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Defect Localization Developments: Science and Impact

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Important Parts of Failure Analysis

Failure Localization

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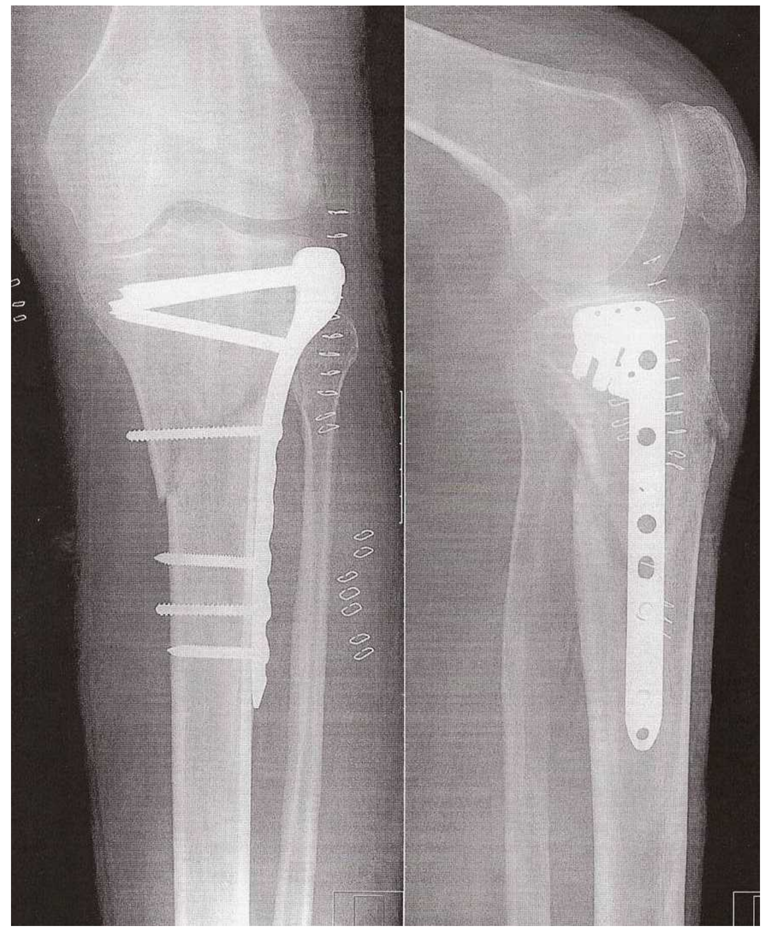
Failure Localization

Corrective Action



Purpose

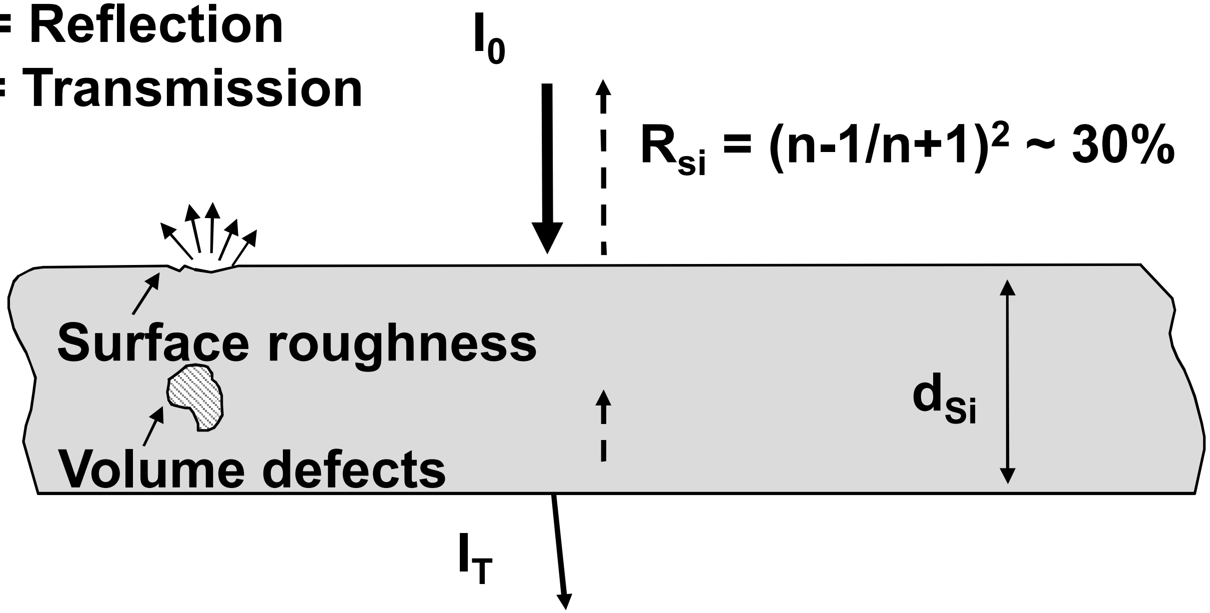
- To describe techniques that have and are still making an impact in defect localization
  - what, why, and how
- Not a complete list by any means
  - highlights in 3 particular areas

Outline

- **Optical beam approaches**
  - **Reflected light, OBIC, LIVA, TIVA/OBIRCH, SEI, SDL/LADA**
  - **Improved resolution with SILs**
- **Light emission and PICA**
- **Magnetic field analysis**
- **Summary**

Transmission Through Bulk Si

R = Reflection
T = Transmission



$T_{Si} = I_T / I_0 = (1-R_{Si})^2 \cdot \exp(-\alpha\, d_{Si})$

scattering due to surface roughness

$\alpha_{Si}(\lambda)$ = bandgap related absorption
$\alpha_{n,p}(\lambda)$ = free carrier absorption
α_{volume} = scattering due to volume defects (neglect)

Optical Image Formation from the Backside of the Die: Key Issues

•Surface roughness: rms < 5nm

$$res = \frac{0.61 \cdot \lambda}{NA}$$

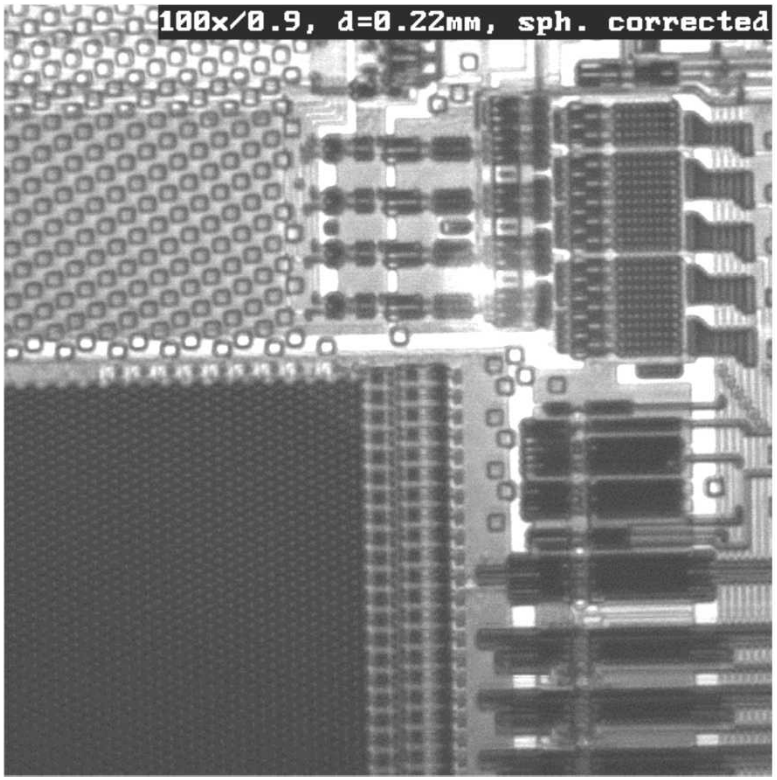
• reduced lateral resolution:

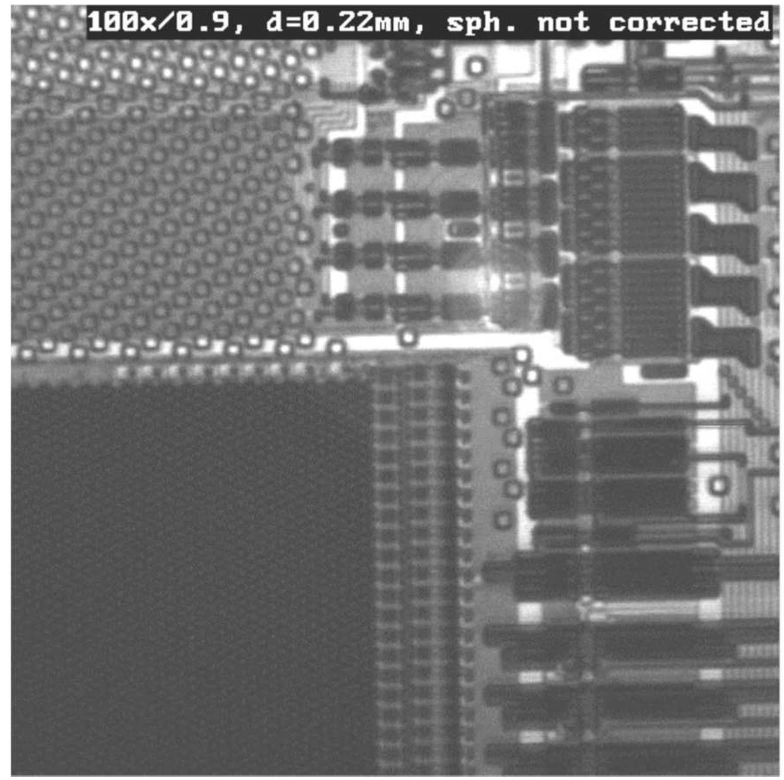
⟶ best image formation: confocal laser scanning microscope

• lens failure for large NA: sperical aberration

⟶ use of a corrected microscope objective (100X) or thinning the die

Zeiss IR confocal LSM (1152 nm)





$p_{substrate}$ = $1x10^{19} cm^{-3}$; d=220µm; 100x objective NA=0.9

Why Use Optically Based Tools?

- Flip-chip packaging, dense metallization
- Si's transparency at infrared wavelengths
- Benign nature of optical techniques
- Availability of scanning laser microscopy equipment

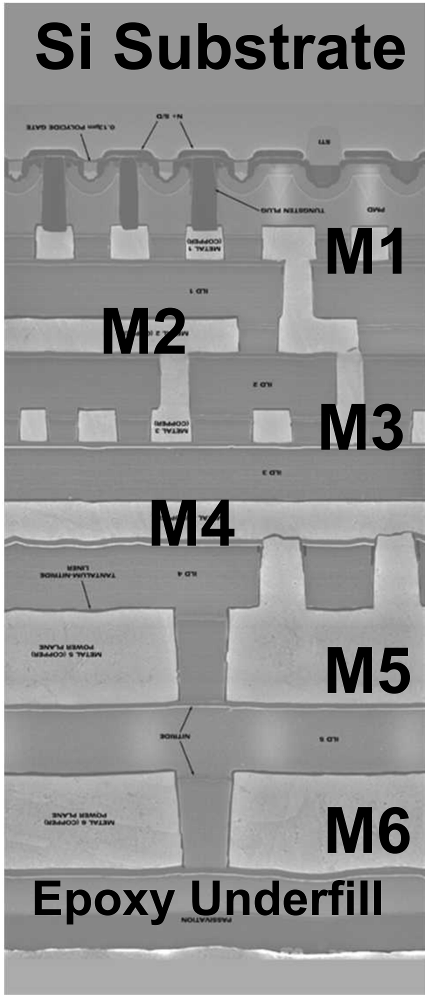
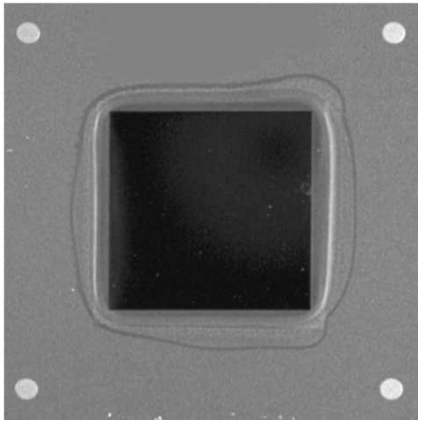


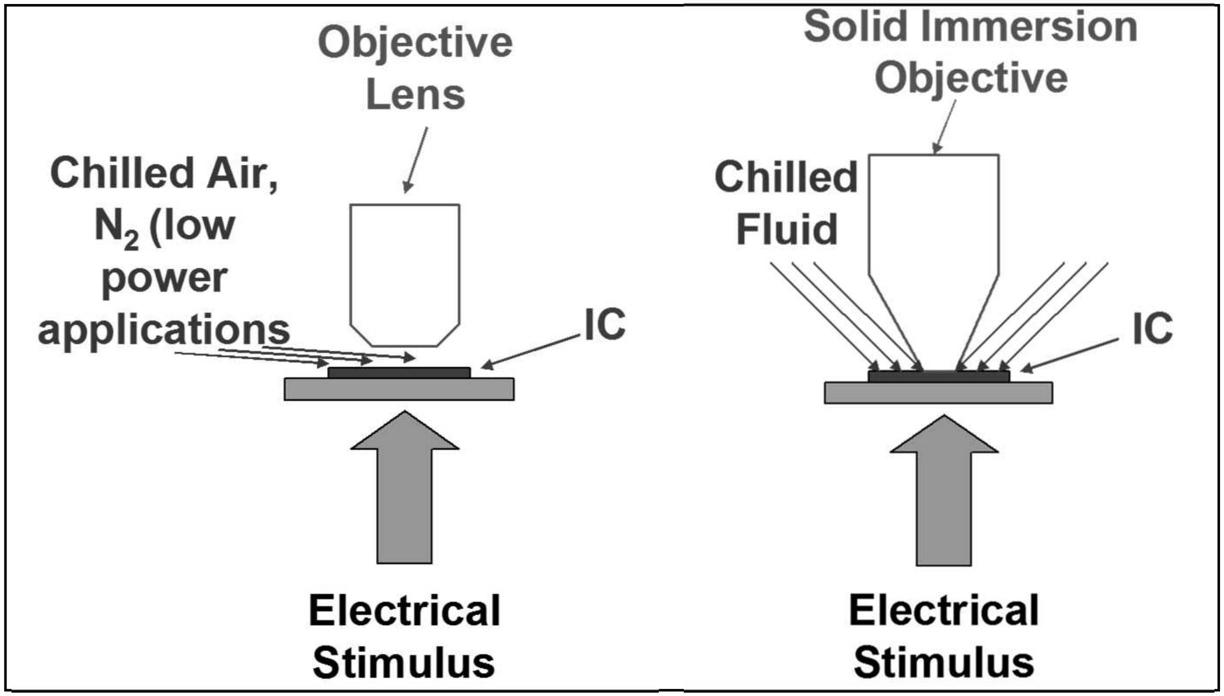
Image from Chipworks (www.chipworks.com)

Practical Issues

- Sample preparation
  - thinning/polishing/AR coating
- Fixturing/Device Stimulus
- Heat Dissipation

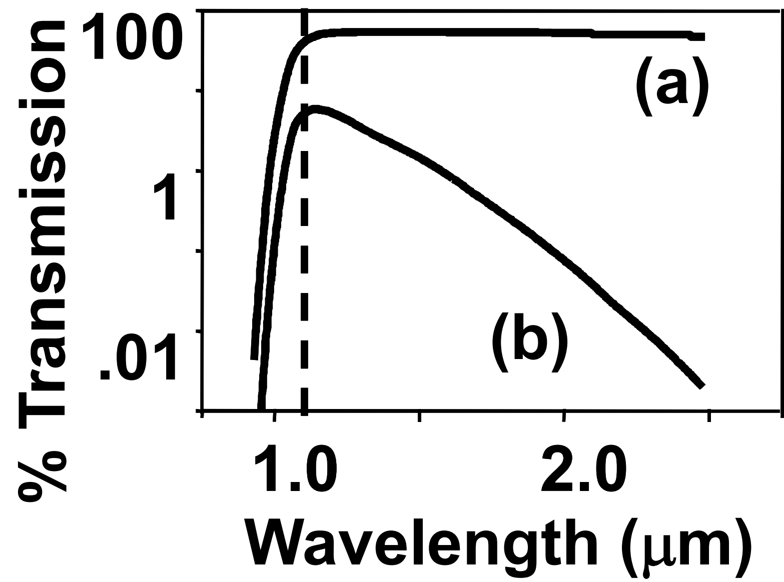


Polished die



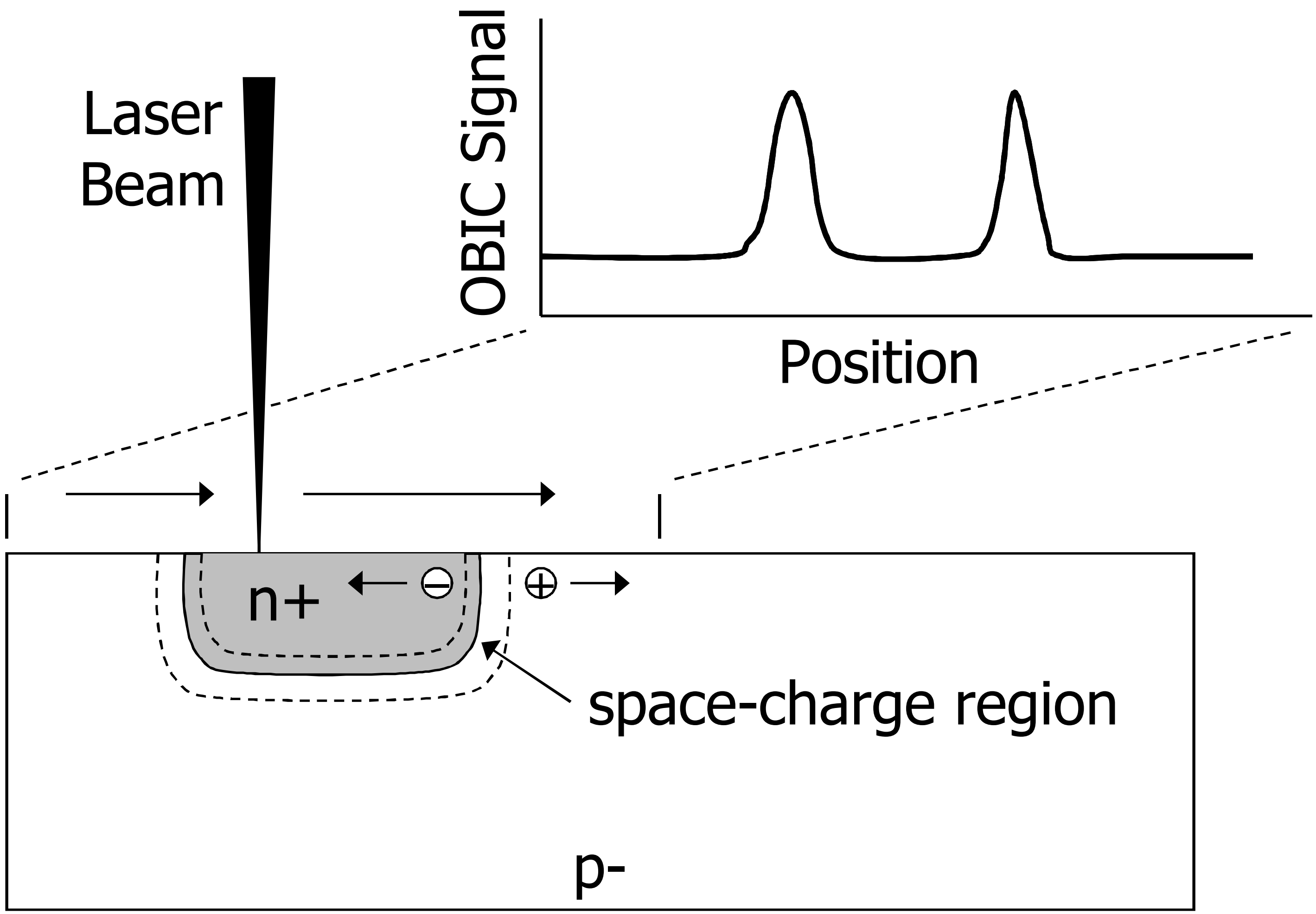
Laser/IC Interaction Physics

- **Transparency**
- **Two main interactions**
  - Photocurrent generation
    - λ < 1100 nm
  - Thermal gradients
    - λ > 1100 nm

