IC inspection and failure analysis using single-photon detection

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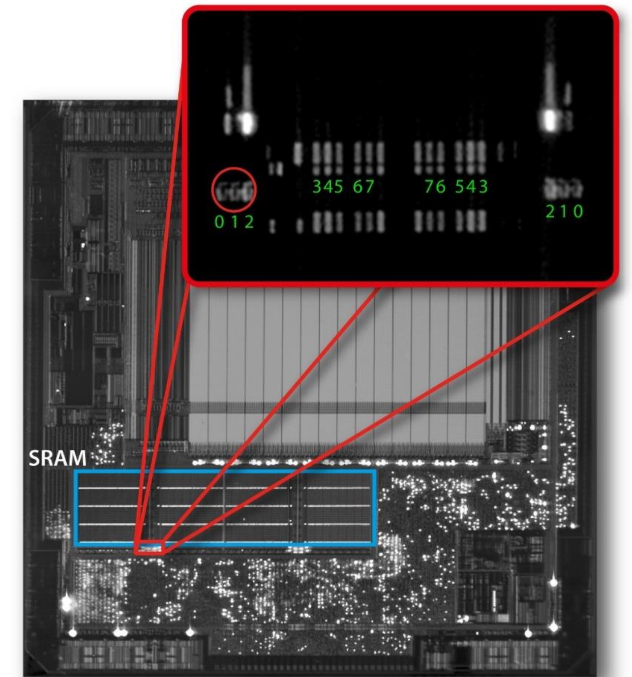
Knowledge for Tomorrow

Outline

- IC Inspector
- IC Preparation
- Mode of Operations
  - NIR Microscopy
  - Optical Beam Induced Current Microscopy (OBIC)
  - Laser Fault Injection Analysis (LFI)
  - Thermal Laser Stimulation Analysis (TLS)
  - Photon emission Analysis (PEA)
    - Pico Second Imaging Analysis (PICA)
- Conclusion



Compact Near Infrared Microscope

for IC and Security IC Inspection

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IC Inspector

CB
TDC
SPAD
Si-CCD
DUT
P1
P2
P3
P4
NIR / PE Microscope
Laser
Laser
Driver
Laser Scanning Module

Data, Trigger
Optical path for λ > 1000 nm
Optical path for λ < 1000 nm
Laser beam, λ = 980 nm

CB: Control Interface Box
DUT: Device Under Test
TDC: Time-to-digital Converter
P1-P4: Optical In-/Output Ports
SPAD: Single Photon Avalanche Detector

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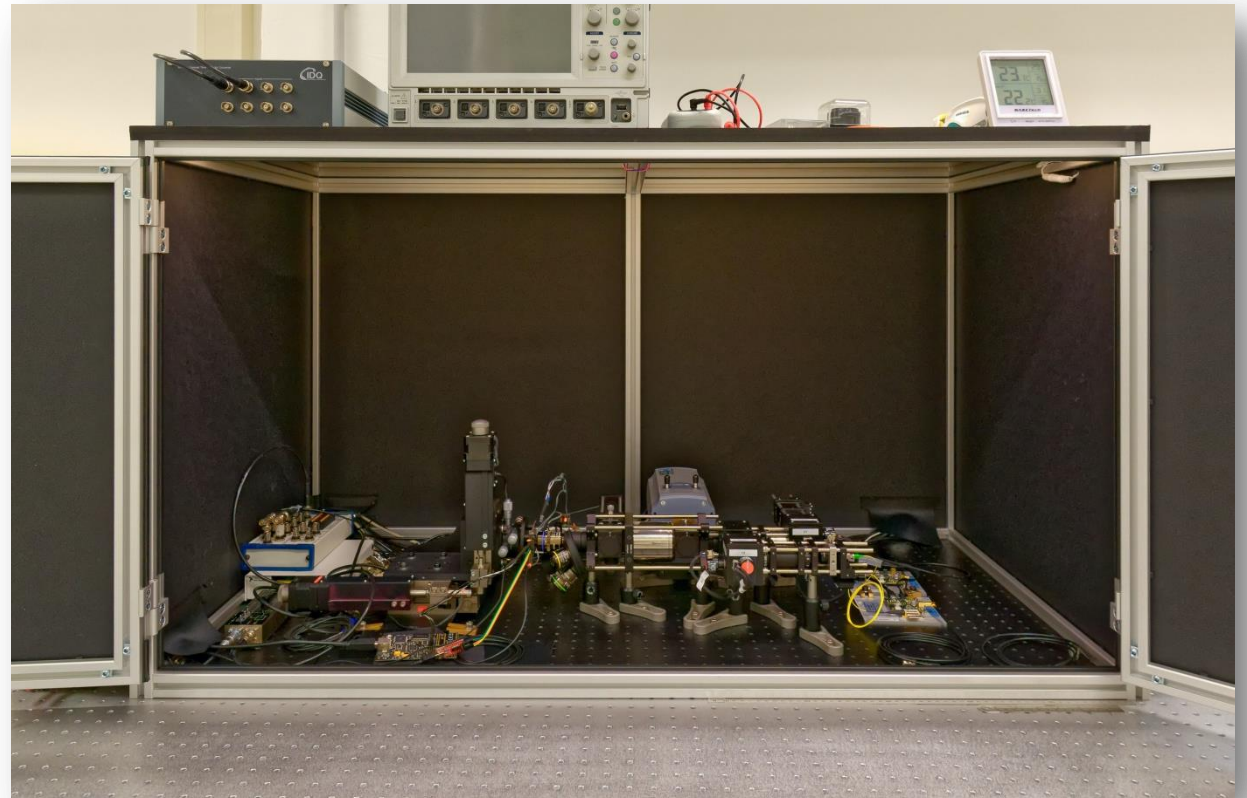
IC Inspector - Summary



- 5 Operation Modes
- 4 optical in- and output ports
- Highly modular and flexible
- Compact size
- Dual laser module (e.g. 980nm)
- Fast laser scanning (galvos)
- Diffraction limited performance
- High positioning precision (<100nm)
- High timing precision (<10ps)

Rugged and easy to use (e.g. no cleanroom environment, no sophisticated vibration isolation, no liquid nitrogen cooling, automated measurements, and autofocus).

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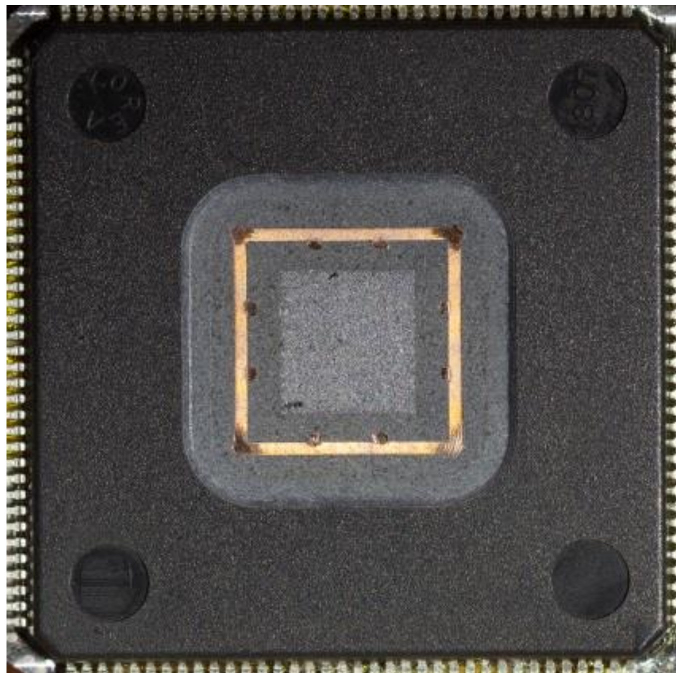
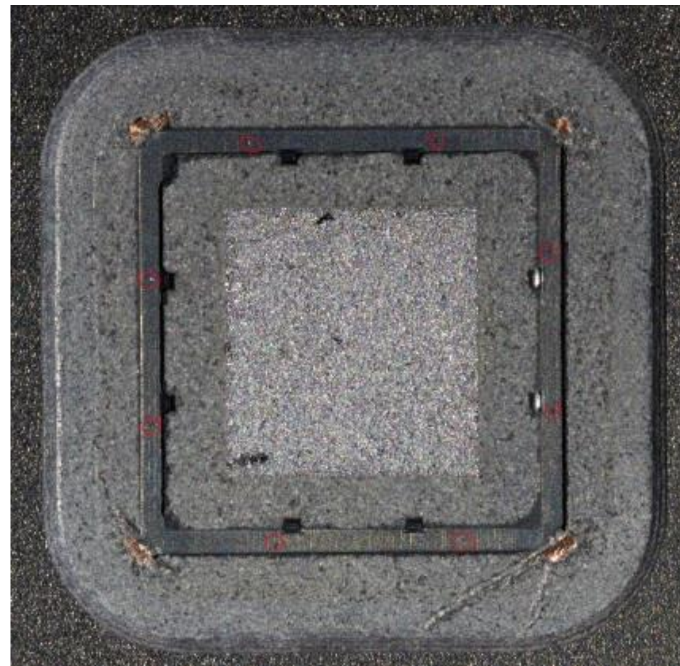
Chip preparation – Back-side

