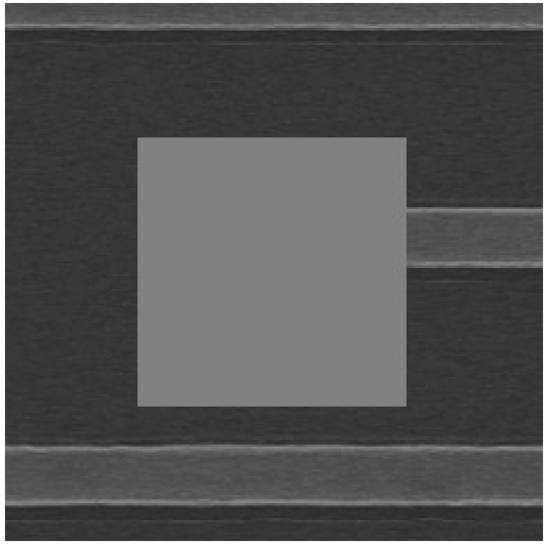
How it works

original





inpainting mask



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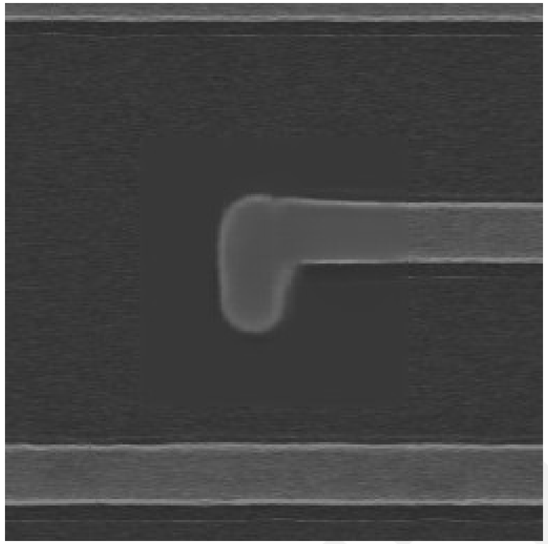

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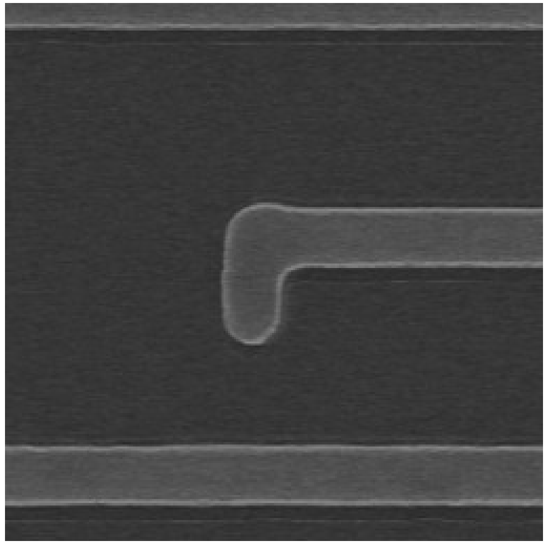
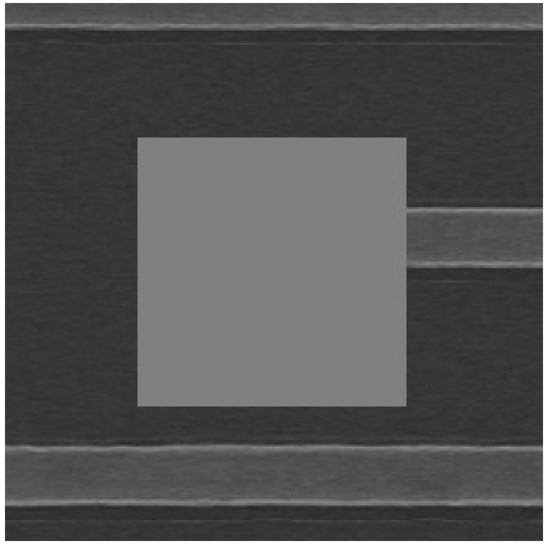
original