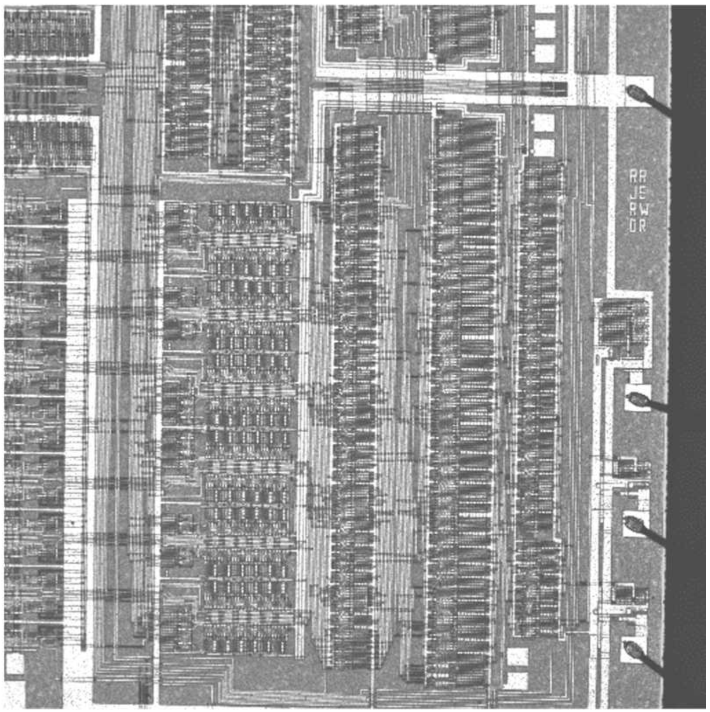


Dopant conc. x 10^{16} cm^3
(a) 1.5 , (b) 730

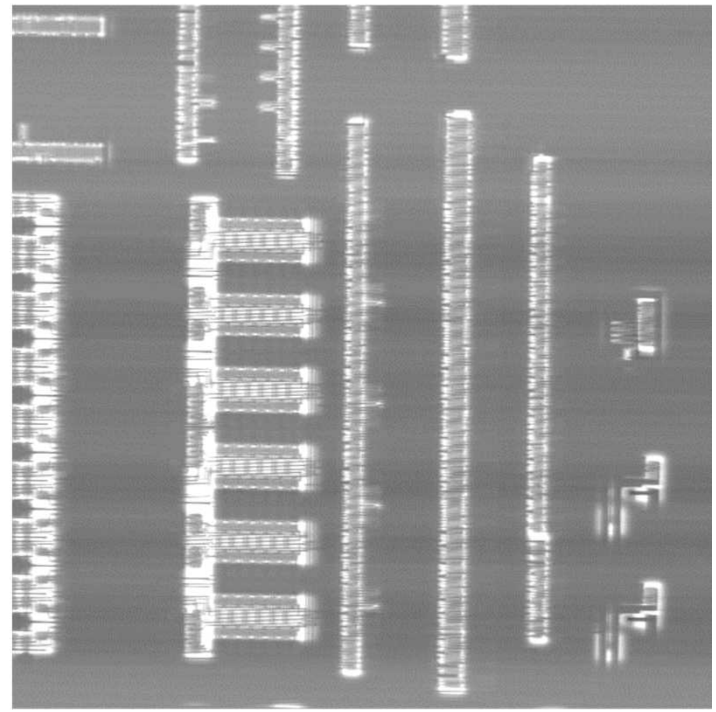
OBIC – Physics of Signal Generation



OBIC Image



Reflected Light Image



OBIC Image

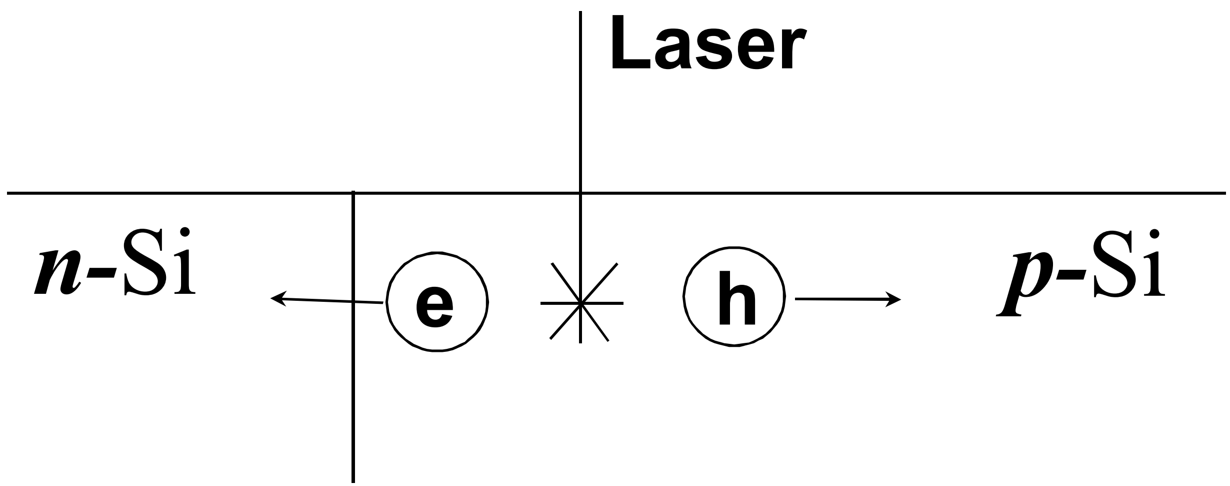
Light-Induced Voltage Alteration (LIVA)

- **Enables:**
  -quick localization of defective junctions and junctions connected to defects
  -imaging of transistor logic states (off or on)
- **Easily implemented on existing scanning optical microscopy (SOM) equipment**

Electron-hole pair (ehp) Generation from Photons

- Photons injected into Si with energies greater than the indirect Si bandgap (~1.1 eV) will produce ehps

- Nonrandom recombination of ehps will produce a "photocurrent" that affects IC operation



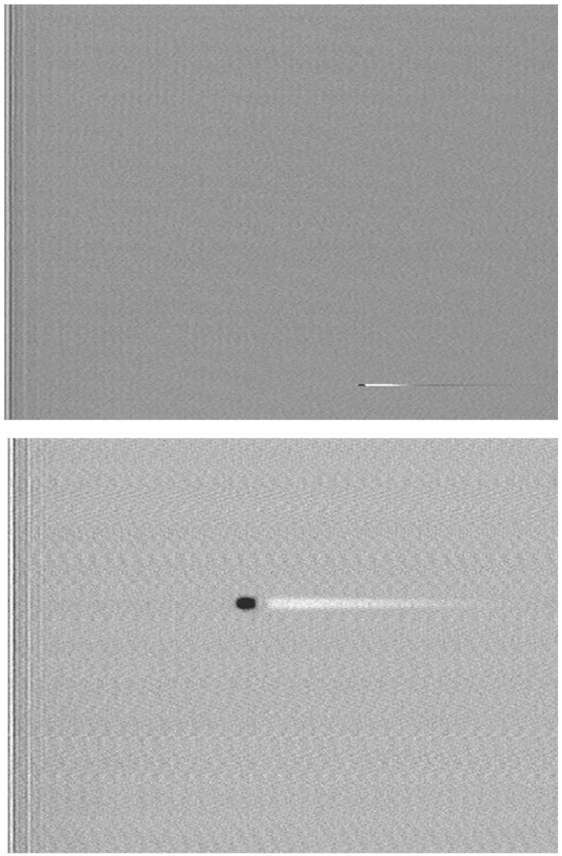
Light-Induced Voltage Alteration (LIVA)

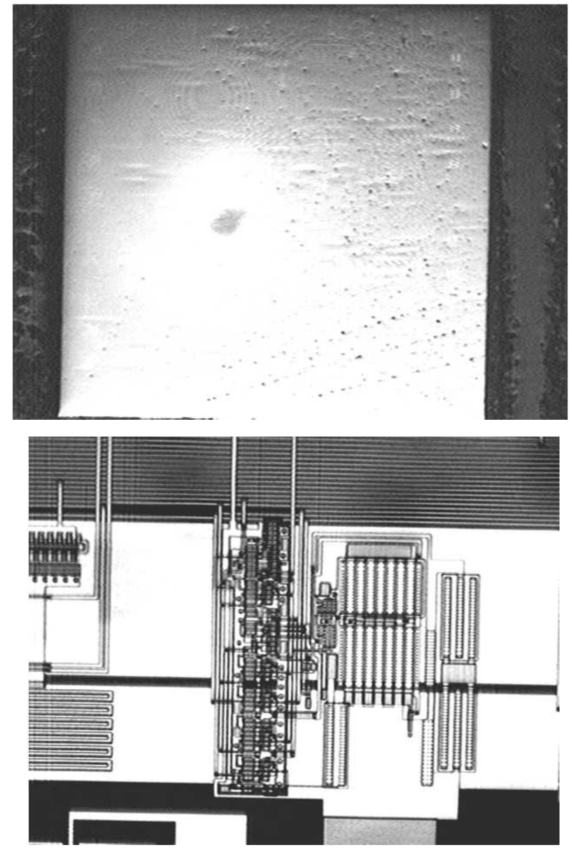
- <u>Information yielded</u>: SOM technique to localize diffusion related defects and transistor logic states from the IC front and backside
- <u>Physics behind use:</u> photons with energy greater than Si indirect bandgap make ehps (like EBIC), ehps affect IC operation, supply IC with a constant current source and monitor voltage changes with photon beam scan (like CIVA), diffusion defects and logic state voltage gradients alter IC power demands, proper IR laser makes backside analysis possible

Light-Induced Voltage Alteration (LIVA) con’t

- **<u>Implementation:</u>** need SOM with proper wavelength lasers, electrical connection, sample preparation for backside analysis, high power ICs and heavy doping decreases signal sensitivity
- **<u>IC damage:</u>** backside sample preparation must be done with care

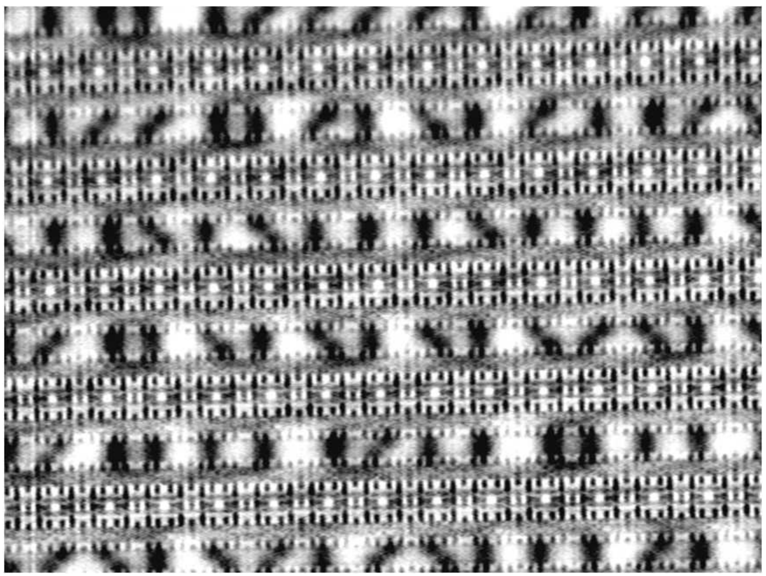
Backside LIVA Defect Imaging



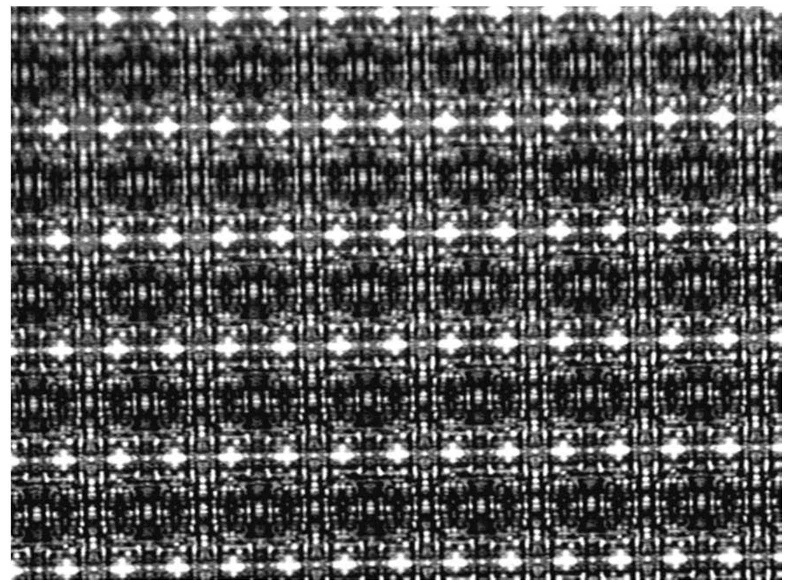


LIVA Images **Reflected Images**

Backside LIVA Logic State Imaging



LIVA Image



Reflected Light Image

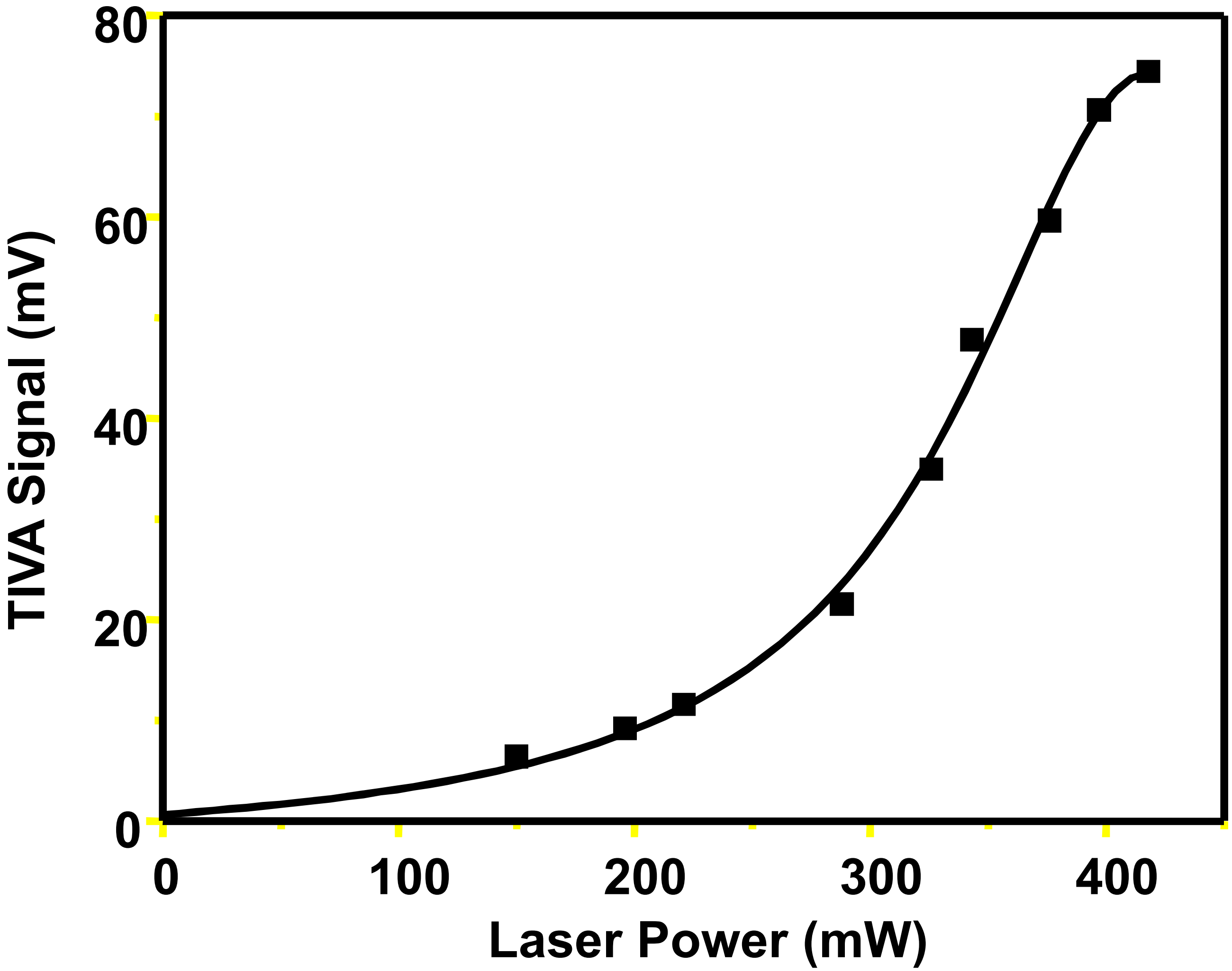
Thermally-Induced Voltage Alteration (TIVA) and Seebeck Effect Imaging (SEI)