Package openend down to the lead frame by grinding

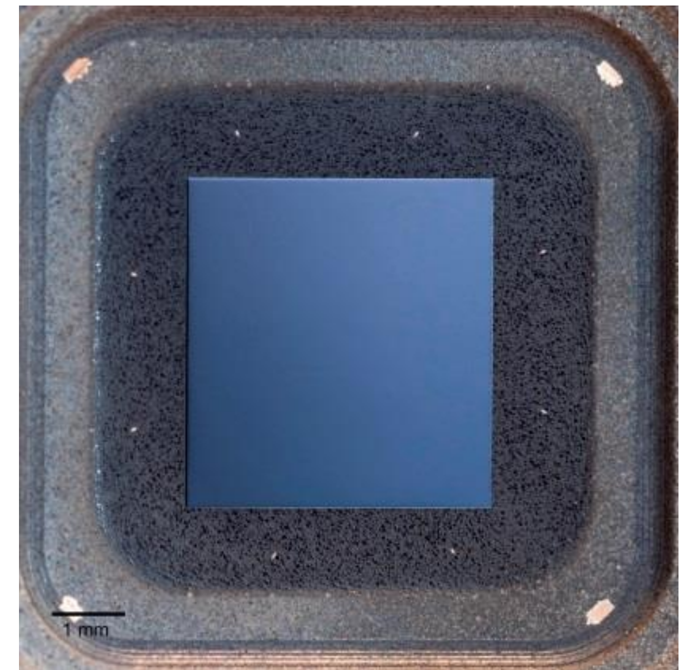


Altera Cyclone IV FPGA, 60nm

Lead frame further partly removed



Thinned and polished die



Substrate thickness 10 µm

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Operation Modes

1. NIR Microscopy
2. Optical Beam Induced Current Microscopy
3. Laser Fault Injection Analysis
4. Thermal Laser Stimulation Analysis
5. Spatial and Temporal Photon Emission Analysis

NIR Microscopy

Dark field reflected light microscopy with NIR light

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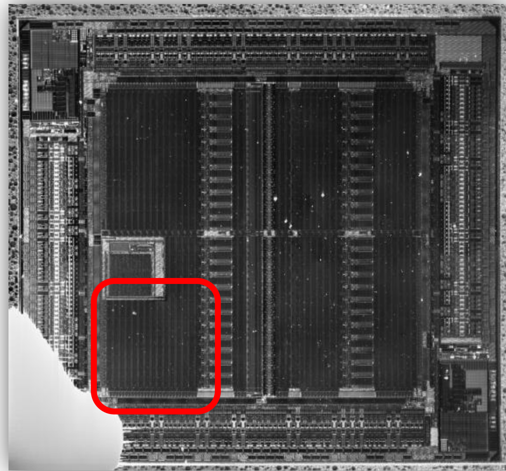
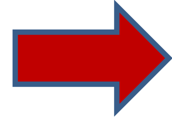
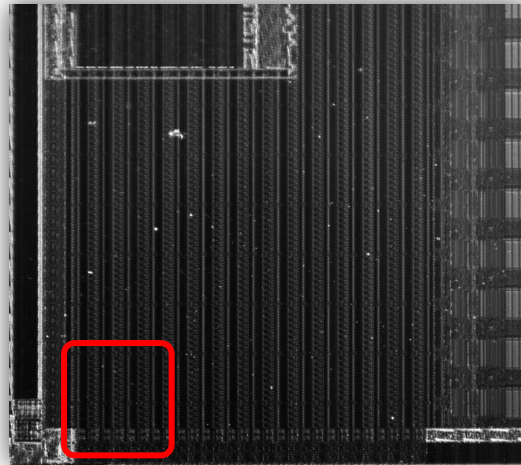
NIR Microscopy – Back-side Image Through Silicon Substrate

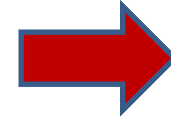


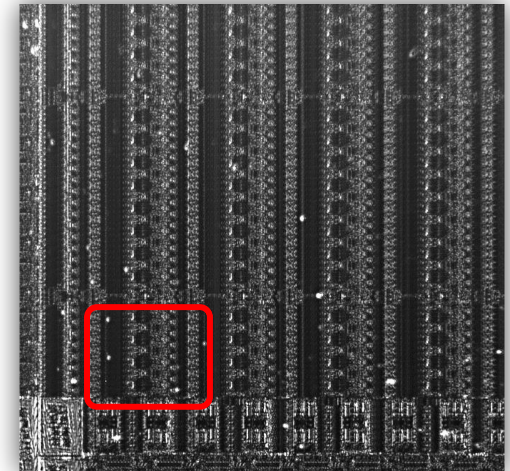
~ 4.5 x 4.5mm



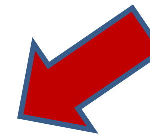


~ 1 x 1 mm

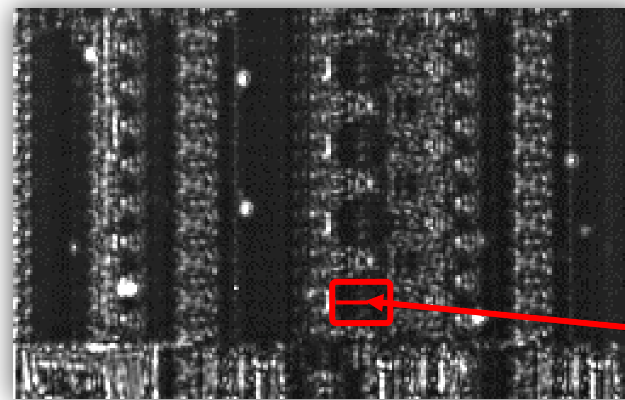




~ 190 x 190 µm



Altera Cyclone IV FPGA (60nm)



Look-up tables
of 2 adjacent LEs

~ 50 x 30 µm

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Optical Beam Induced Current Micrcoscopy

The standard method for failure analysis to locate buried diffusion regions, damaged junctions and gate oxide shorts