inpainting mask



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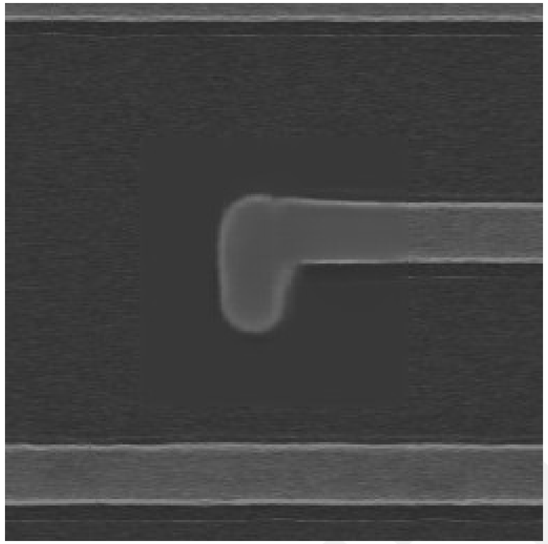
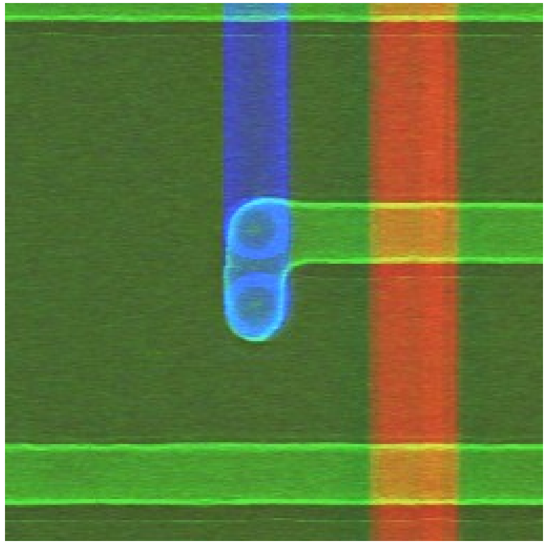
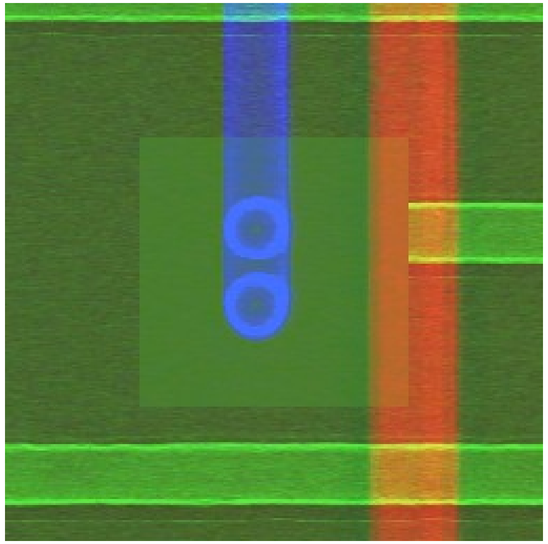