- Information yielded: SOM technique to localize open interconnections and short sites from the IC front and backside
- Physics behind use: photons with energy less than Si indirect bandgap to generate heat, no ehps, shorts localized by resistance change (OBIRCH), opens located by Seebeck effect-thermal gradients produced voltage gradients, sensitivity increase using constant current biasing, (constant current OBIRCH proposed by Nikawa), non-linear signal gain with laser intensity

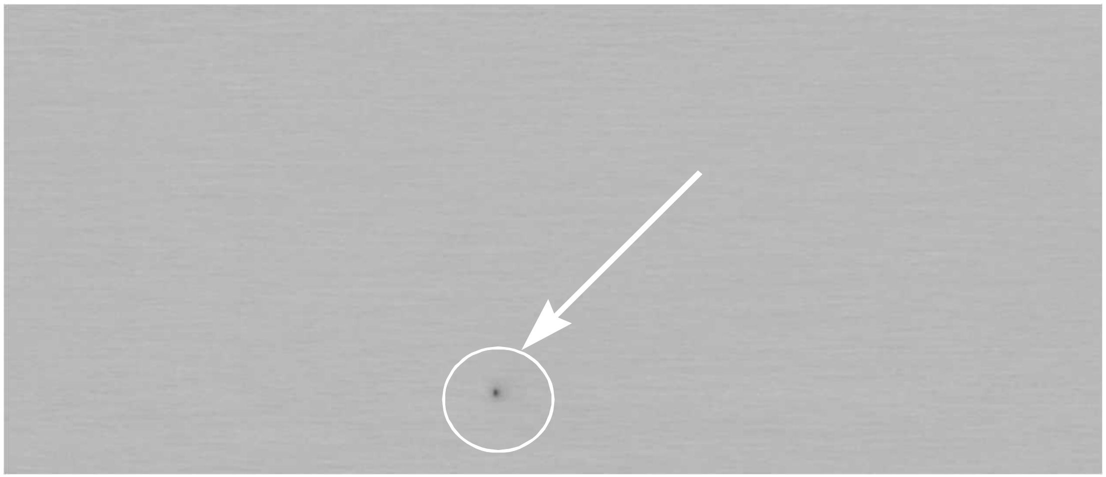
Thermally-Induced Voltage Alteration (TIVA) and Seebeck Effect Imaging (SEI)

- **Implementation:** same as LIVA, need proper laser λ, same limitations apply as with LIVA, SEI signals weaker than other "IVA's"
- **IC damage:** backside sample preparation must be done with care

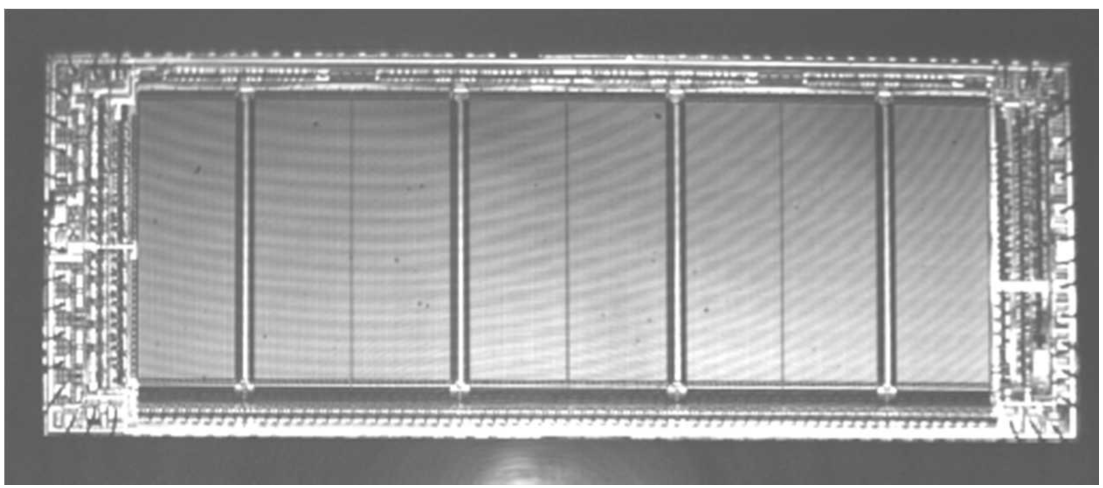
Non-Linear Response with Laser Power



Front Side TIVA Imaging Example, 1 MB SRAM

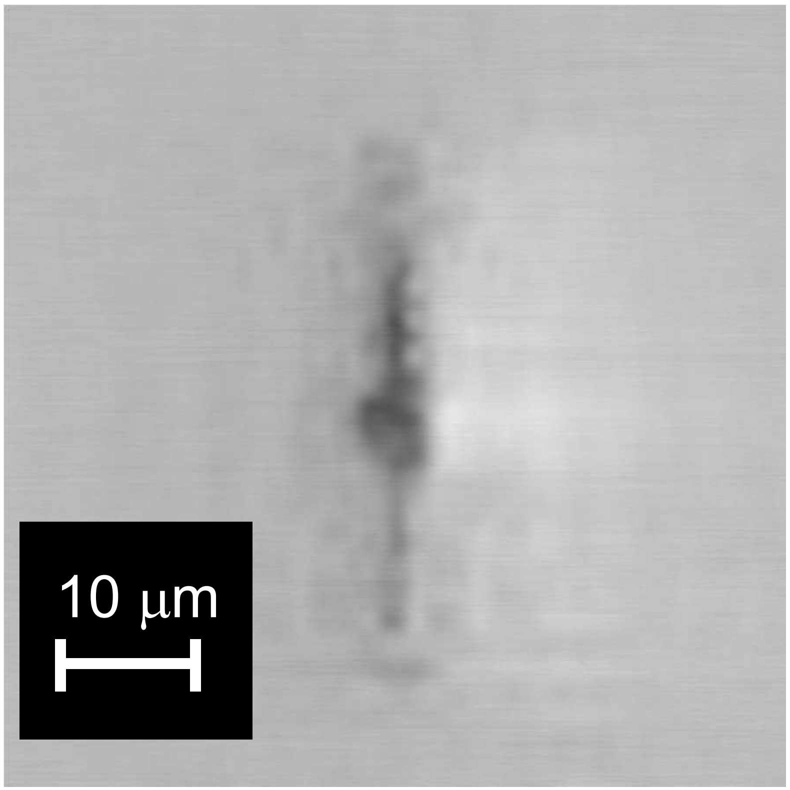


TIVA image

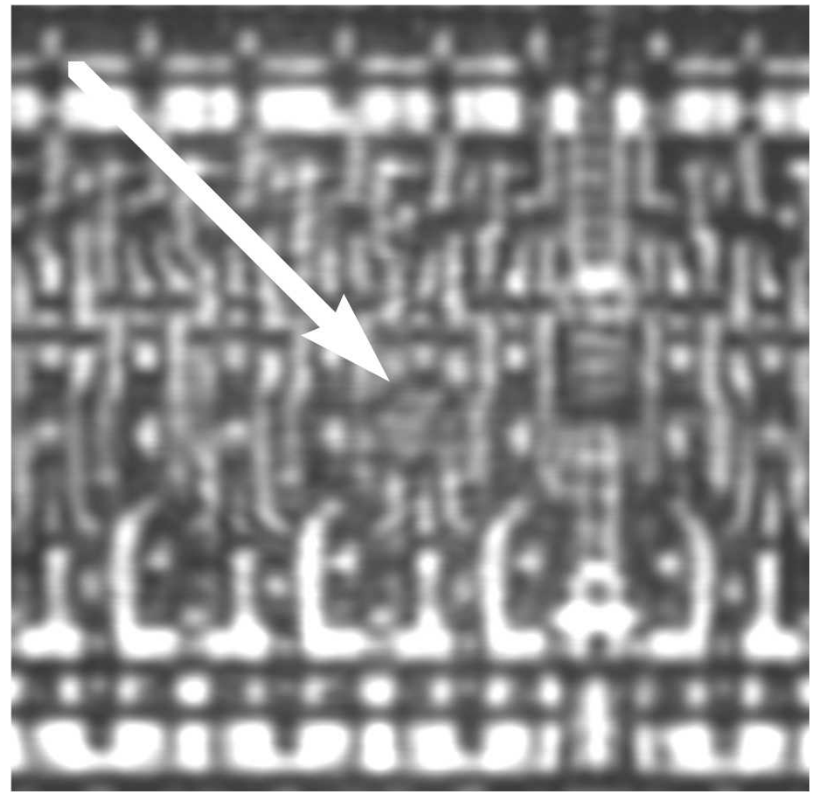


Reflected light image

Front Side TIVA Example - 1Mb SRAM Particle Short

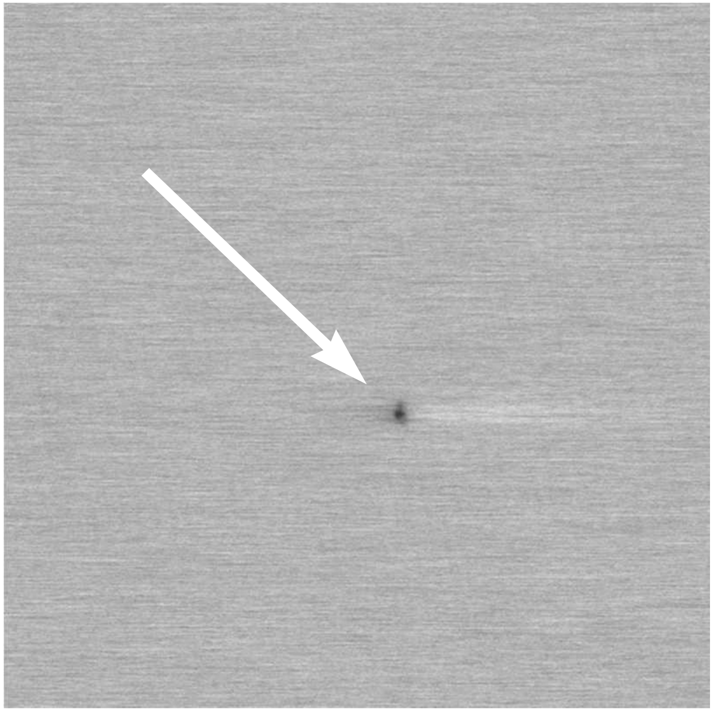


TIVA Image

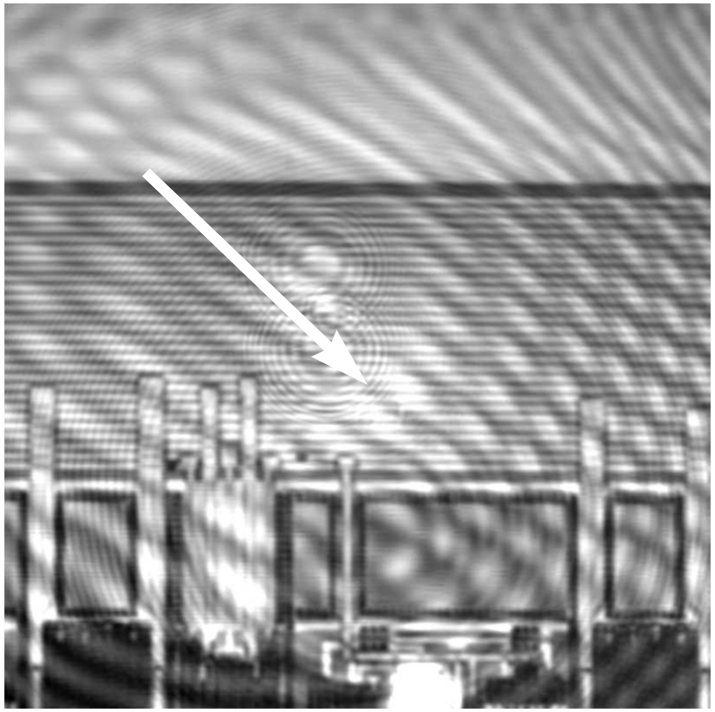


Reflected Image

Backside TIVA Example

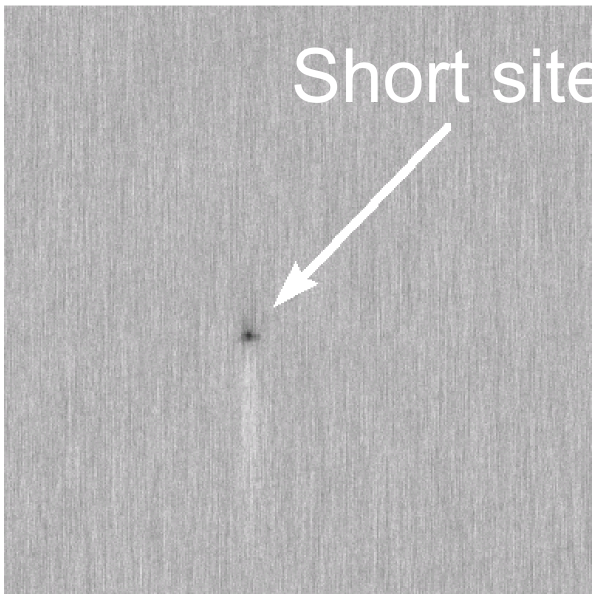


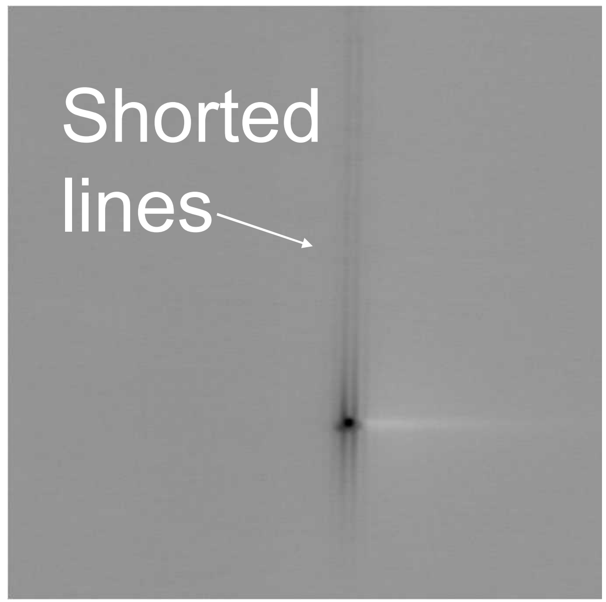
TIVA image

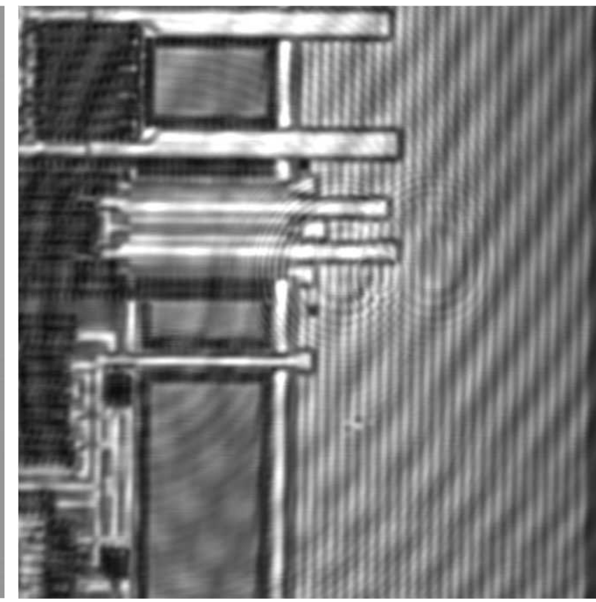


Reflected light image

TIVA Signal Improvement
1 Mbit SRAM (Backside)