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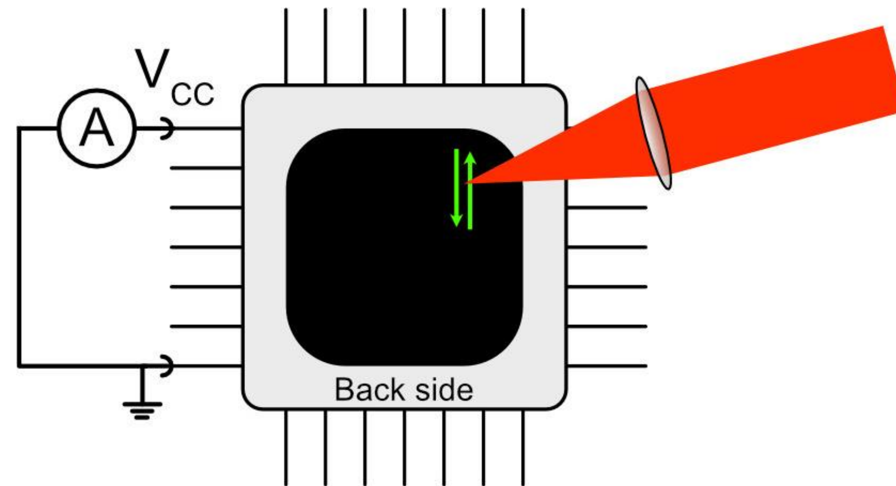
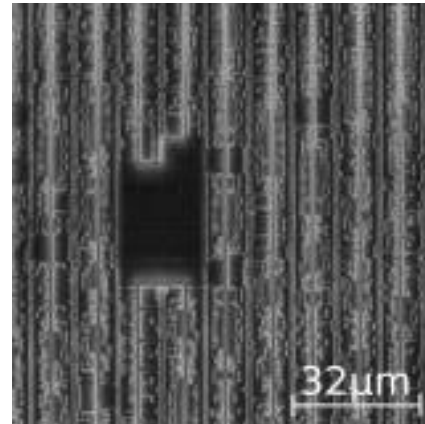
Optical Beam Induced Current – Principle

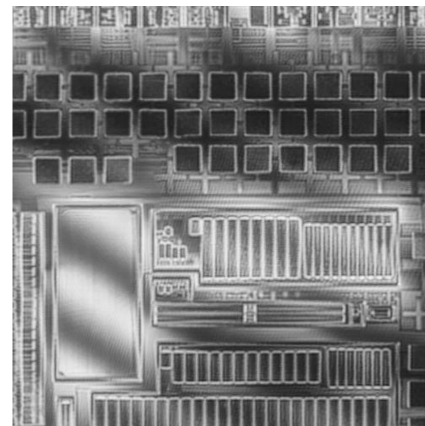


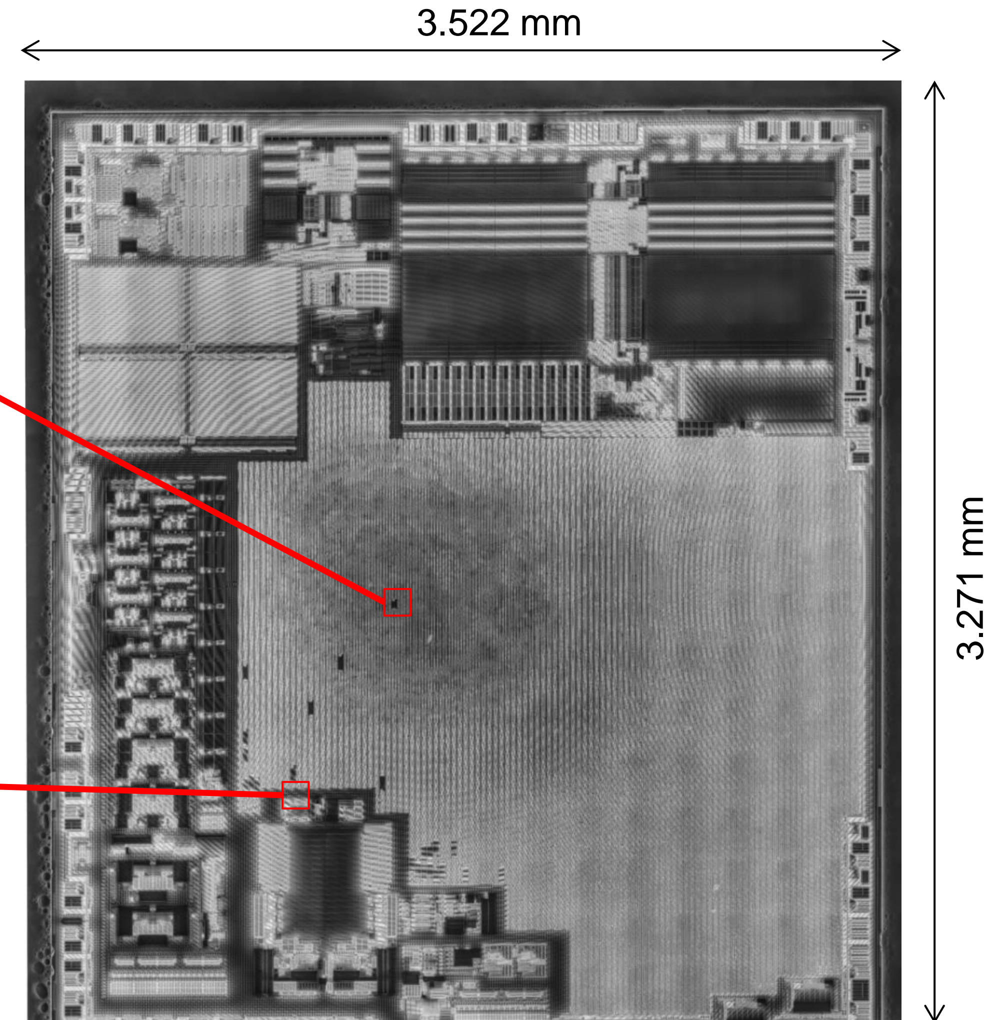
- Laser photon energy > semiconductor band gap energy
- Images are formed by a locally induced photocurrent

Optical Beam Induced Current – Example

- OBIC Images are showing the electronic structure and defects
- Photocurrent from pn-junctions of transistors or diodes that are connected to output pins used
- Bias voltage can enhance image contrast







Laser Fault Injection Analysis

Manipulation of code execution by altering the logical state of

single transistors or logical elements

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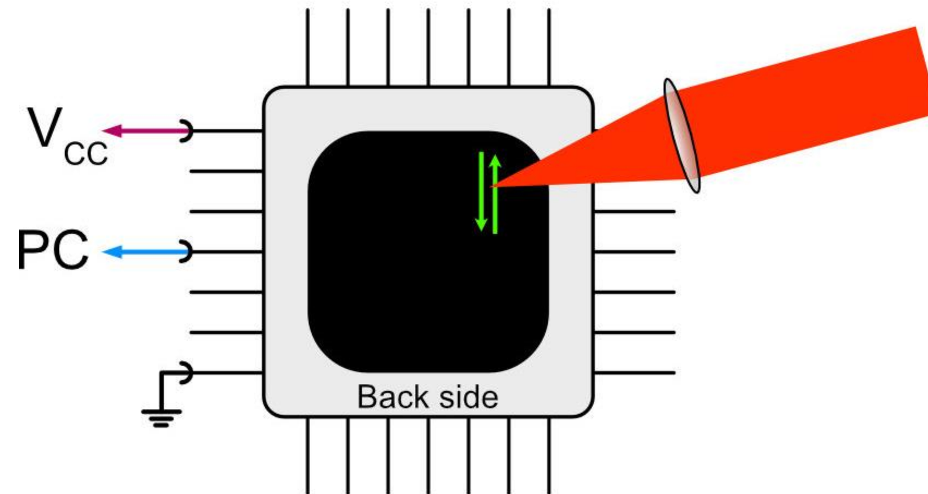
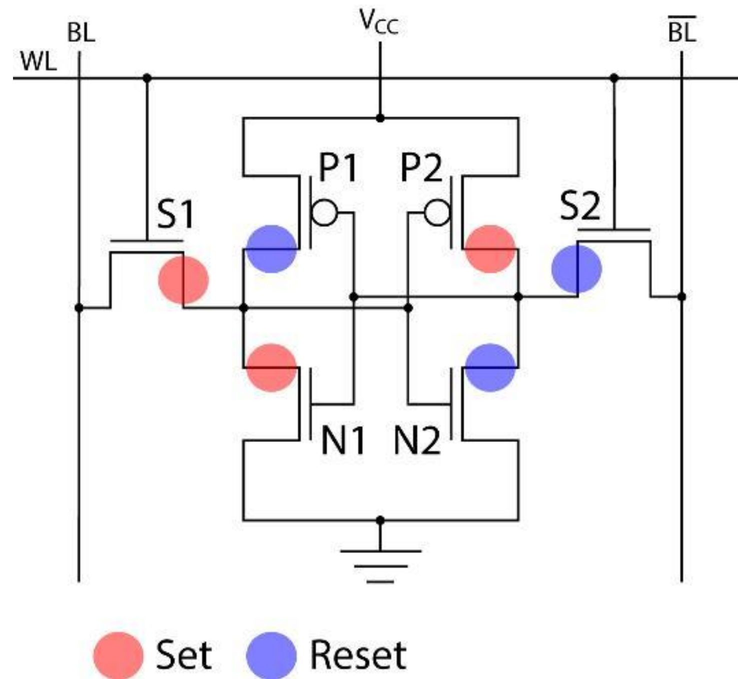
Laser Fault Injection – Principle