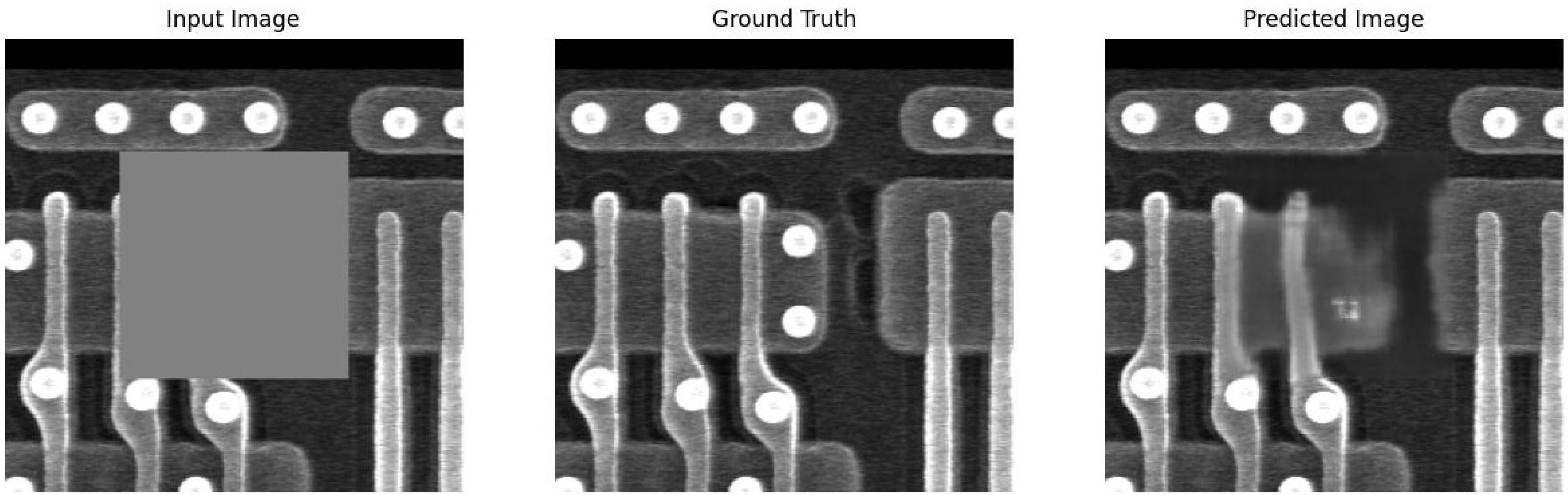


Results

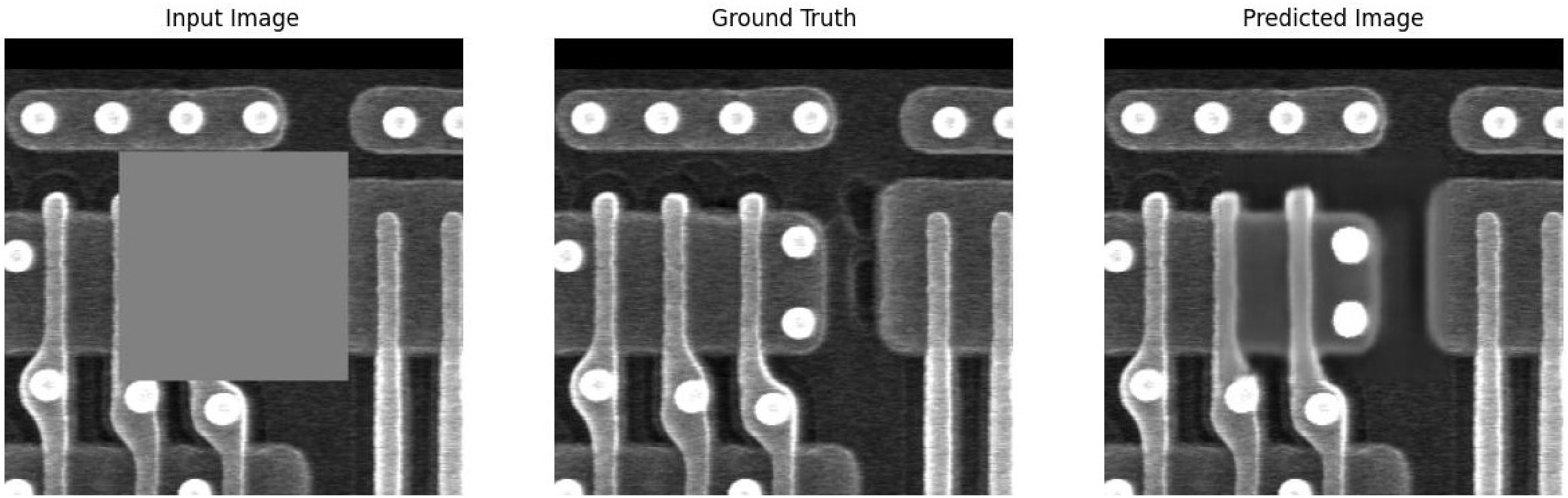
Results

- Single Vs Multiple