Before
16 min acquisition

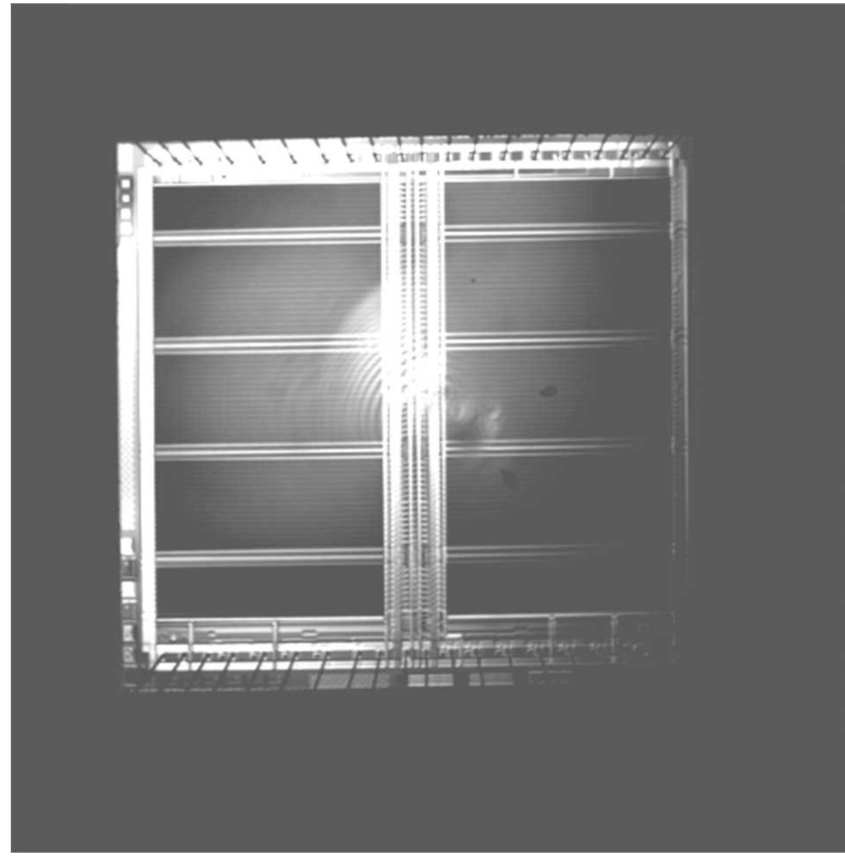
After
2 min acquisition

TIVA Images

Reflected image

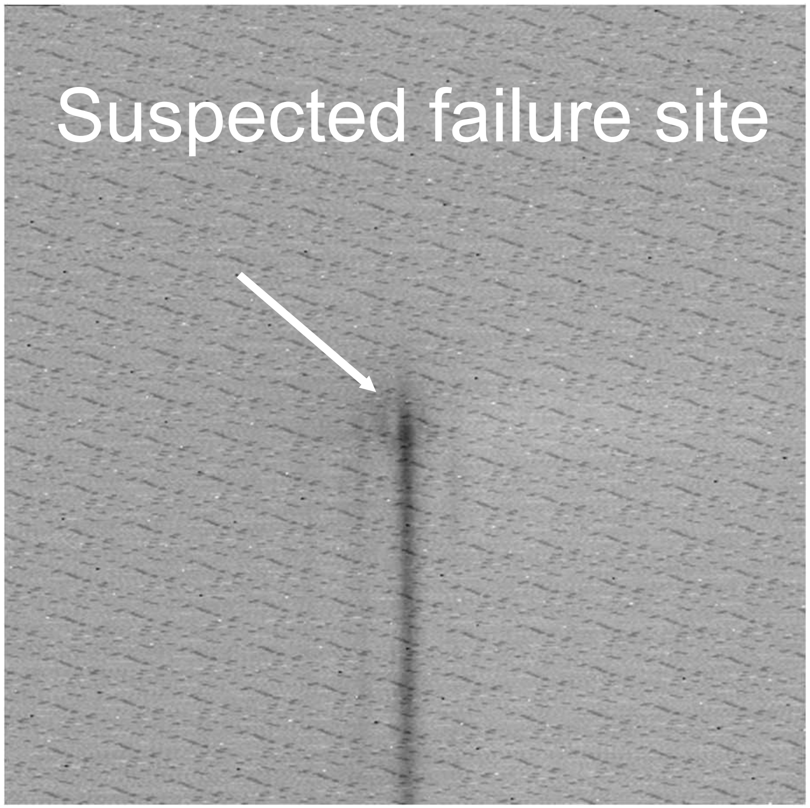
SRAM Short Failure
256k SRAM, 3LM, 0.5μm

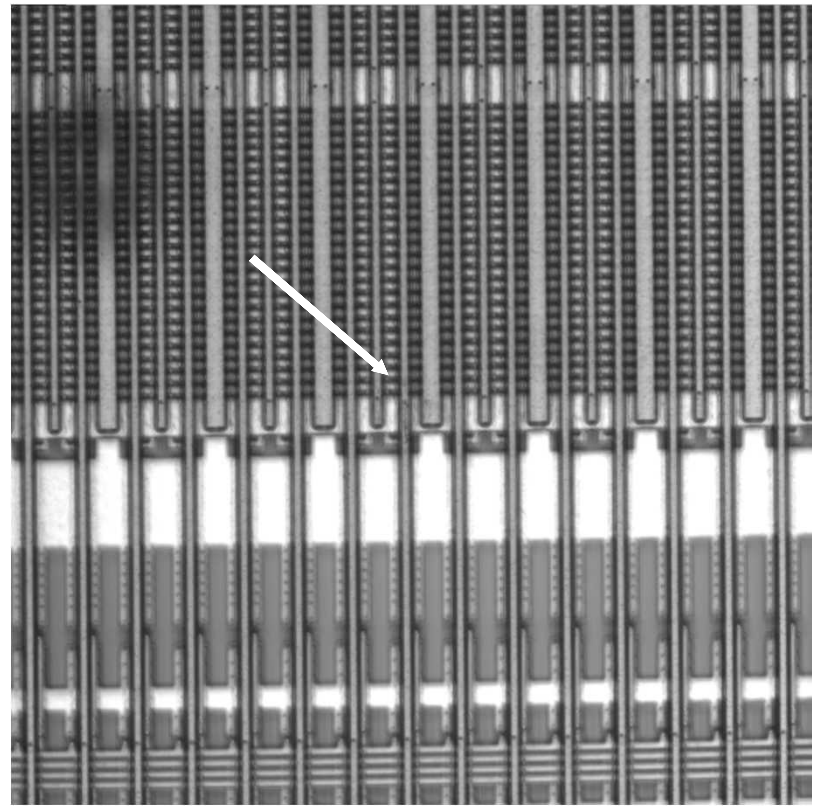
TIVA Image



Reflected image

SRAM Short Failure
High Magnification

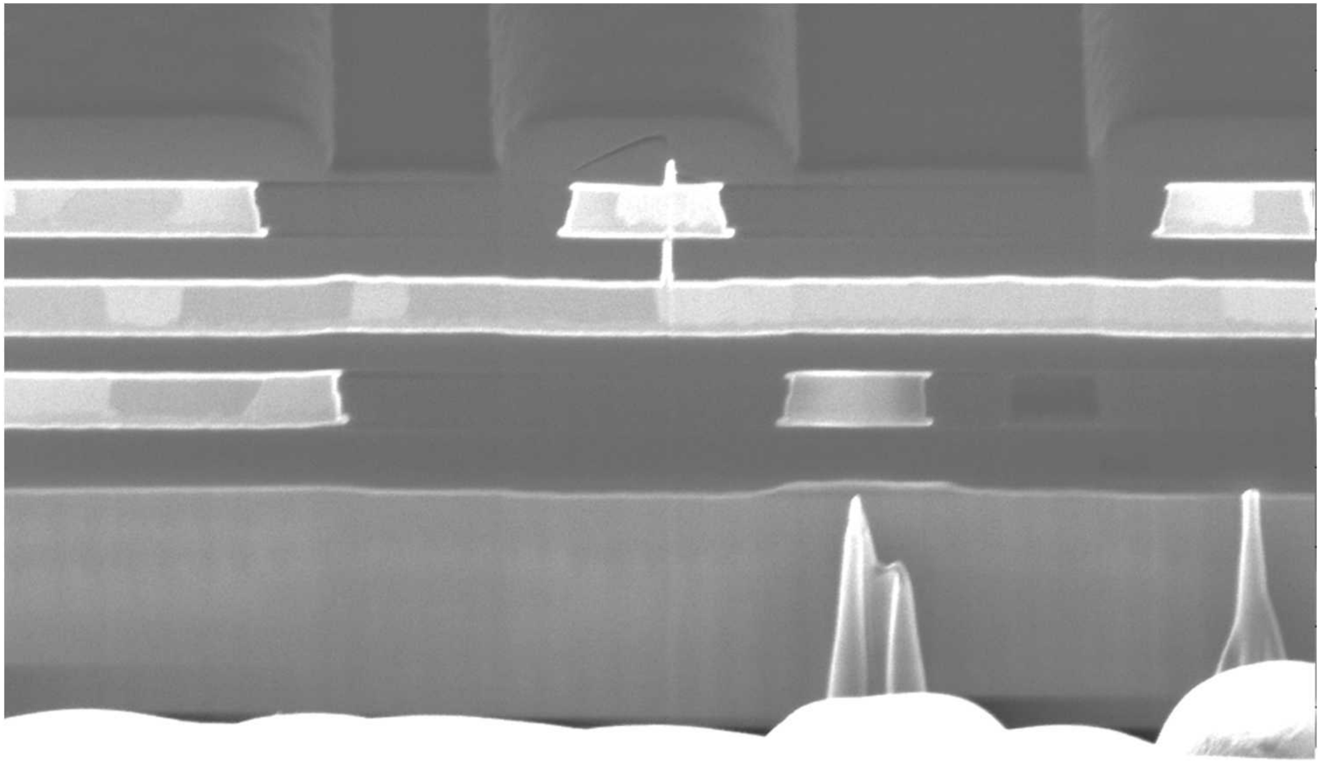




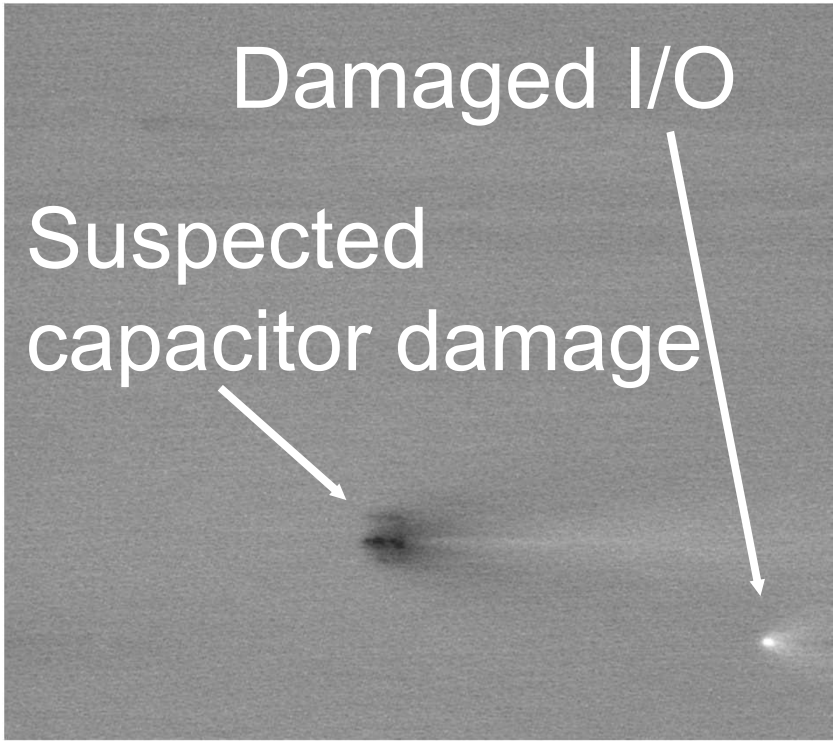
TIVA Image

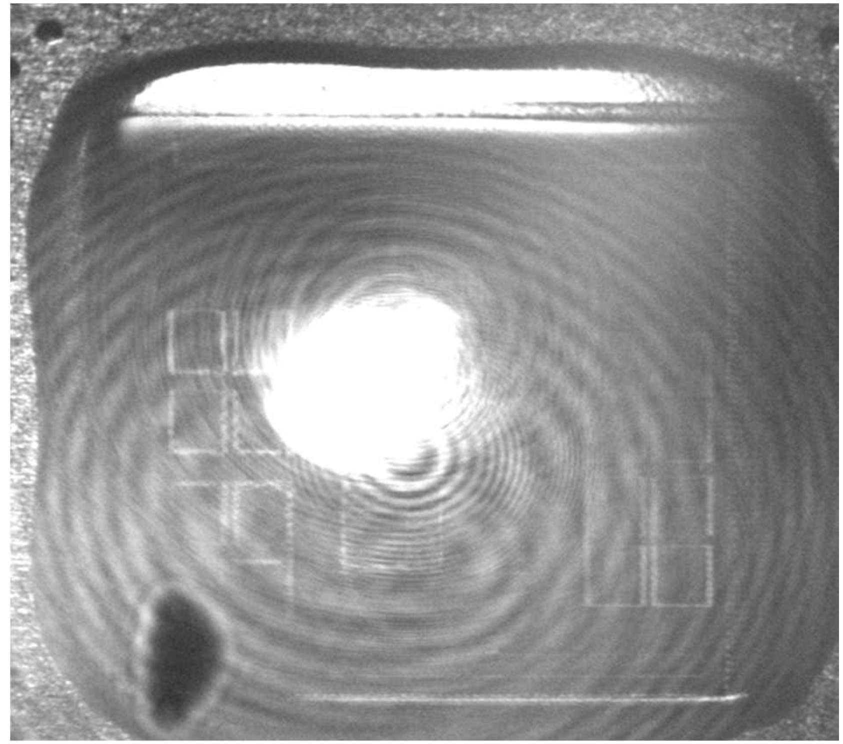
Reflected Image

Cross Section of SRAM Short Failure



TIVA Example - Microprocessor

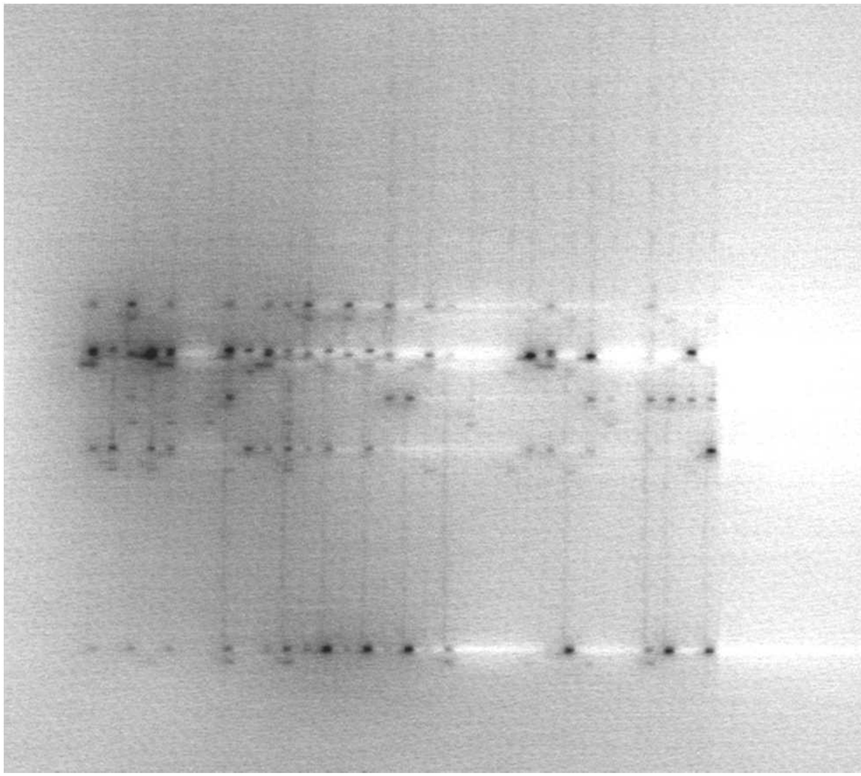




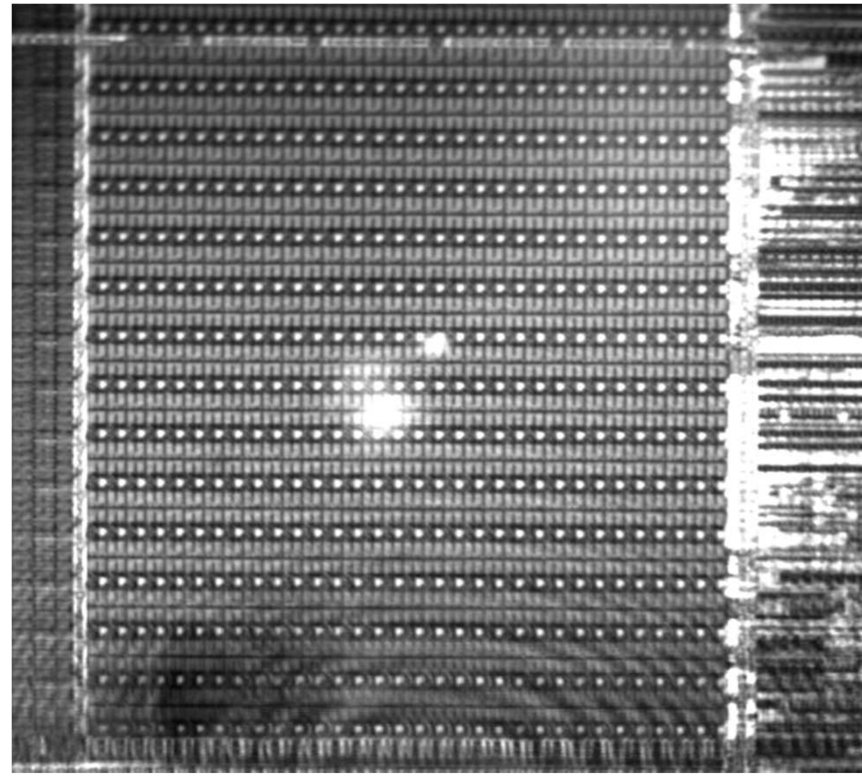
TIVA Image
(6LM 0.3 μm technology)

Reflected Image

TIVA Microprocessor Failure: Suspected Capacitor Damage



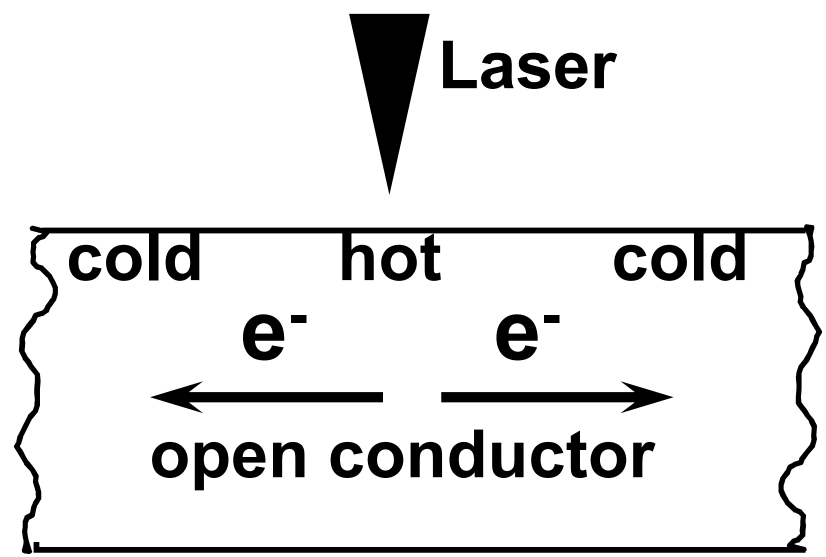
TIVA Image
(6LM 0.3 μm technology)