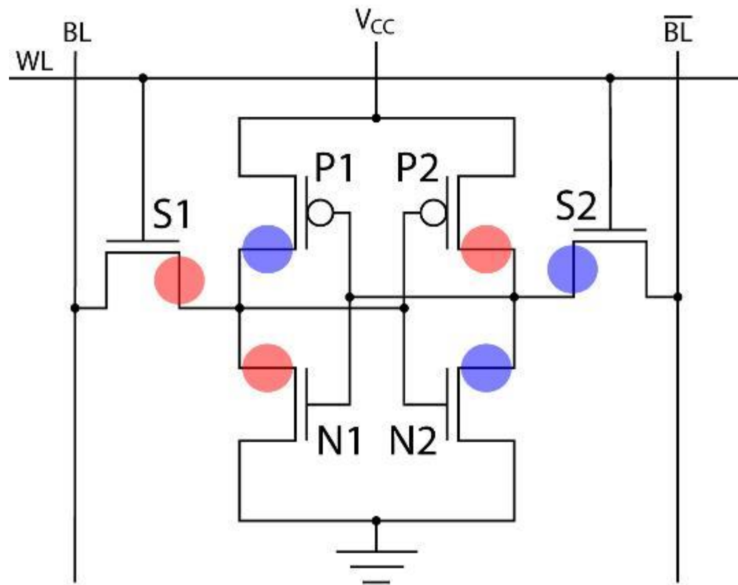
- Laser photon energy > semiconductor band gap energy
- Free charges causing a short current that can alter the state of a transistor or a logical group

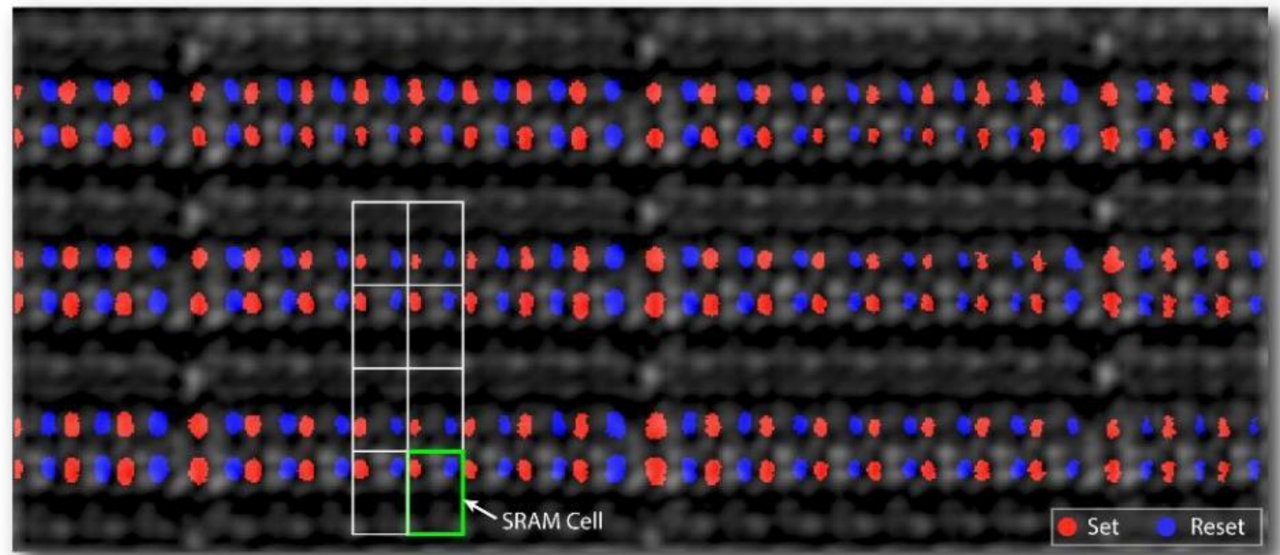
Example: SRAM Manipulation in Microchip ATXMega 16A4

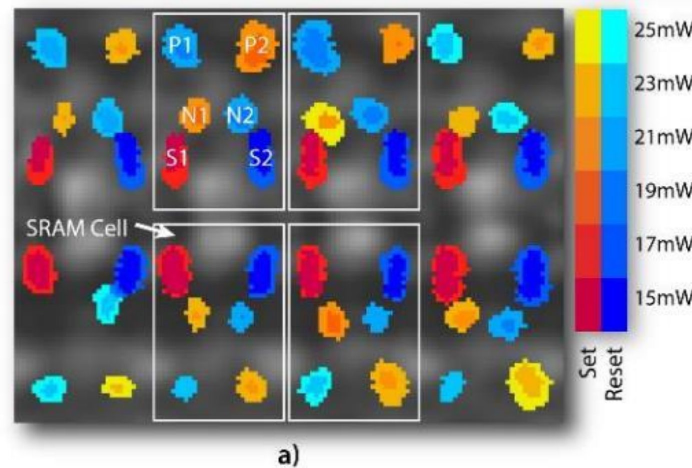


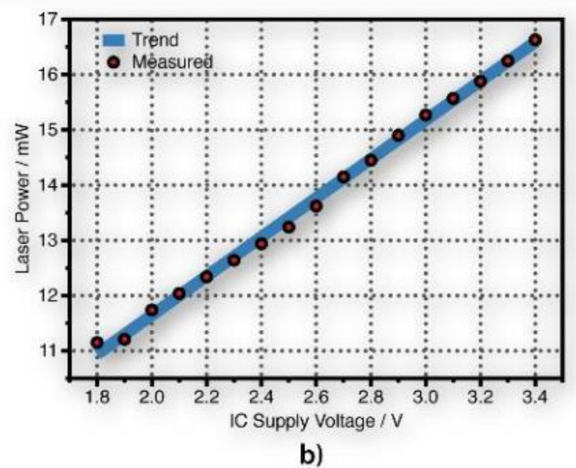
- A standard SRAM-cell has three pn-junctions/transistors where its value can be set and three where it can be reset
- Individual SRAM-cells can be precisely addressed to alter the stored bit value