Single



Multiple

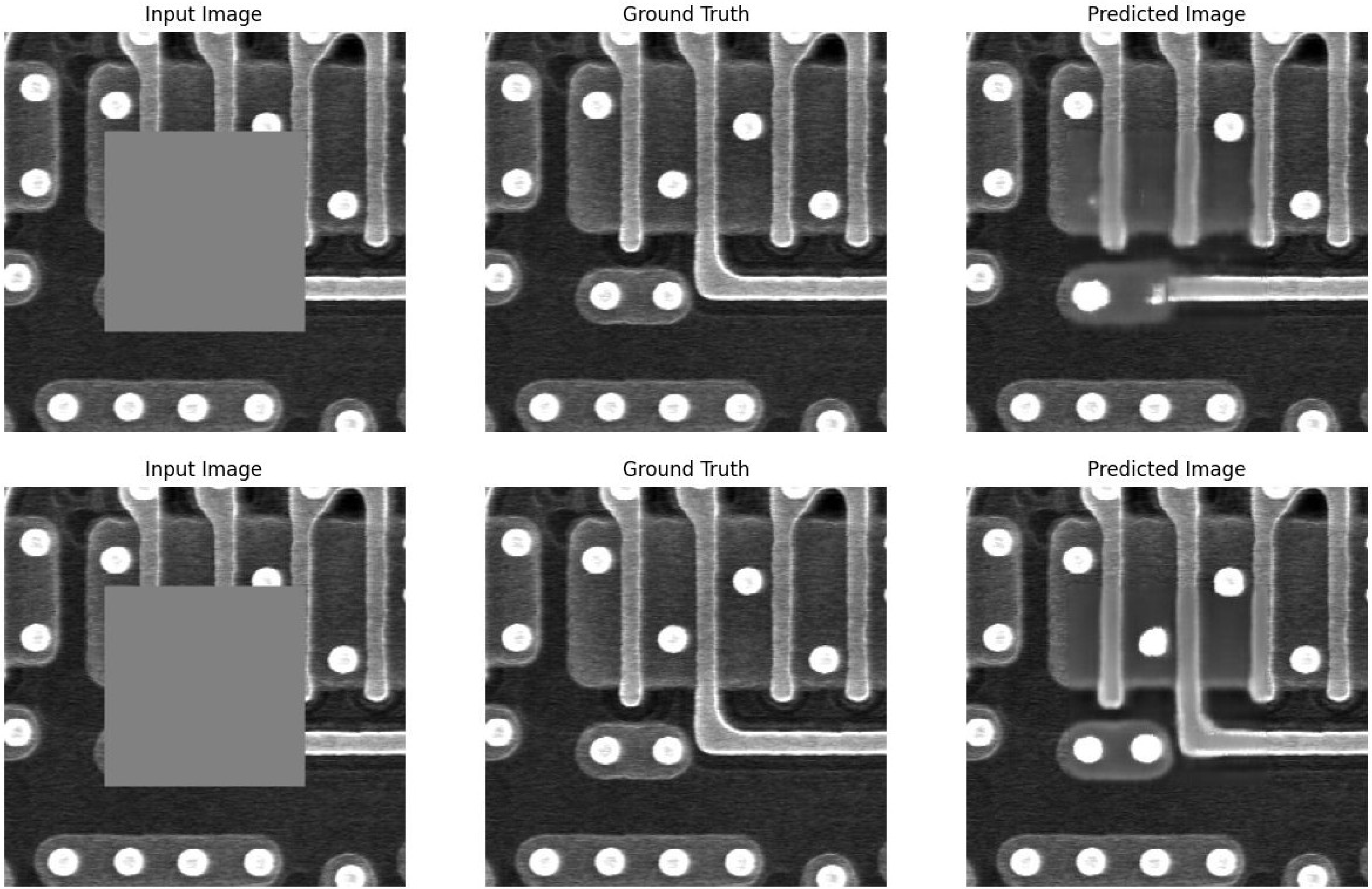


Results

- Single Vs Multiple