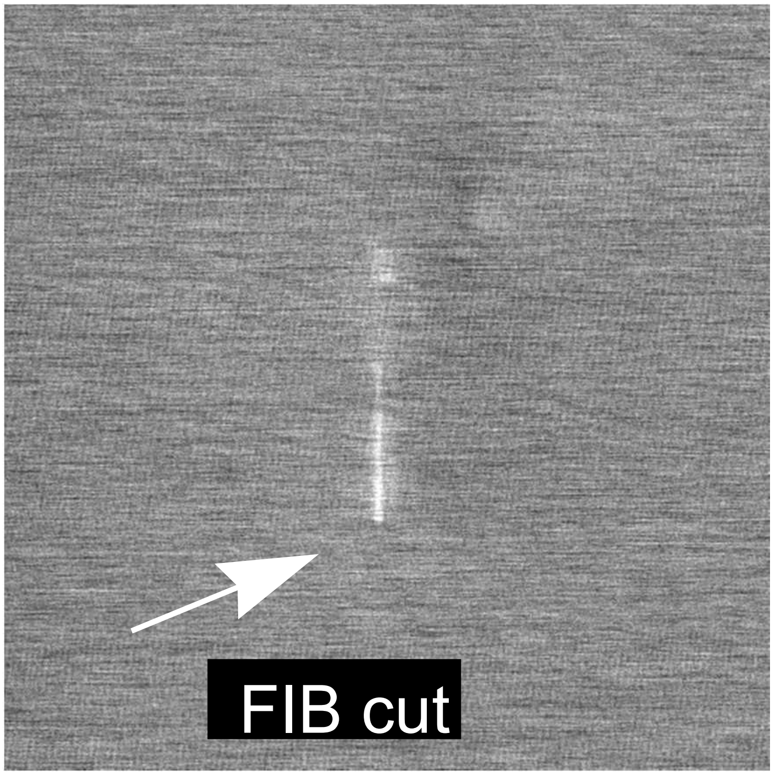
Reflected image

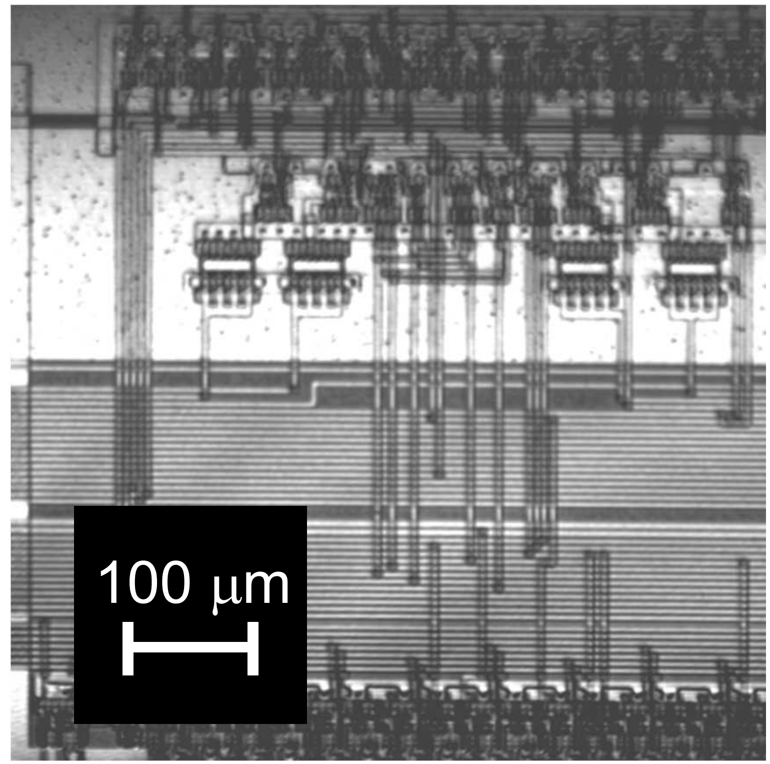
Thermal Gradient Techniques – Localizing opens

- Thermal gradients produce voltage gradients on open interconnections (Seebeck Effect)
  – typically μV/K for metals
- Localized heating using focused laser
  – used to detect voids in conductors
  – changes voltage of open conductors
  – alters IC power demands



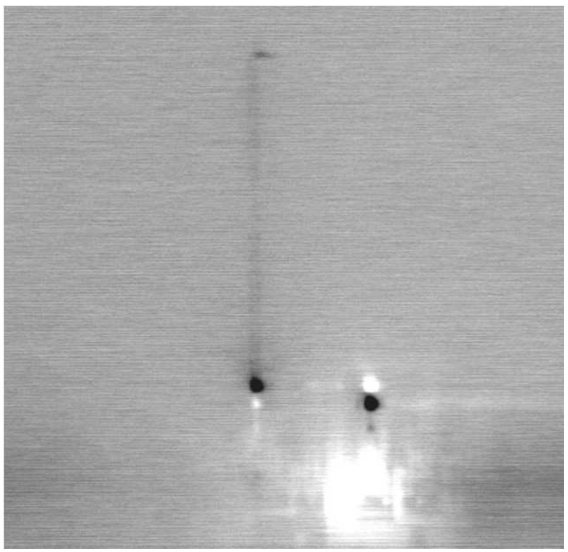
Front Side SEI Example - 80C51



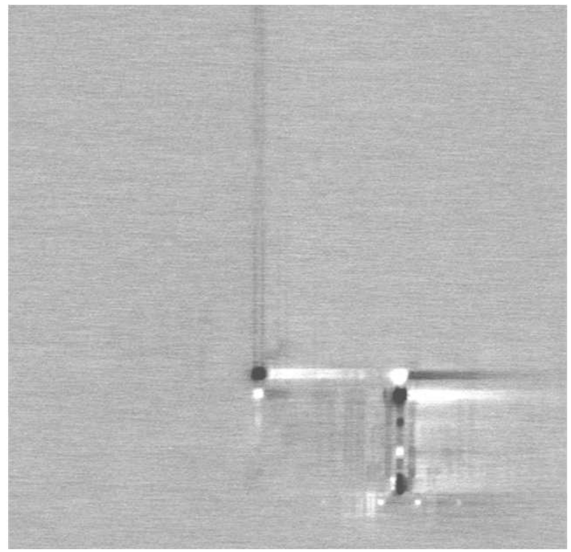


-signal visible *under* power bus

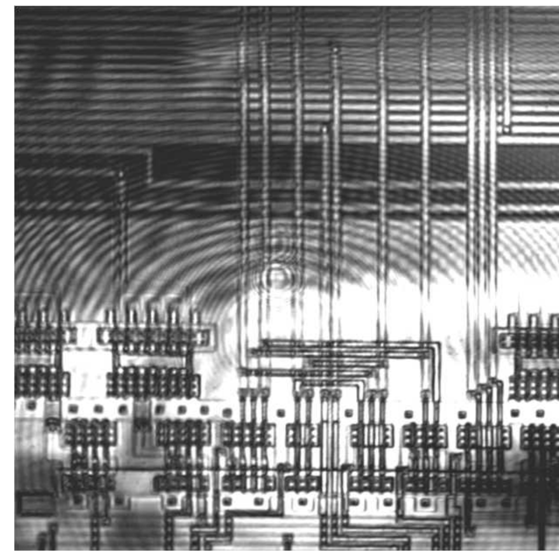
SEI Signal Improvement, 80C51 FIB Cut (Backside)



Before
45 min acquisition



After
2 min acquisition



SEI Images

Reflected image

Combining Testing and Laser Stimulus

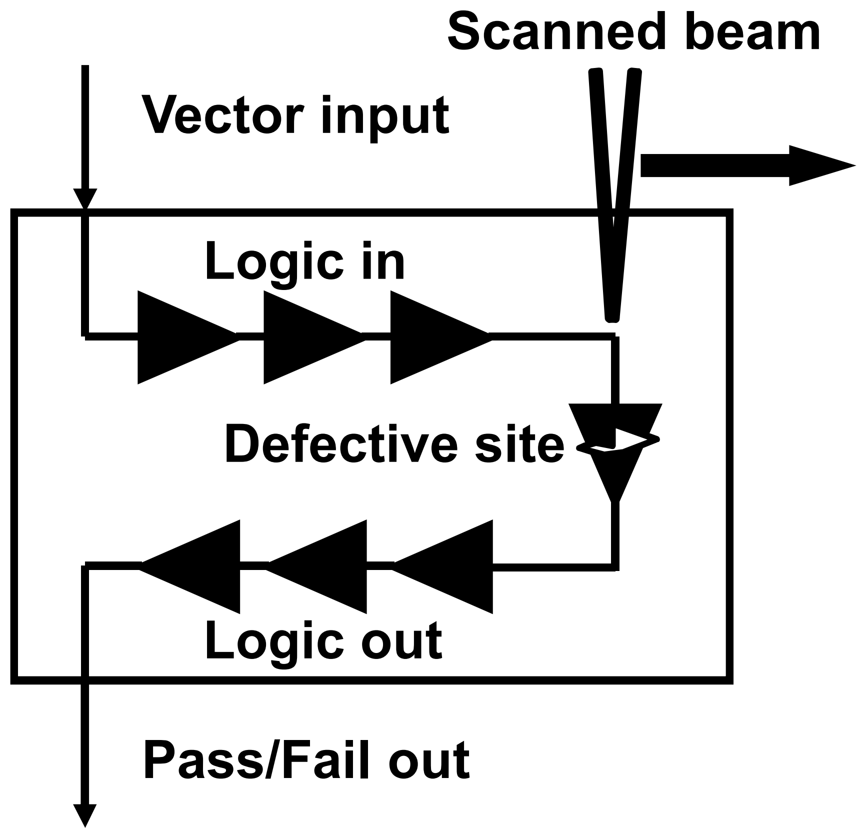
- **Monitor test results during laser scan**
  - image contrast shows pass/fail changes
  - alter conditions for detection (freq, V, T)
- **Soft Defect Localization (SDL)**
  - uses thermal gradients
  - identifies many types of "soft defects"
- **Laser Assisted Device Alteration (LADA)**
  - uses localized photocurrents
  - timing analysis

Soft Defects - Definition

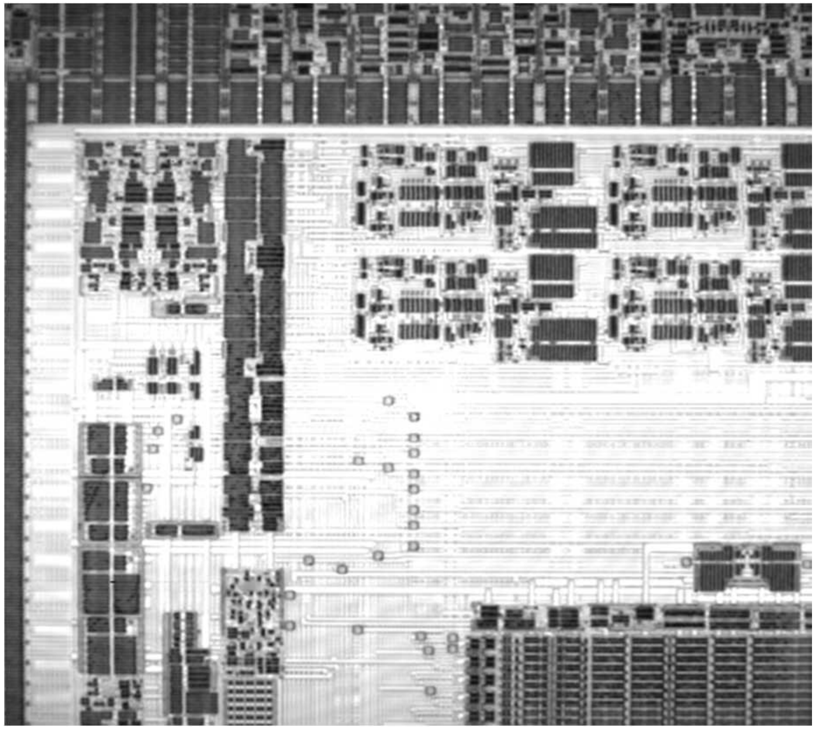
- Functional failure of an IC, but only under certain conditions
  - may be within or outside normal limits
  - will operate under specific conditions
  - most common variables are temperature, voltage, and frequency

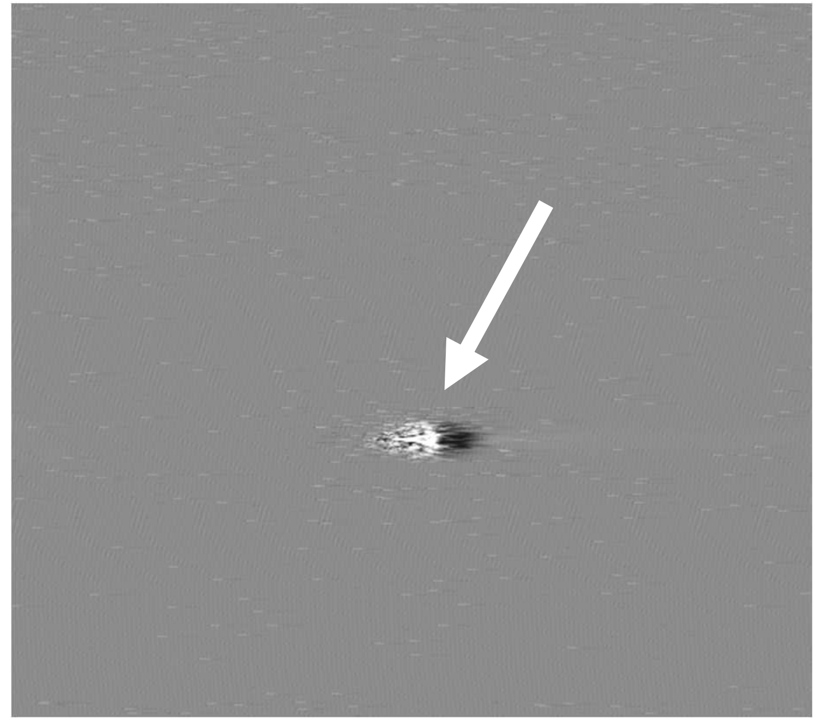
SDL Imaging

- Vector input to IC
- Laser heating changes pass/fail condition
- Pass/Fail condition used to produce image contrast
- 1.3 μm laser wavelength avoids photocurrents