Example: SRAM Manipulation in Microchip ATXMega 16A4









Each transistor of the 6T-Cell is resolvable

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Thermal Laser Stimulation

Thermally induced leakage current for

side-channel analysis

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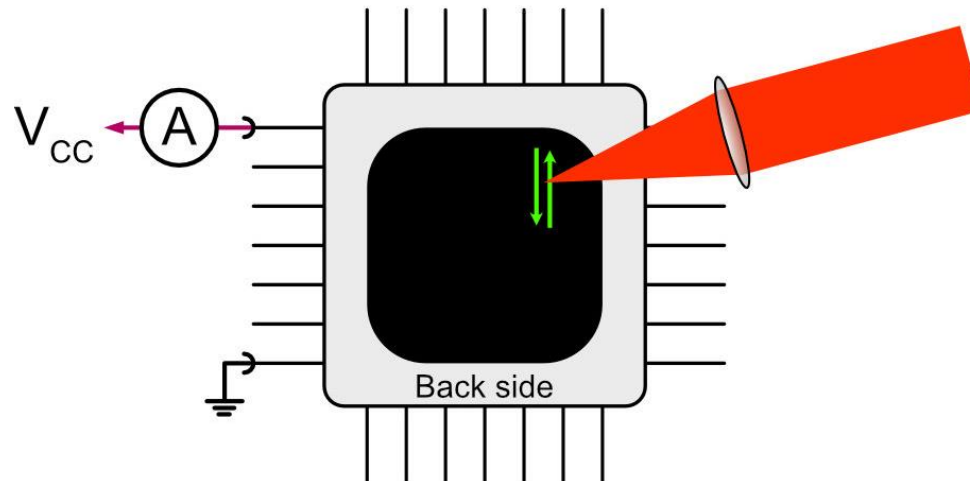
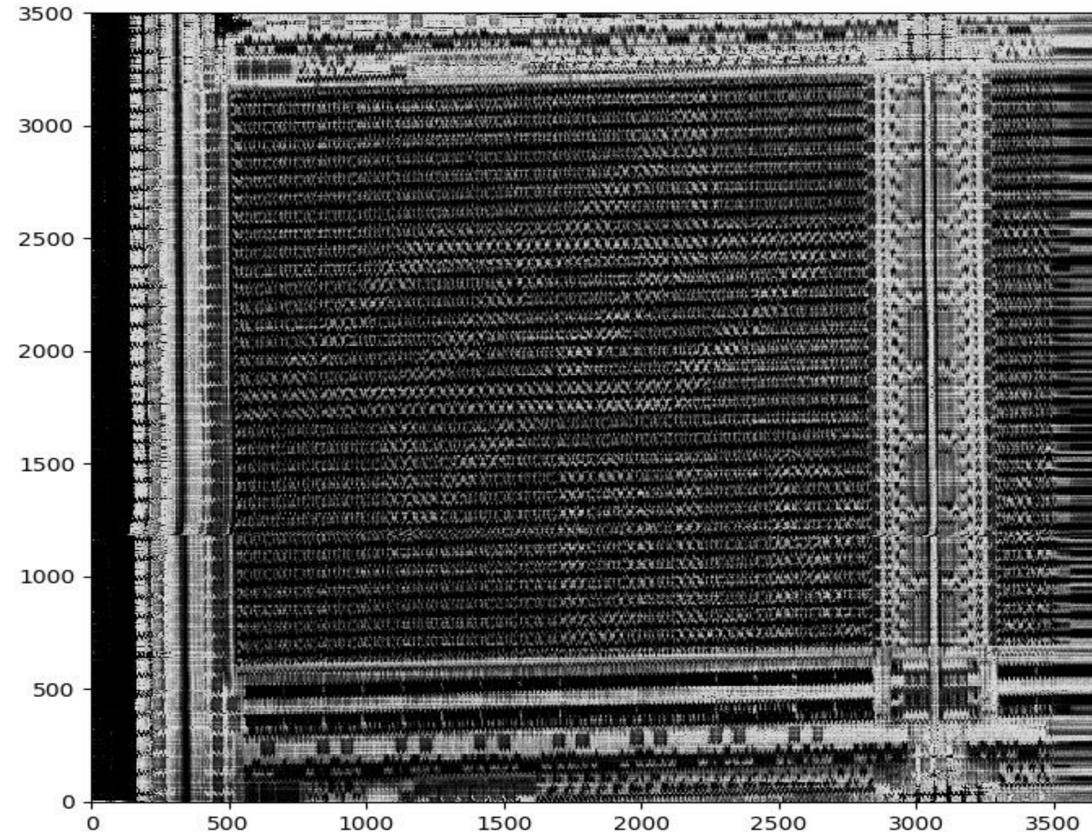
Thermal Laser Stimulation – Principle



- Laser photon energy < semiconductor band gap energy
- TLS scans induce an additional leakage current in switched-off transistors

TLS Example – Direct SRAM Data Read Out

- TLS map reveals the state of the transistors
- E.g. memory cell have a characteristic TLS scan pattern that can be used to read out the memory content



TLS-image of a SRAM-Block in ATXMega 16A4

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Photon Emission Analysis

Failure localization and side-channel analysis with

spatial and temporal techniques

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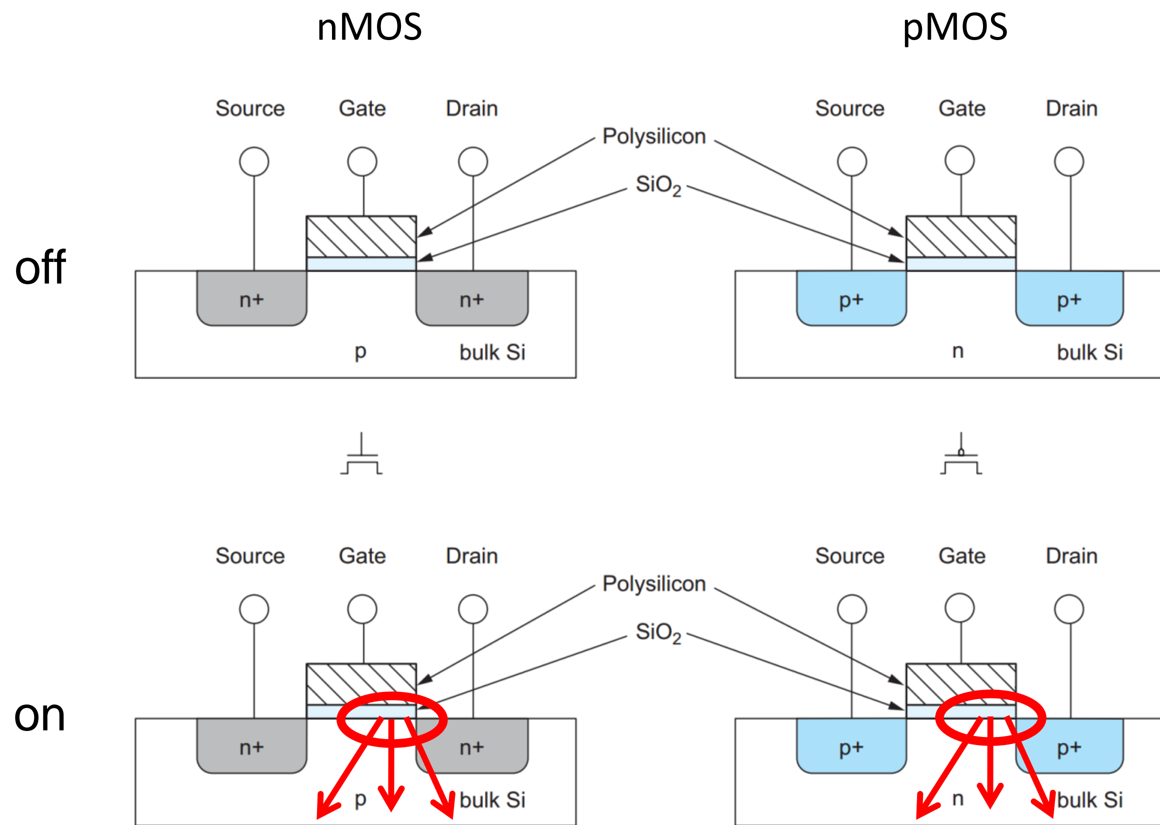
Photon Emission Analysis – Field Effect Transistors, HCL



Hot carrier luminescence (HCL)

- Occurs when transistors operate in saturation mode and charge carriers flow through the conduction channel.
- The electrical field attains its maximum near the edge of the drain where some carriers gain enough energy to emit photons by direct and indirect transitions.
- The spectrum of HCL is given by the energy distribution of the carriers and hence ranges from the visible to the infrared.
- The photon emission probability depends on the supply voltage and is about 10^{-4} to 10^{-6} photons per electron.