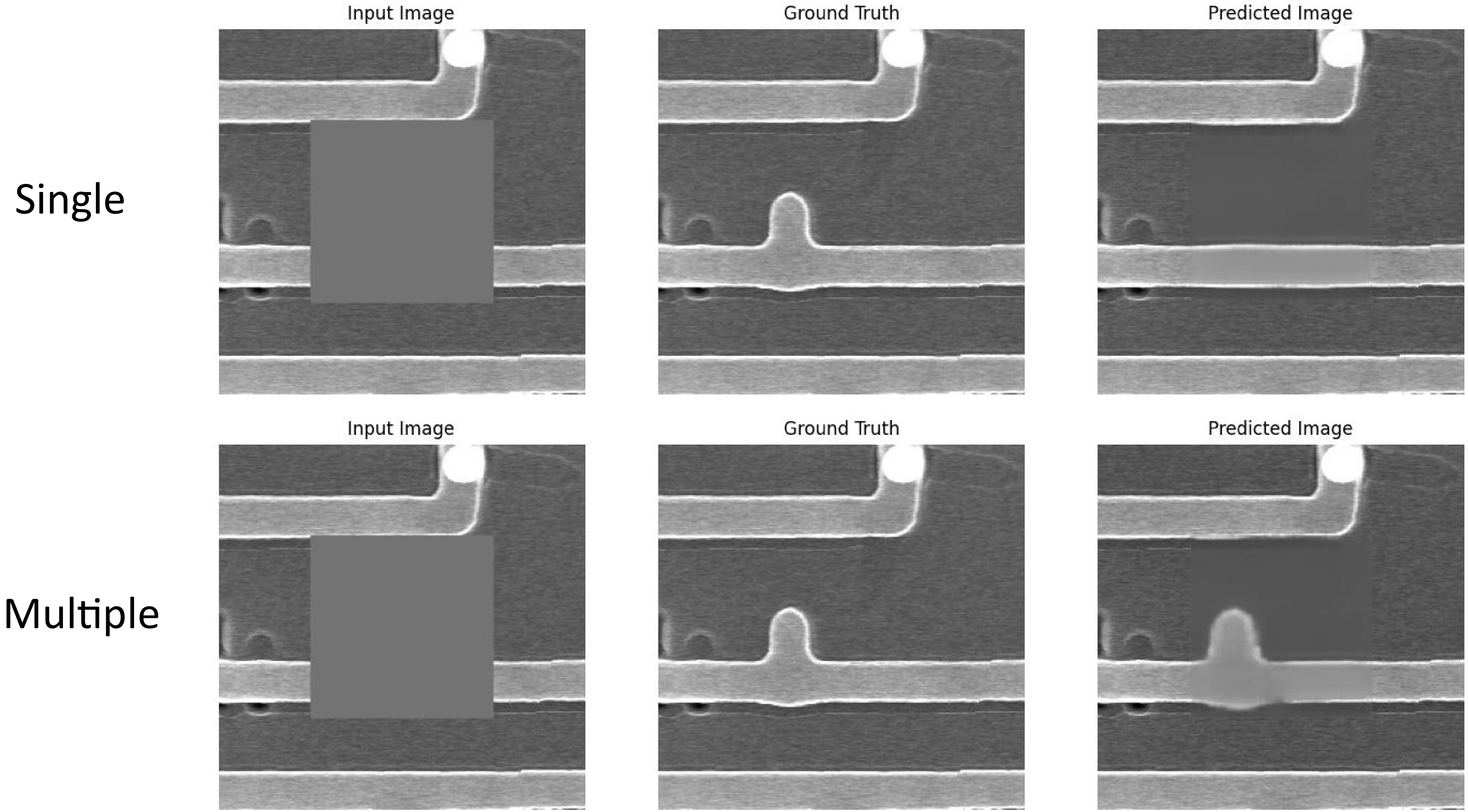
Single

Multiple



Results

- Single Vs Multiple

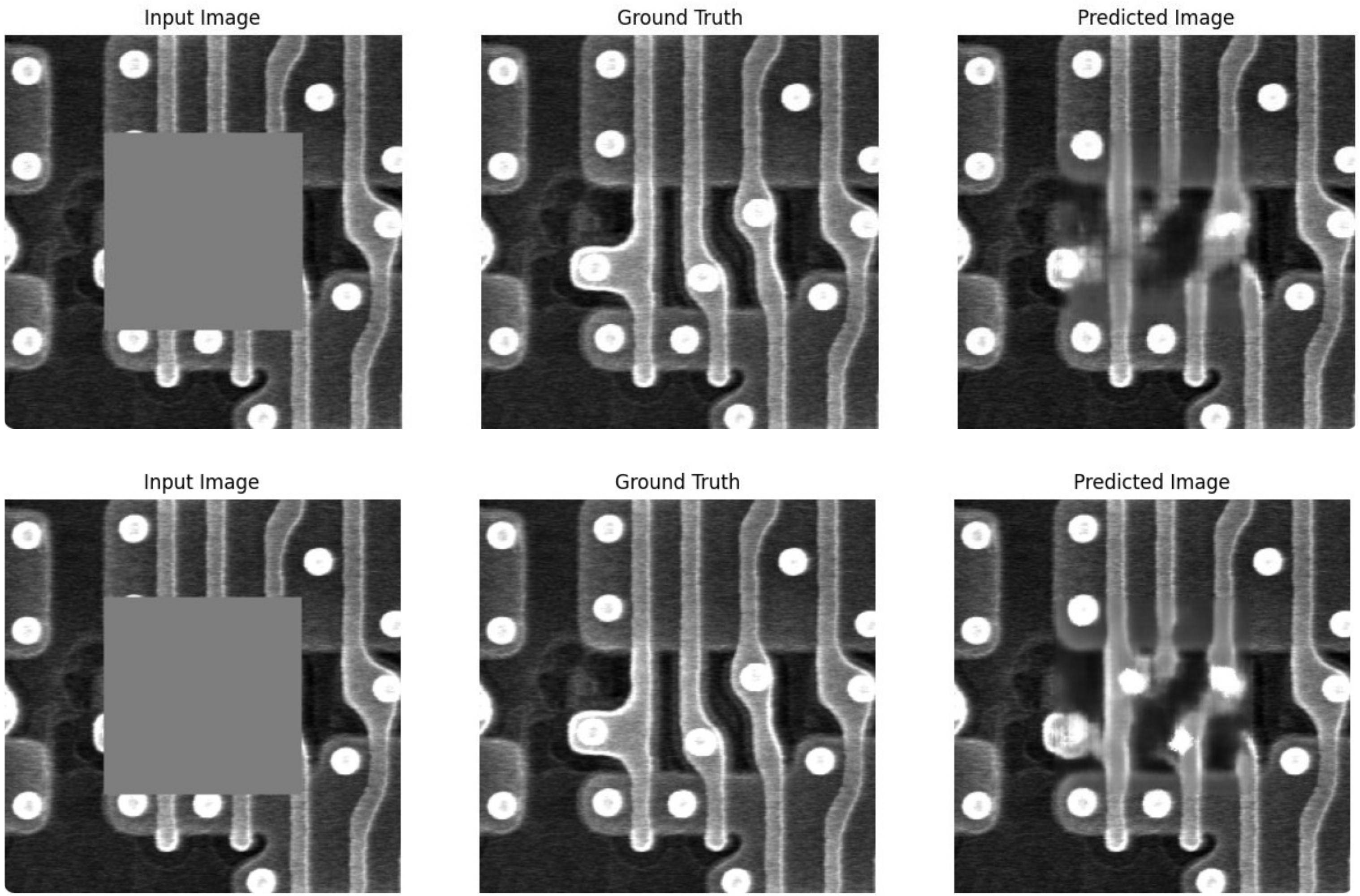


Results

- BAD Reconstructions
  - Unsupervised dataset → We need to model all types of structures!