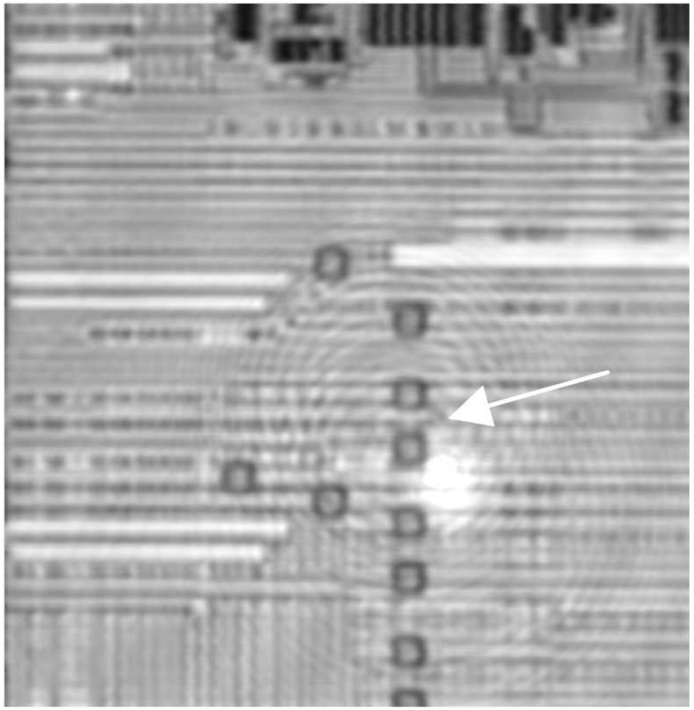
SDL Example-Resistive Interconnection



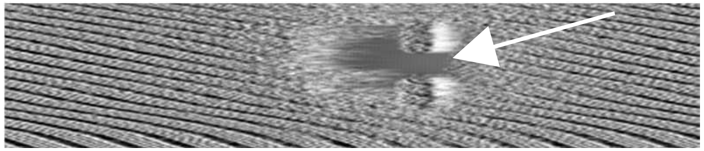


Fails at low temperature, high speed

Higher Magnification



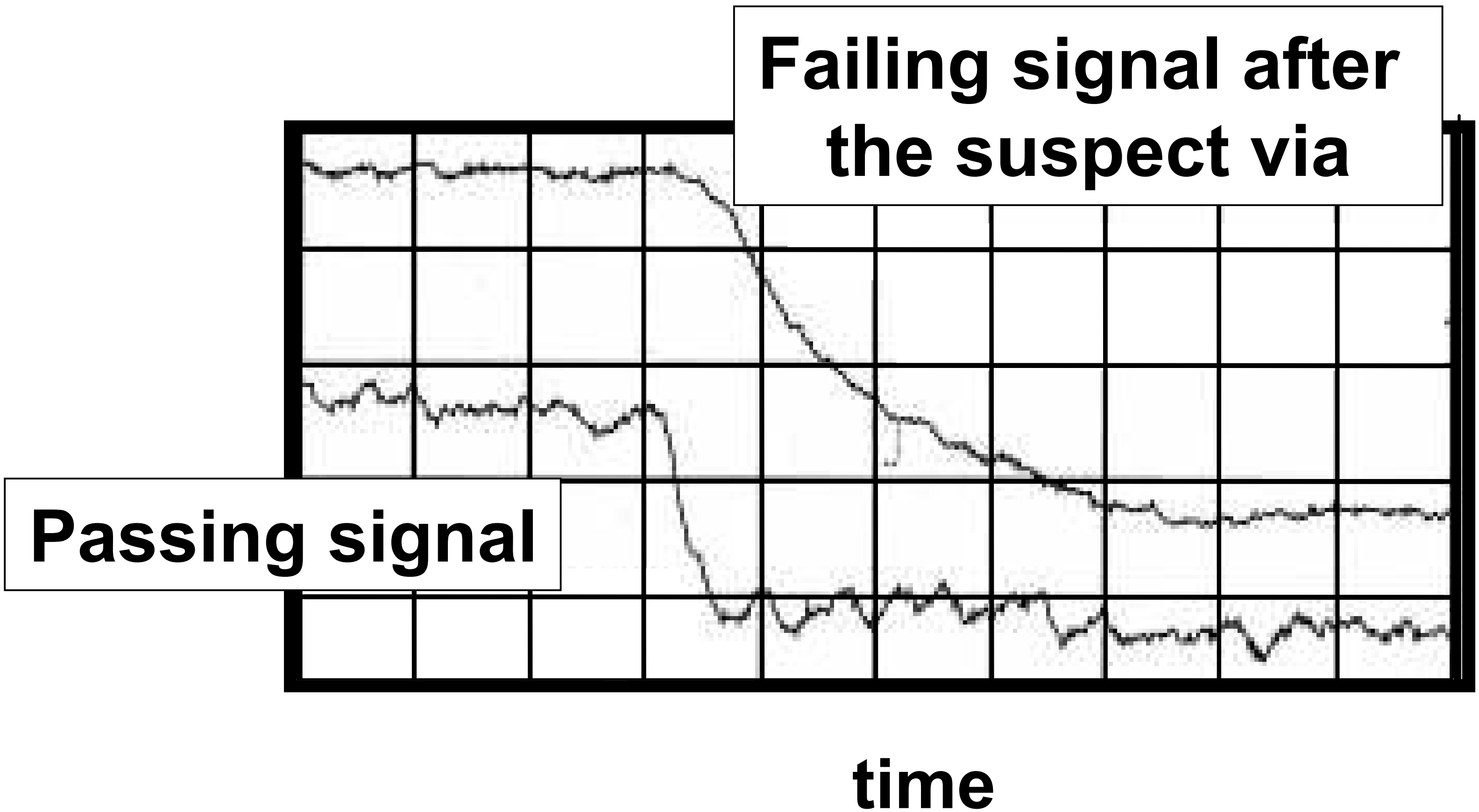
Backside reflected



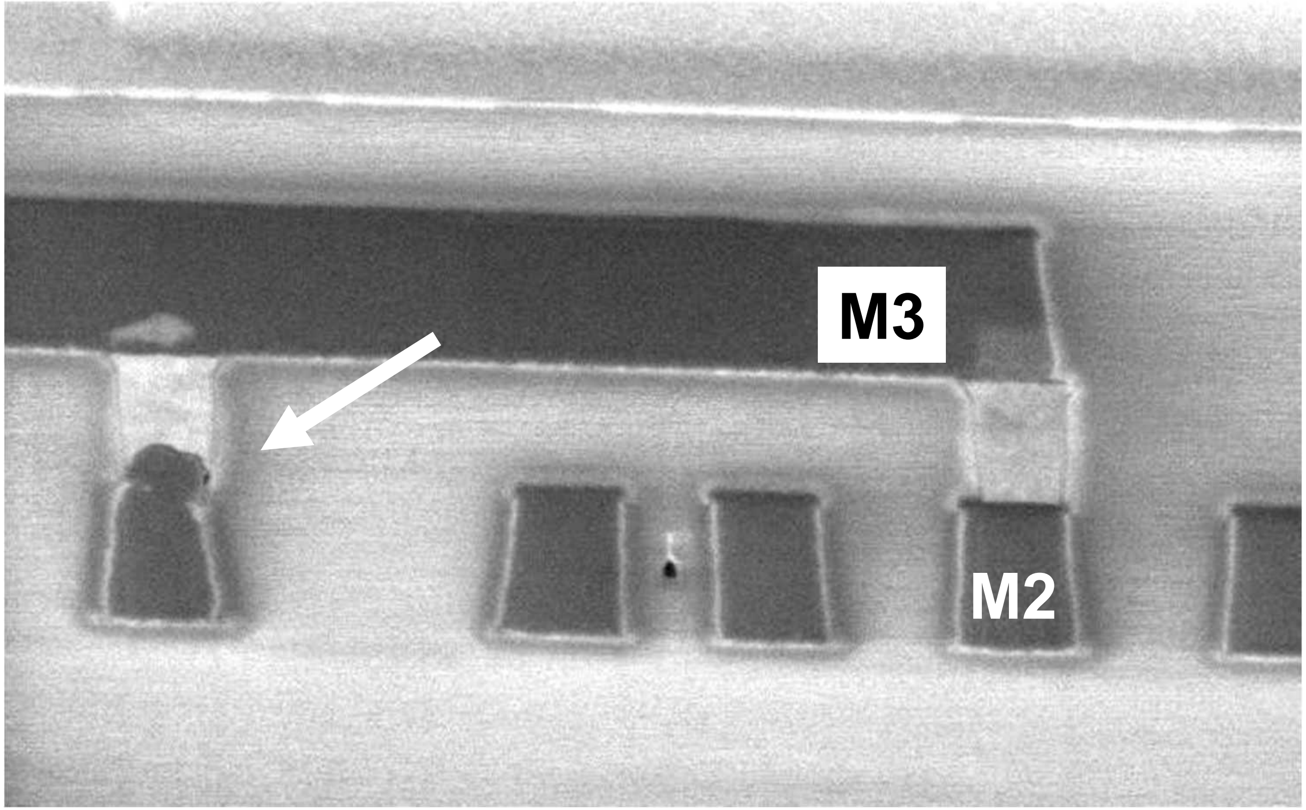
region of interest scan

SDL

Backside Waveforms



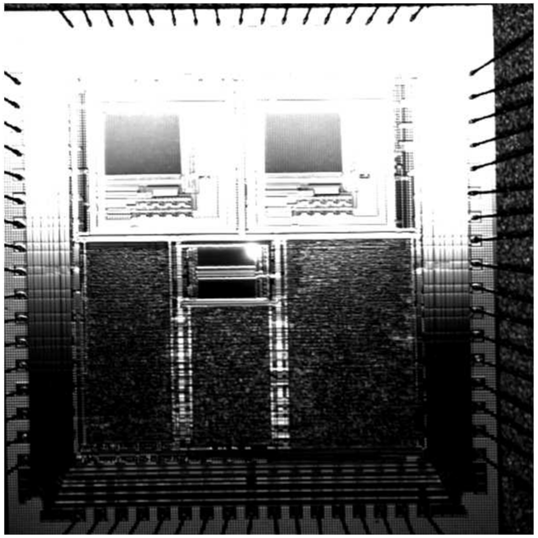
SDL Example-Resistive Interconnection



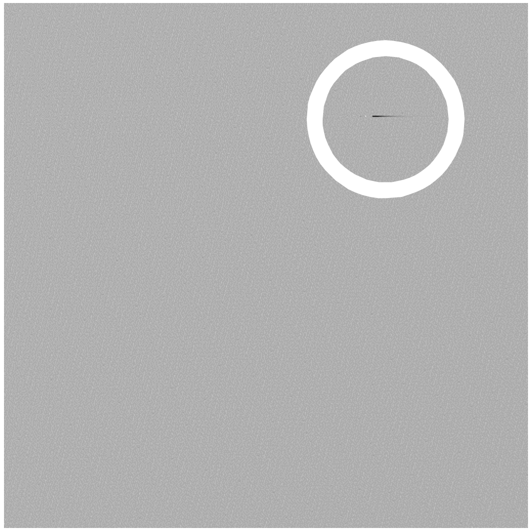
Al extrusions clearly seen on left via

SDL on an ASIC

- Examination of an ASIC from the front side
- Changes from failing to passing with laser heating
- SDL site identified as a parallel path in a race condition
- No physical defect found
- Modifications eliminated the race condition



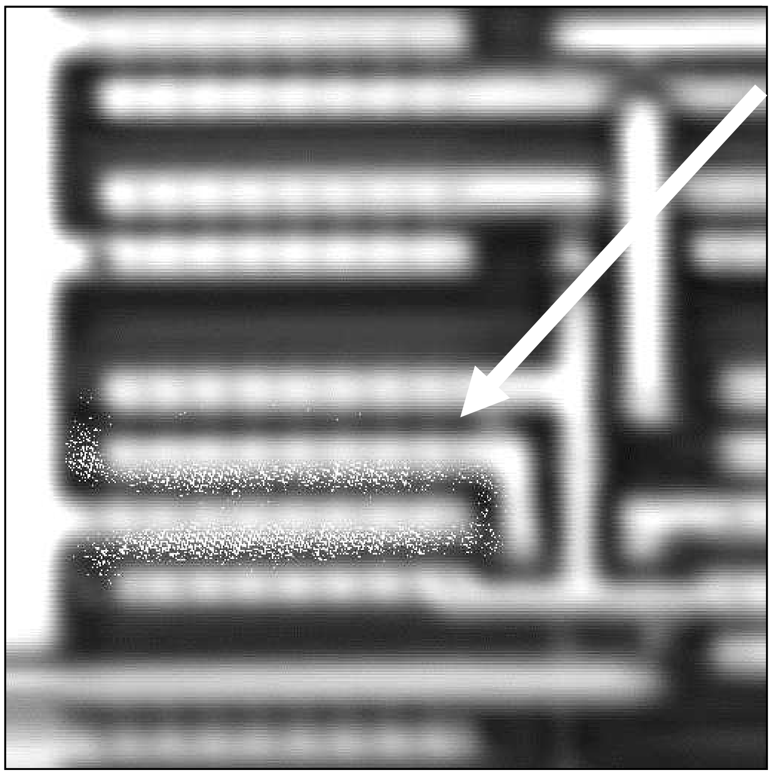
Front side reflected image



SDL Image

SDL on an ASIC

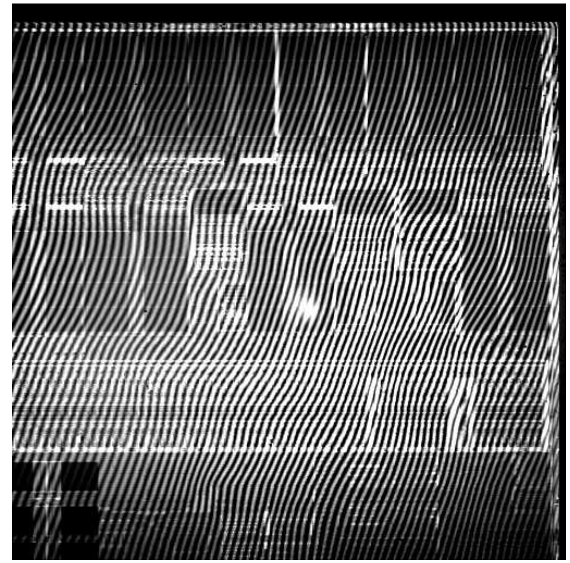
Higher Magnification SDL/Reflected image

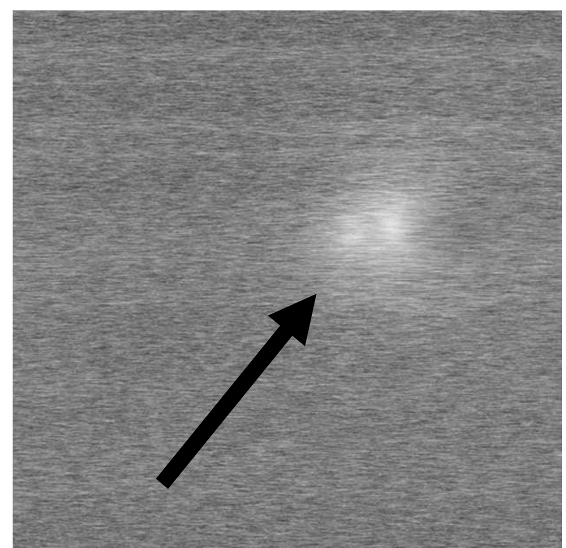


Transistor slowed down by laser heating

SDL on a Microprocessor

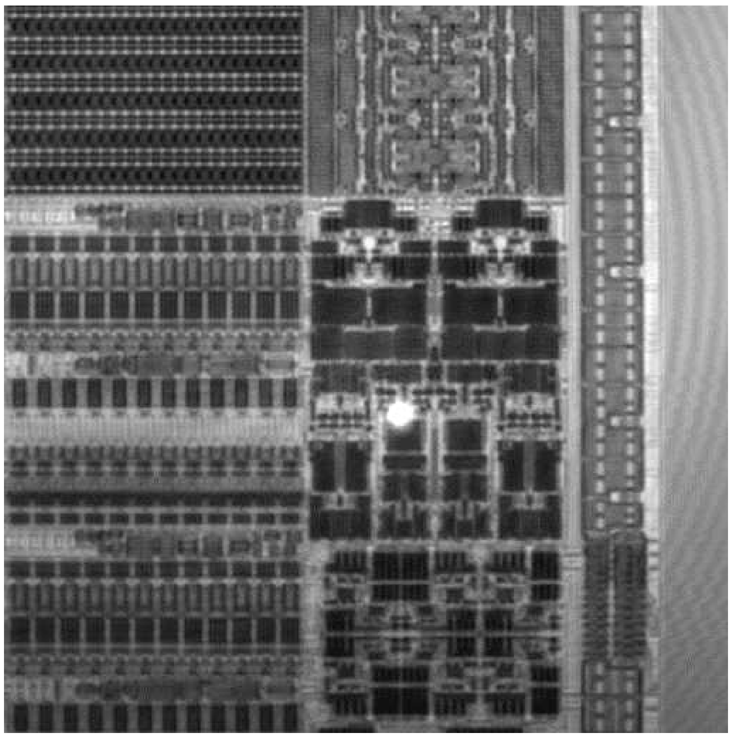
- Examination of a microprocessor from the backside
- Intermittently failing in control circuitry of instruction cache
- SDL site identified as a weak link in a serial path
- Improvements made the site less susceptible to process variations





SDL on a Microprocessor

Higher Magnification Images



Reflected light image

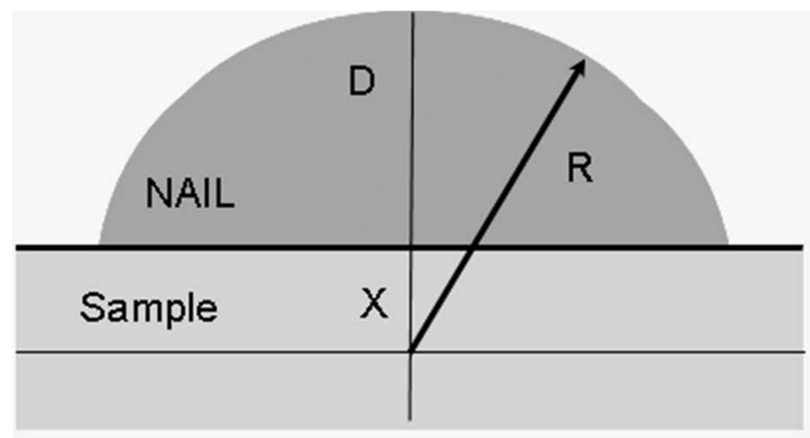
SDL image

Spatial Resolution Improvements – Solid Immersion Lenses (SILs)

- **Major limitation is conventional optical resolution**
- **SILs increase the numerical aperture (NA) and improve resolution**

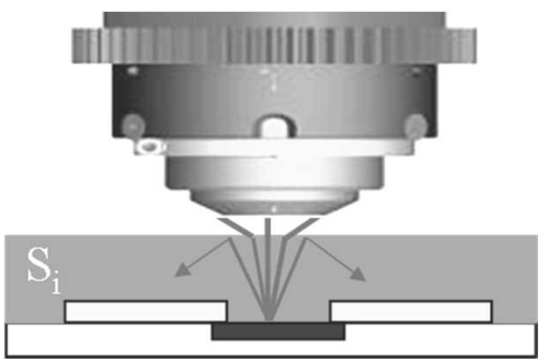
$$\text{Res.} = \frac{0.6\,\lambda}{NA}$$

- **Three types**
  - **surface NAIL (NA increasing lens)**
  - **machined hemisphere or FOSSIL (forming substrate into SIL)**
  - **machined diffraction or (Fresnel) lens**

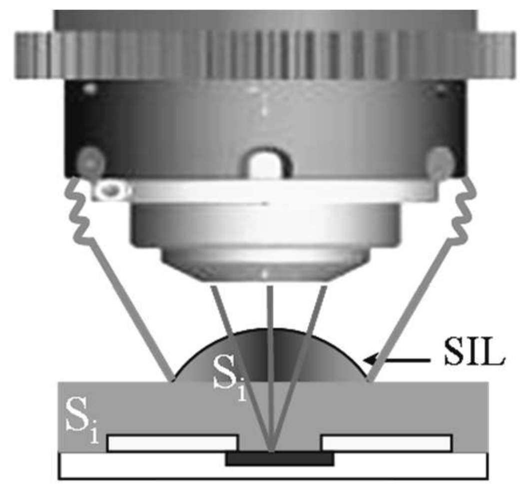


SIL Considerations

- **Motivation**
  - **< 0.13 μm devices difficult to see**
  - **Need improved light collection efficiency**
- **Engineering Challenges**
  - **Making mechanical contact without breaking DUT or SIL**
  - **Navigation**
  - **Cooling**



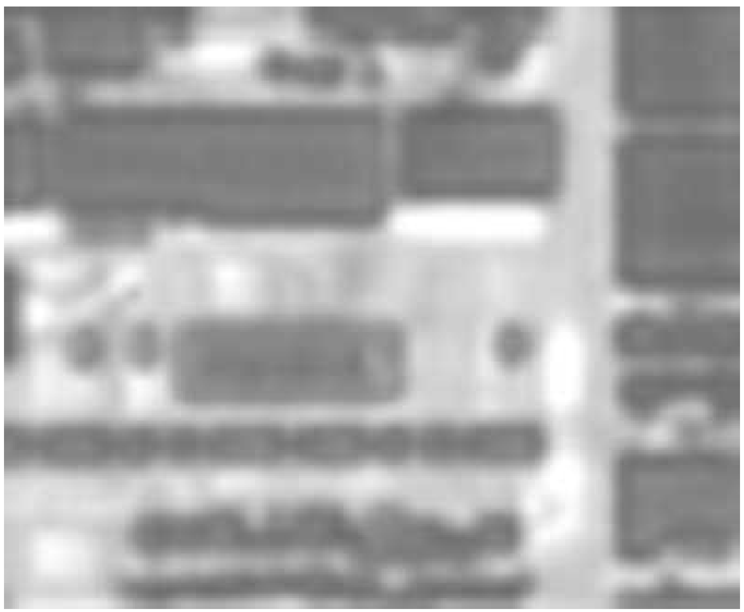
Air/S_i interface



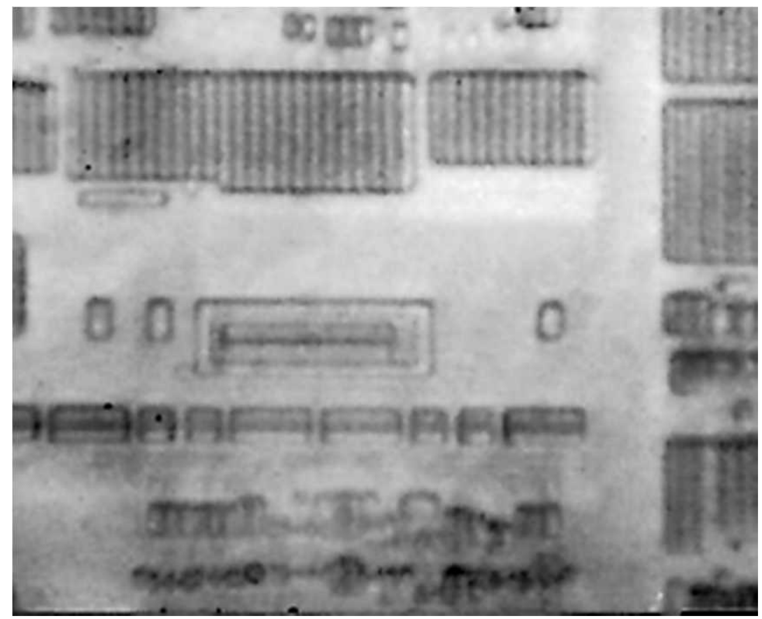
S_i/S_i + normal incident
Si/air interface