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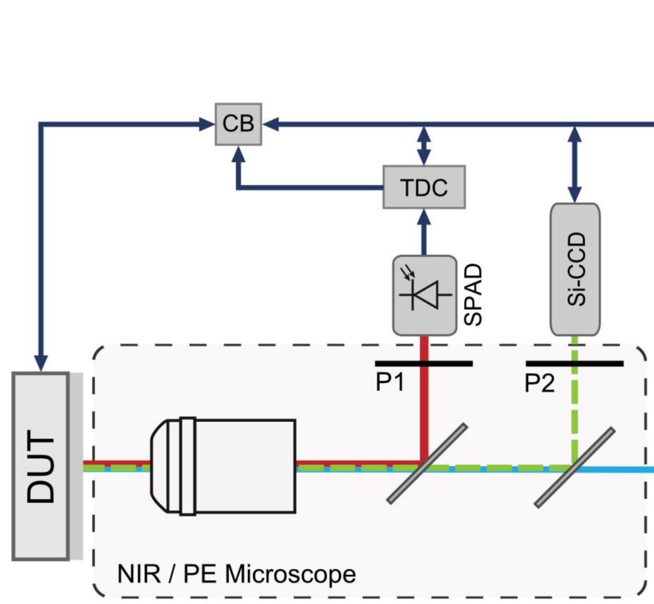
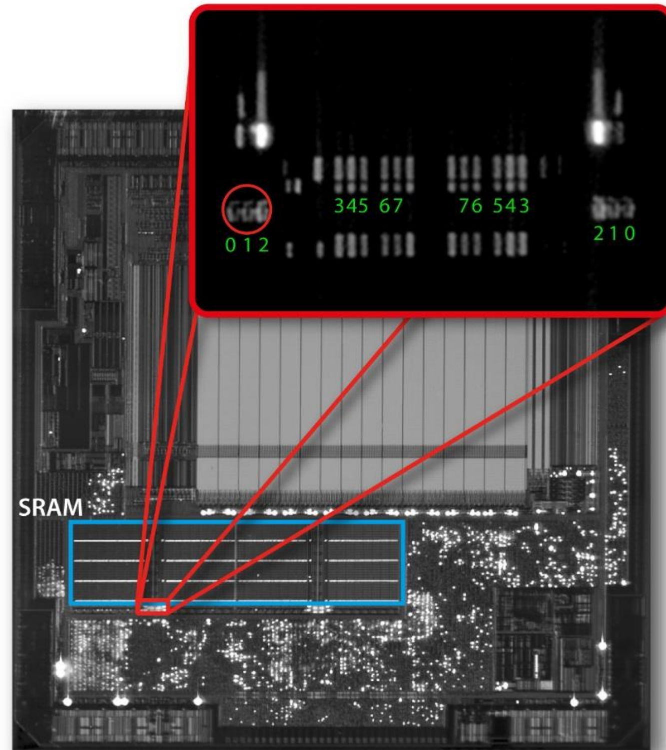
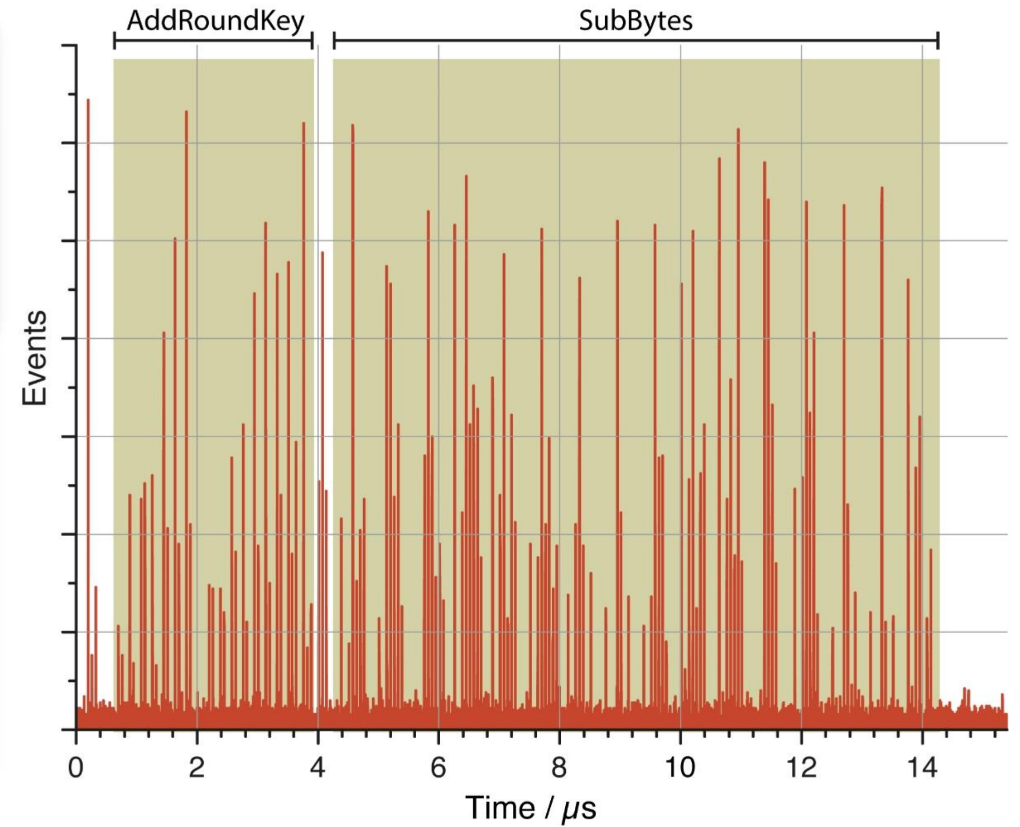
Photon Emission Analysis



NIR Microscope



CCD Image



SPAD Signal

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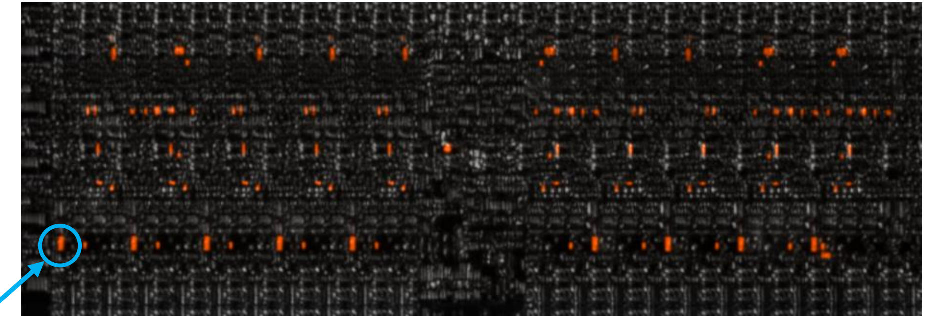
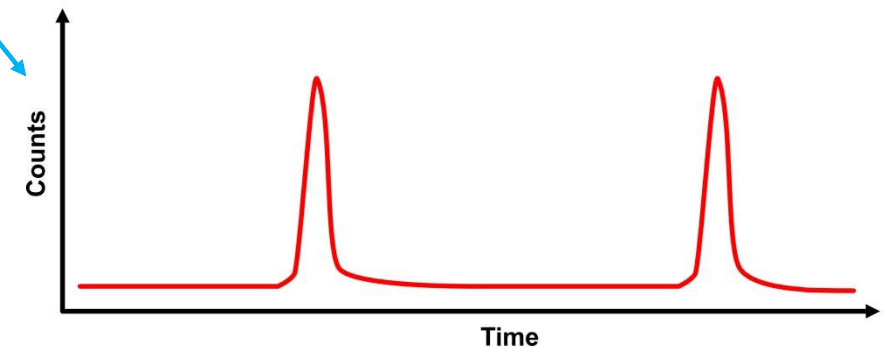
Pico Second Imaging Analysis