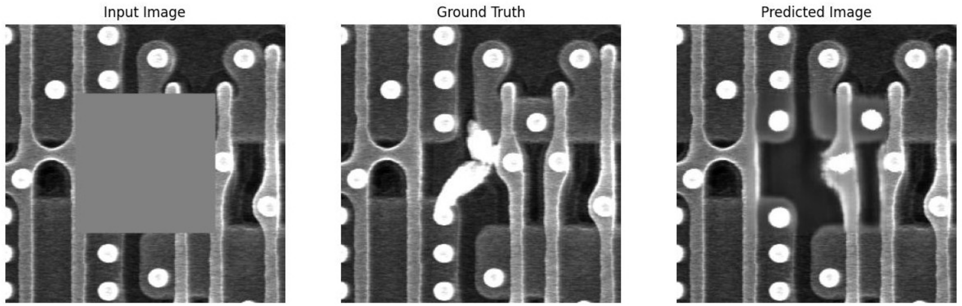
Single

Multiple

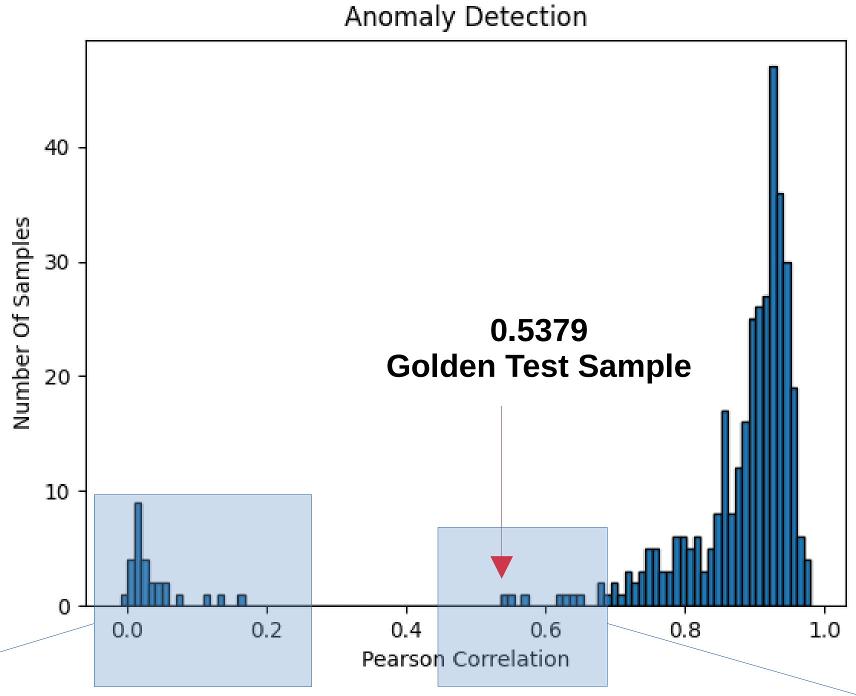


Results

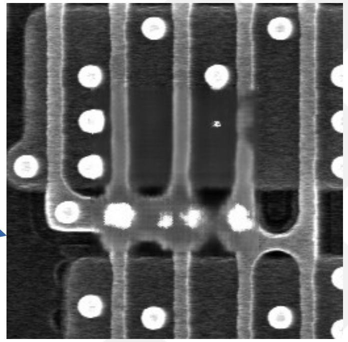
- Anomaly Detection
  - Evaluate the reconstruction error to detect anomalies → Poly Test Set
    - Reconstruction errors are identified as anomalies



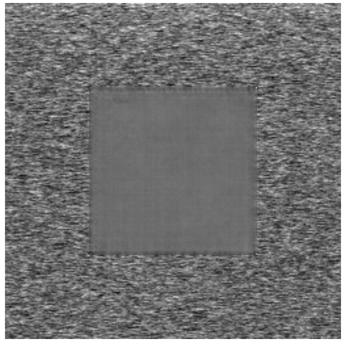
Golden Test Sample



Bad reconstructions are the **real pain.**



Nosiy Background present low values. <u>Easy to filter</u>



Conclusions

Conclusions

- Inter-layer information is <u>essential</u> to properly recover the information

- Simple Deep Learning Architecture
  - It is compulsory, if we want to deploy it and used by non-expert users
    - User must be able to train the network → Easiness of **convergence** (GANs are not)
  - Required **dataset does not need to large** (less than 100 SEM images!)
  - **Self-supervised task** → Easy to generate the dataset (No human annotation)

- **Triplet dataset** images generation could be difficult
  - It requires a good **inter-layer alignment**
    - In entails **stitching** and **distortion** correction of the stacked layers

Conclusions

- Reconstruction **texture** is still quite **blurry**
  - Experimenting with **Diffusion Networks** but a **larger dataset** is required…
    - Difficult to use by non-experts
  - But it has **enough quality** for our **segmentation** model (ultimately the main goal)
- Inpainting results **supervision is mandatory**
  - Some reconstructions cannot be reliable (statistic layer modeling)
- Tested for Anomaly Detection
  - If we evaluate the reconstruction, we could try to detect anomalies.
    - Highly dependent to layer complexity (upper Metals a lot easier than Poly)
    - All the reconstruction errors will be labeled as anomalies, **high success** rate needed!

Thanks for your attention

further questions to Raul Quijada:
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