Optonics Solid Immersion Lens

- **3x better resolution than best air-coupled lens**
  - **0.25 μm for SIL vs. 0.7 μm for air-coupled lens**
- **5x faster acquisition time**



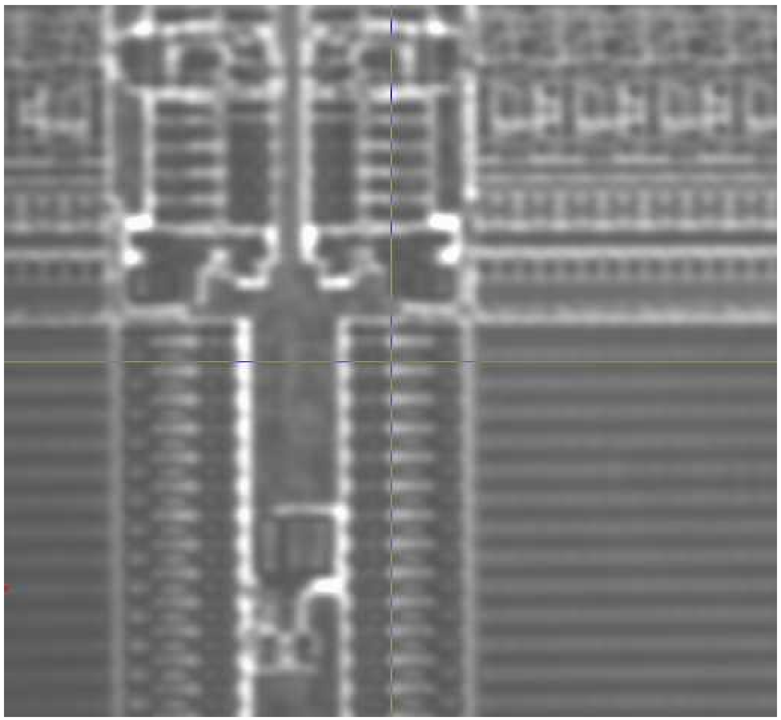
Air Lens, NA=0.85



SIL, NA=2.45

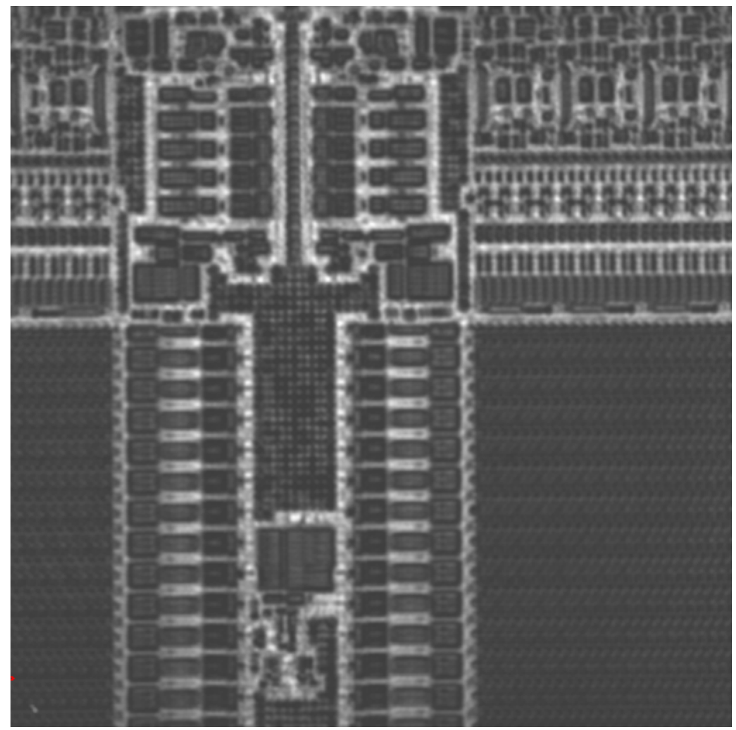
Image Comparison

High NA air coupled objective



0.7 NA Lieca 63X

High Resolution with SIL

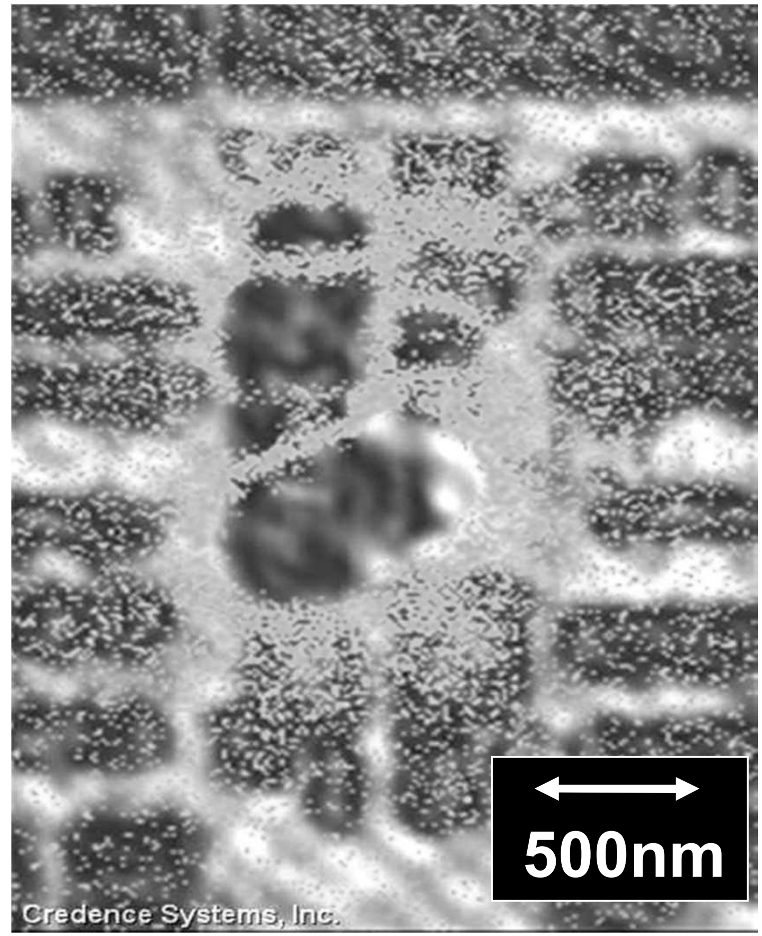


Checkpoint SIL, ~ NA 2.4
50 μm to 150 μm thick

Courtesy of Michael Jupina, Checkpoint Technologies, LLC

Thermal Stimulus Using a SIL on 90 nm Sample

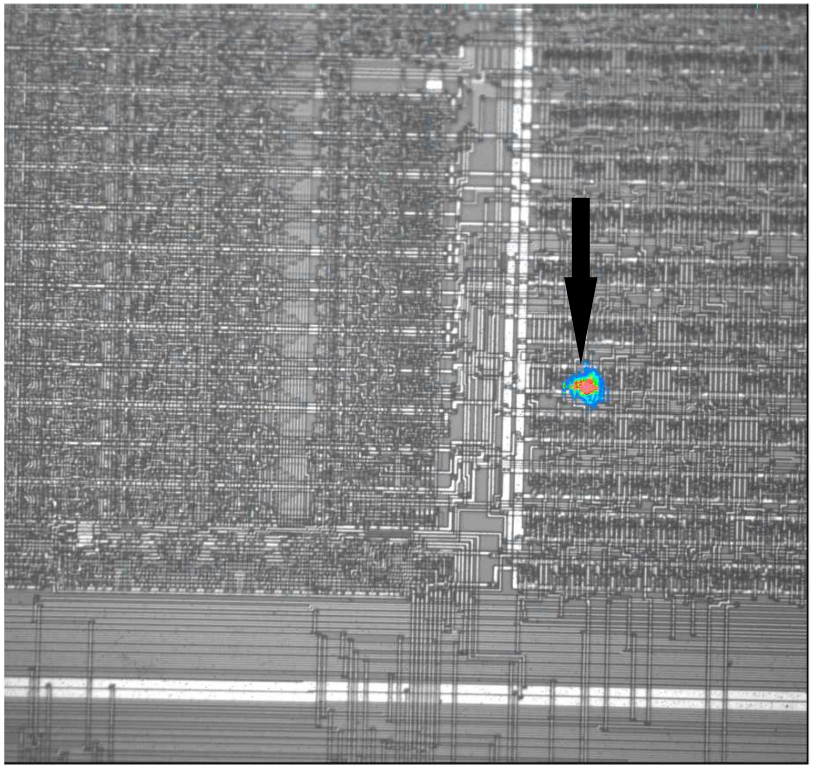
- **Better than 200 nm resolution demonstrated**
  - **220X SIL**
  - **Grey signal indicates a passing condition**



Courtesy of Steven Kasapi, Credence Systems, Inc.

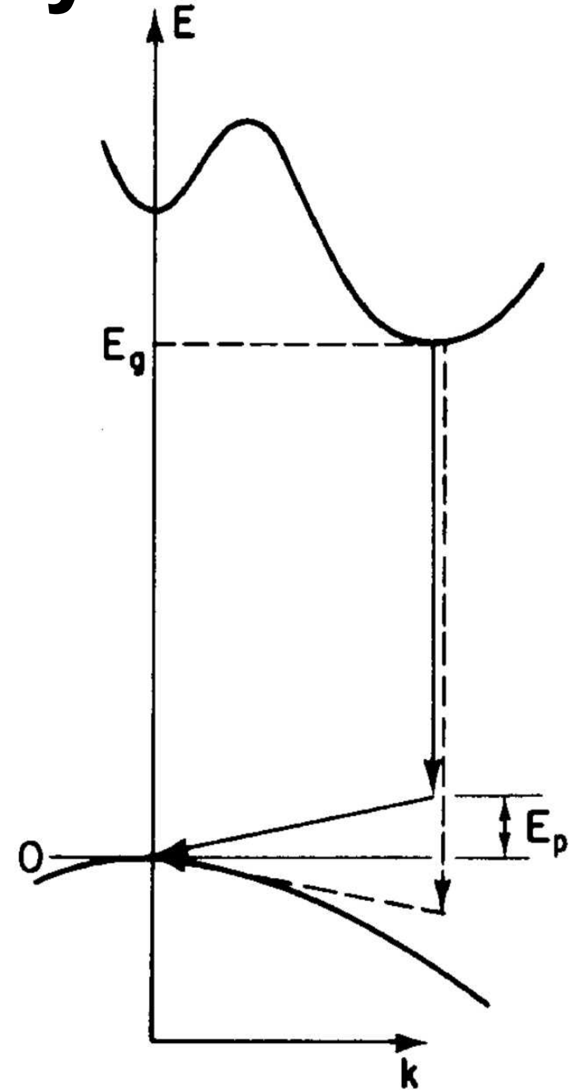
Light Emission-Based Analysis

– **NIR light emission**
– **PICA - IBM**



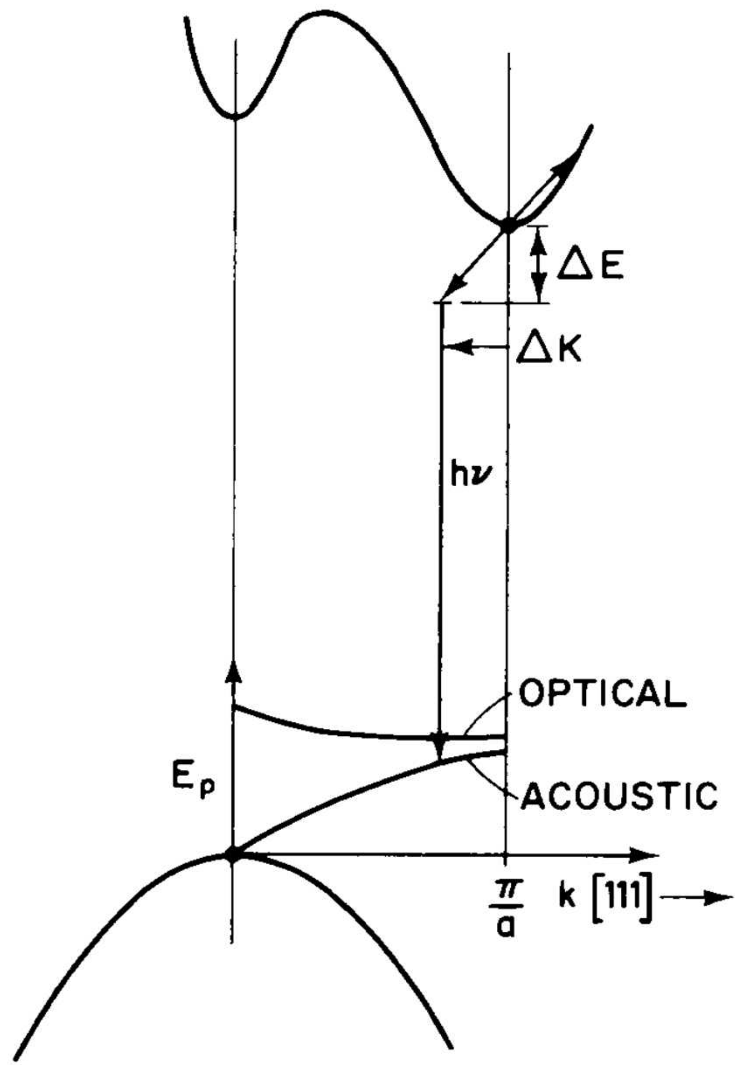
Emission Theory

- **Recombination can be intraband or interband**
- **Momentum must be conserved - phonon emission likely**
- **E_G = 1.11 eV or (1.12 μm) at 300 K**



Emission Theory

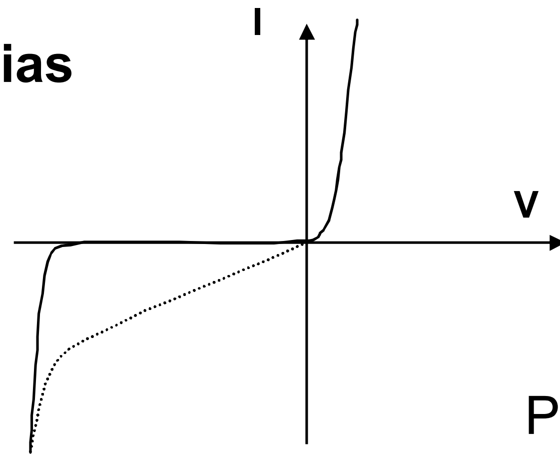
- **Only chance for short wavelength emission is from hot carriers**
- **$dE = k_B T_e$**
- **Possible under high field situations**
- **Visible: 390 - 770 nm**
- **NIR: 770 - 1500 nm**



Two Basic Mechanisms of Photoemission in IC

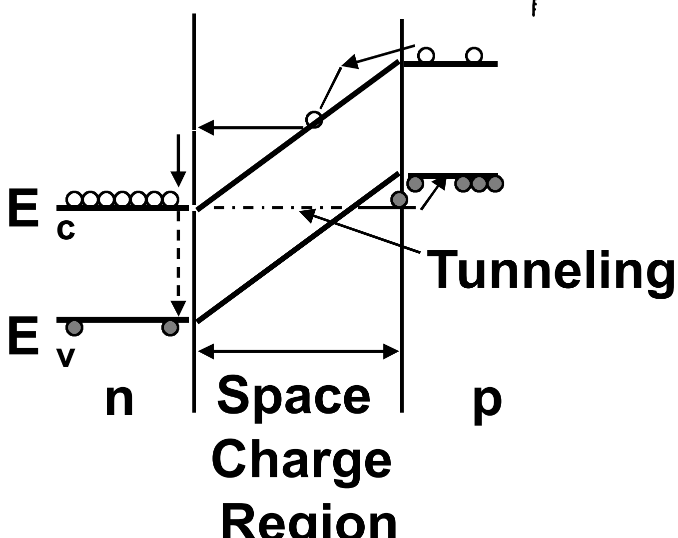
Junction: Reverse Bias

Forward Bias

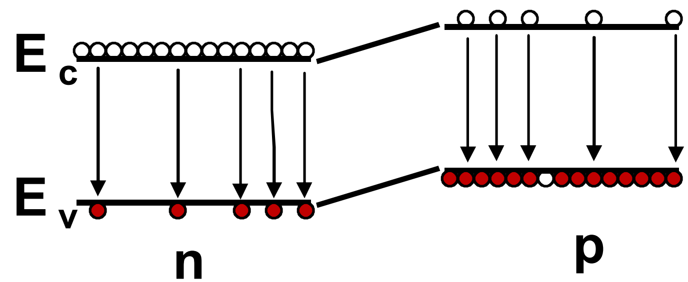


Scattering of Field Accelerated Carriers (+ Recombination)