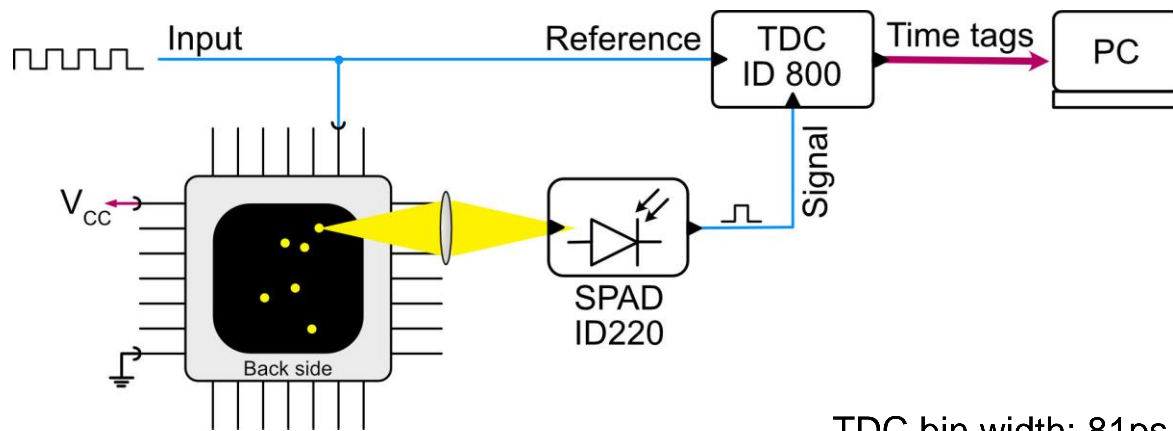
1. Microscope NIR overview image
2. Photon emission overview image -> Region of interest (ROI)
3. Temporal photon emission measurement of single ROIs
4. Correlation & computation of emission time tags



Overlayed NIR microscope and photon emission image (red).

ROI

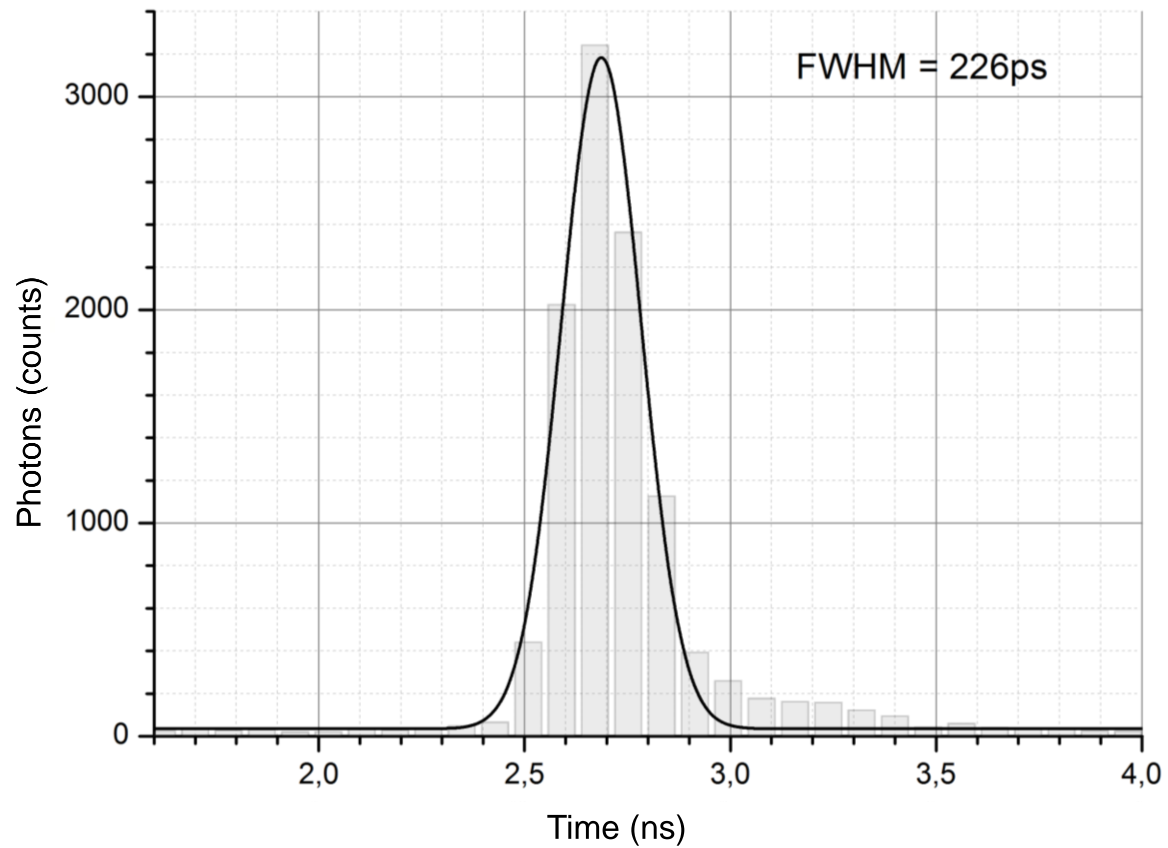


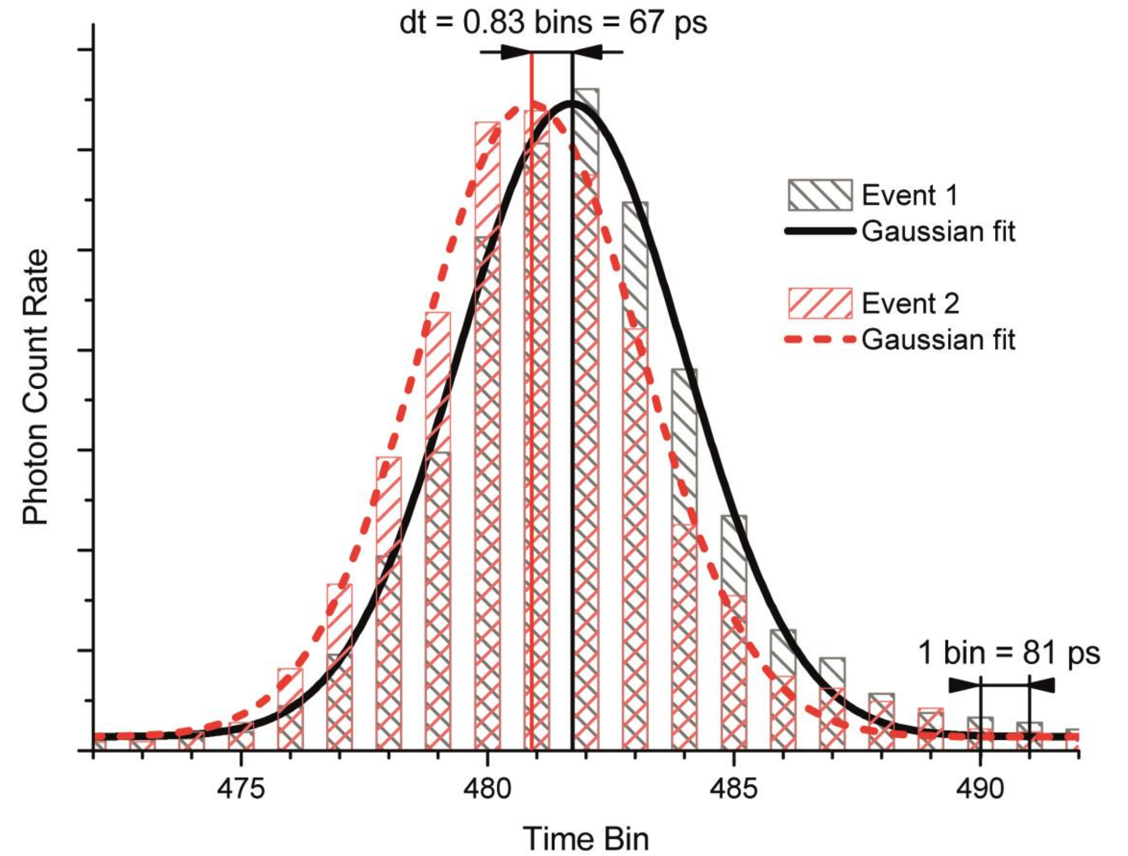


TDC bin width: 81ps.

Pico Second Imaging Analysis – Temporal Super Resolution

Total system jitter for detecting a single HCL photon





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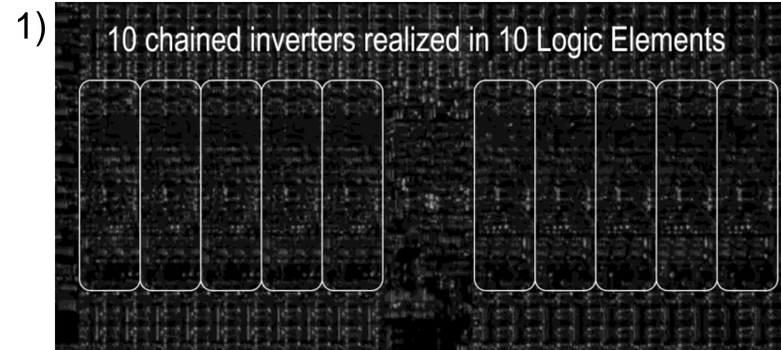
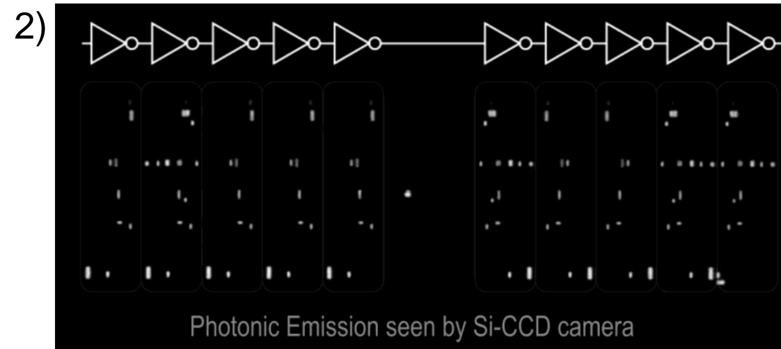
Pico Second Imaging Analysis – Example

1)


2)


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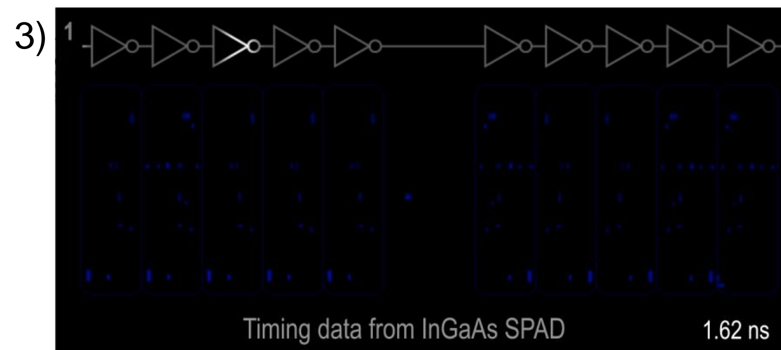

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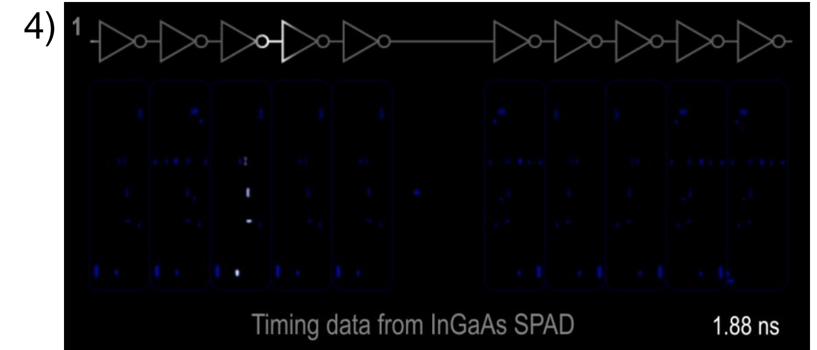

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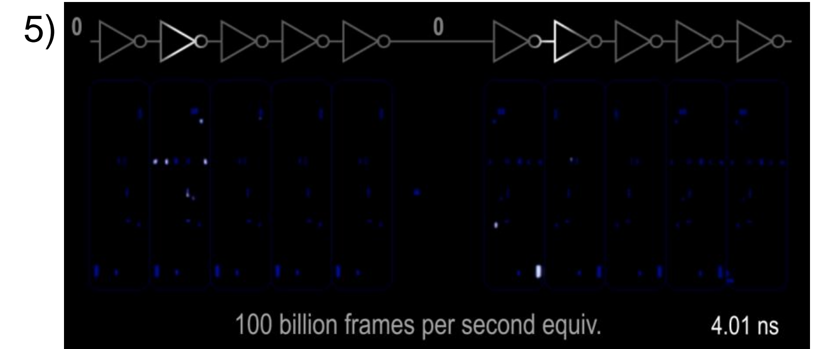

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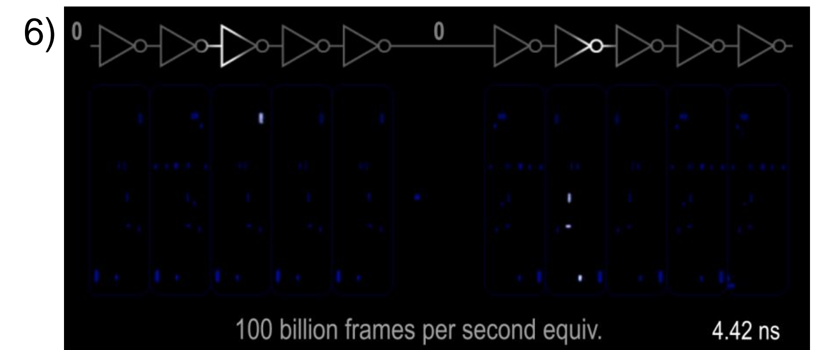

Screenshots from a PICA video showing the signal propagation through an inverter chain consisting of 10 elements in an Altera Max V CPLD.

The video was created from the temporal data from the SPAD and the spatial data from the CCD.

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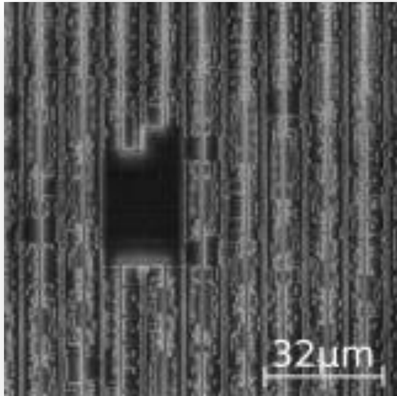
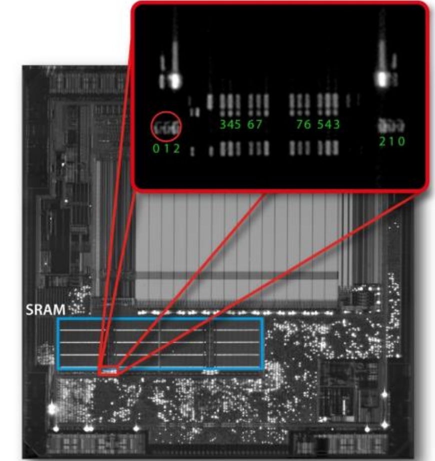
Summary

- Semi-invasive optical signal tracking in fully operational ICs on the gate or transistor level possible
- High timing precision of < 10 ps for optical analysis like PEA
- 5 different methods can be used for analyzes without having to make additional modifications and adjustments to the system:
  - NIR Microscopy
  - OBIC
  - LFI
  - TLS
  - PEA
- Diffraction limited performance
- Modular design allows adaptation to new ICs and analysis methods with little effort

Contacts





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