Minority Carrier Injection



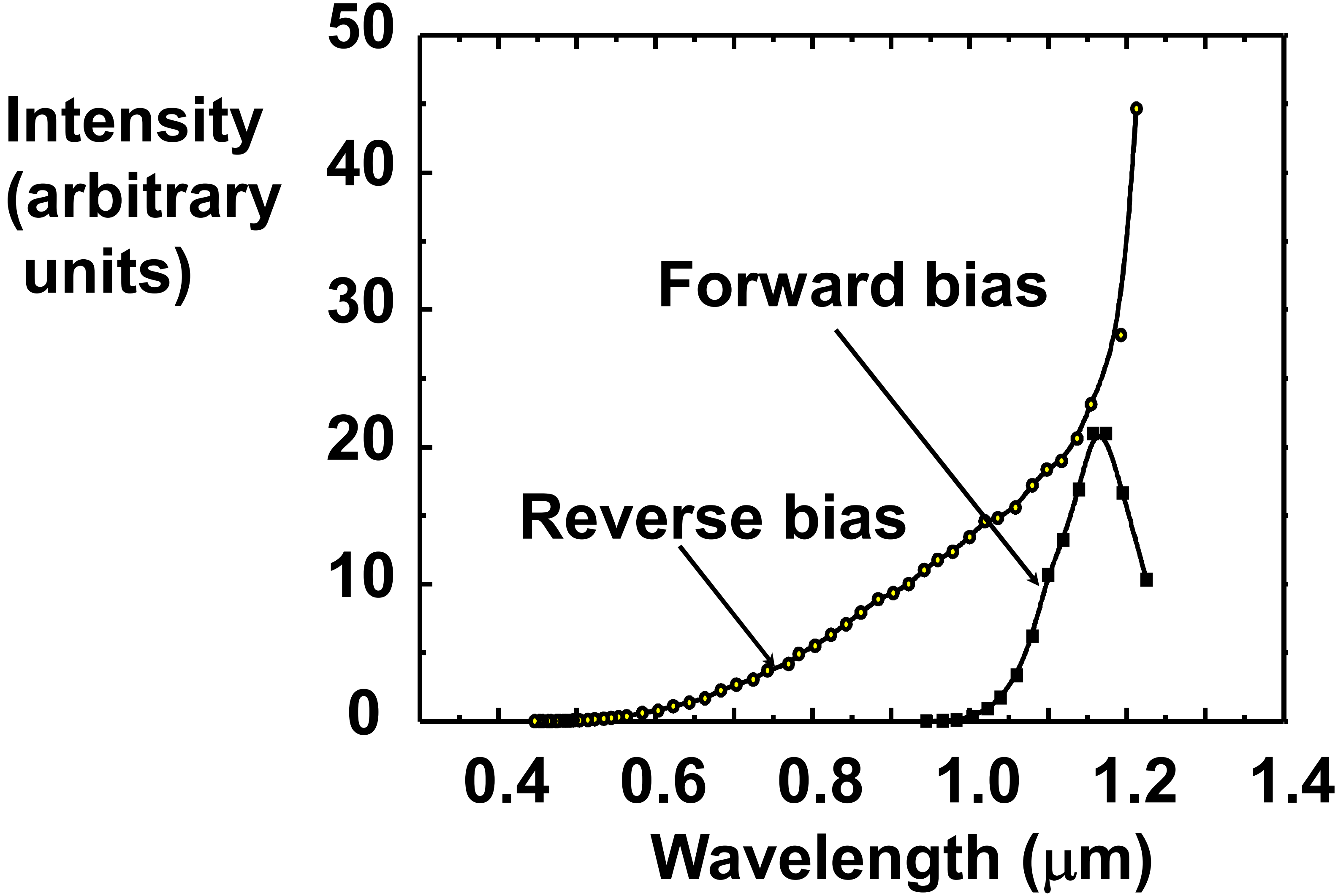
Photoemission via Band-Band Recombination



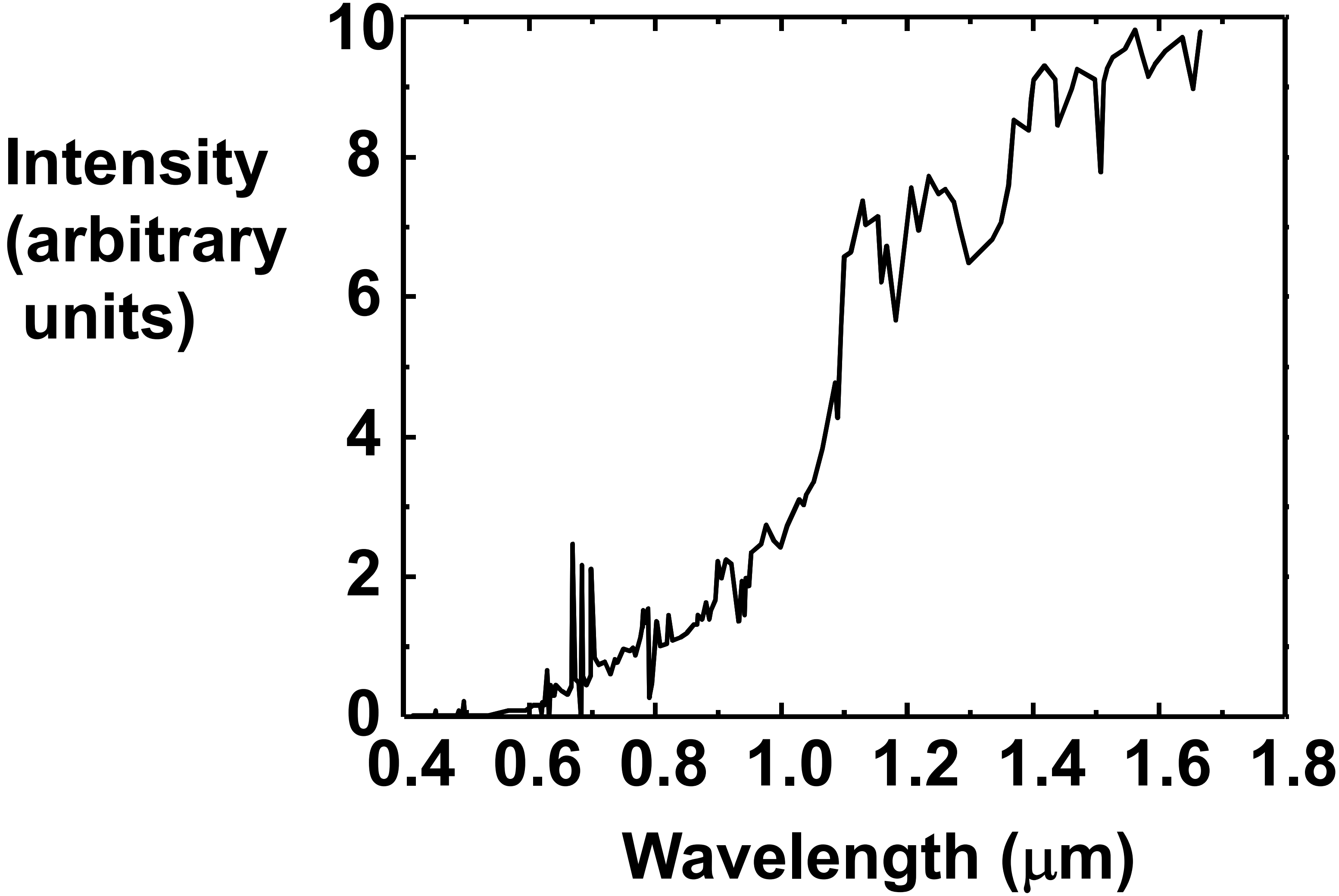
Si Integrated Circuit Emission

Light Emitting Process	E-Field
Forward biased junctions	Low
Reverse biased junctions	High
Latchup	Low
Transistor saturation	High
Gate shorts	Mixed

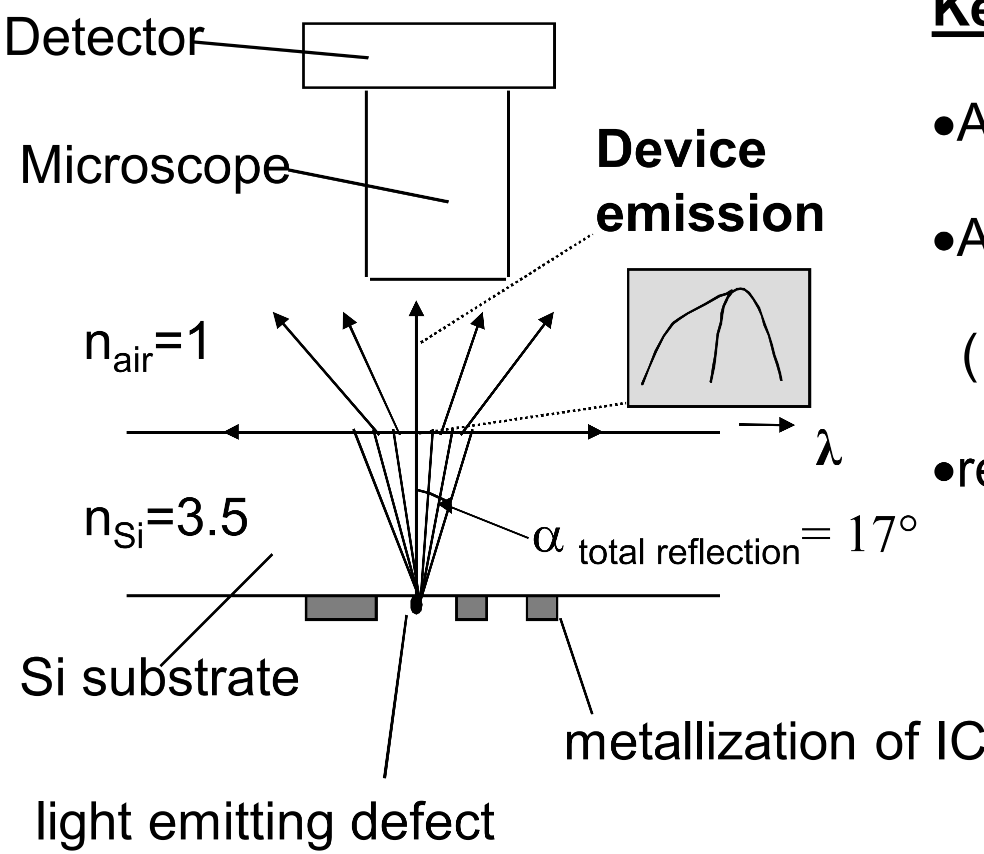
p-n Junction Emission



n-MOSFET Saturation



PEM Inspection from Backside: Key Issues



Key issues:

- Absorption of the Si substrate
- Absorption by free carriers

  (doping density of the Si substrate)
- reflection micrograph:

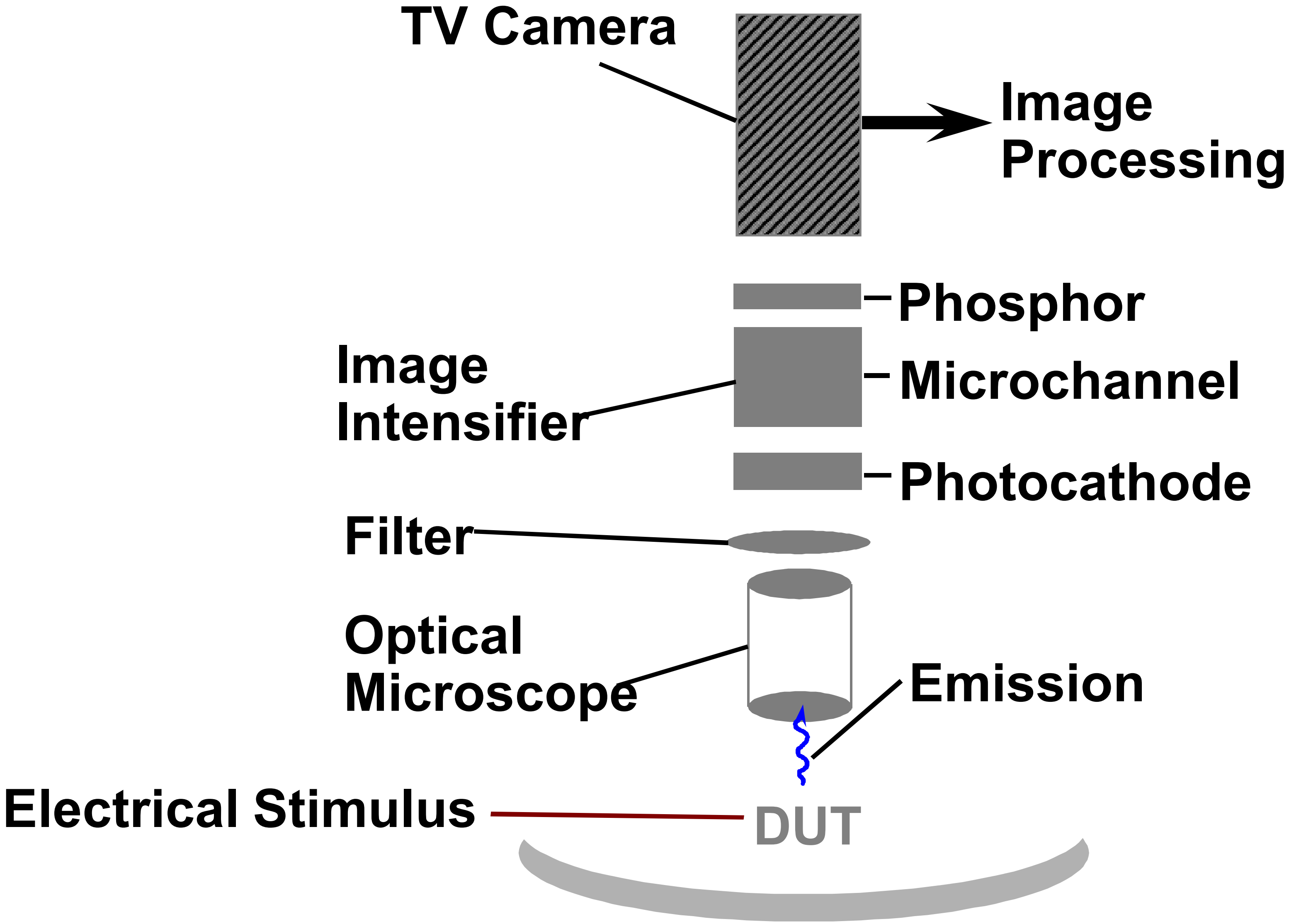
  ⇒hard to get +

  reduced lateral resolution

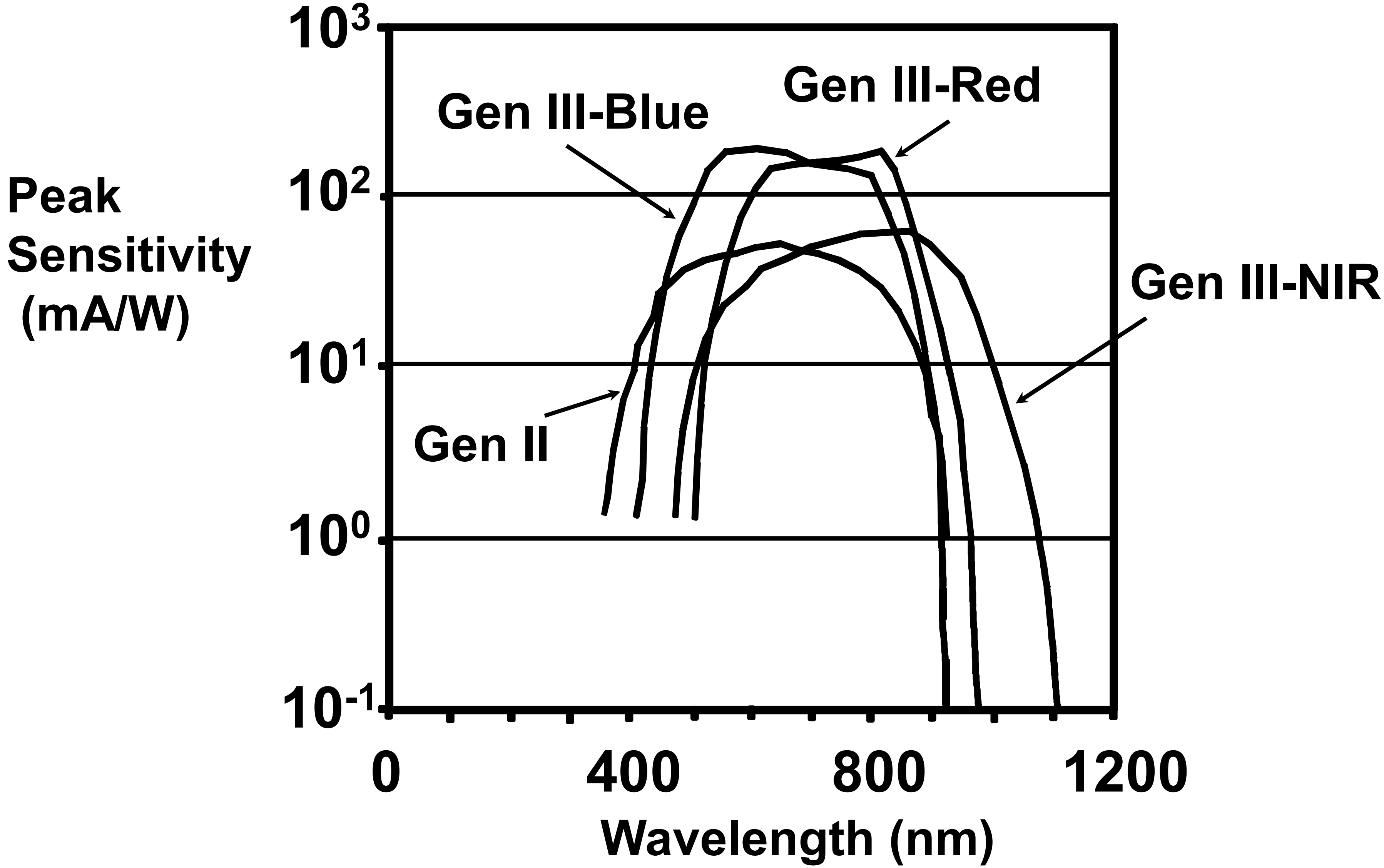
Cameras

- **Intensified cameras**
  - **Developed for military night vision use**
  - **Spectral response centered in visible range**
- **Cooled Array Cameras**
  - **Developed for high performance imaging applications (Astronomy)**
  - **Many detector materials and formats available**
  - **External cooling usually required**

Intensified Cameras



Intensifier Response



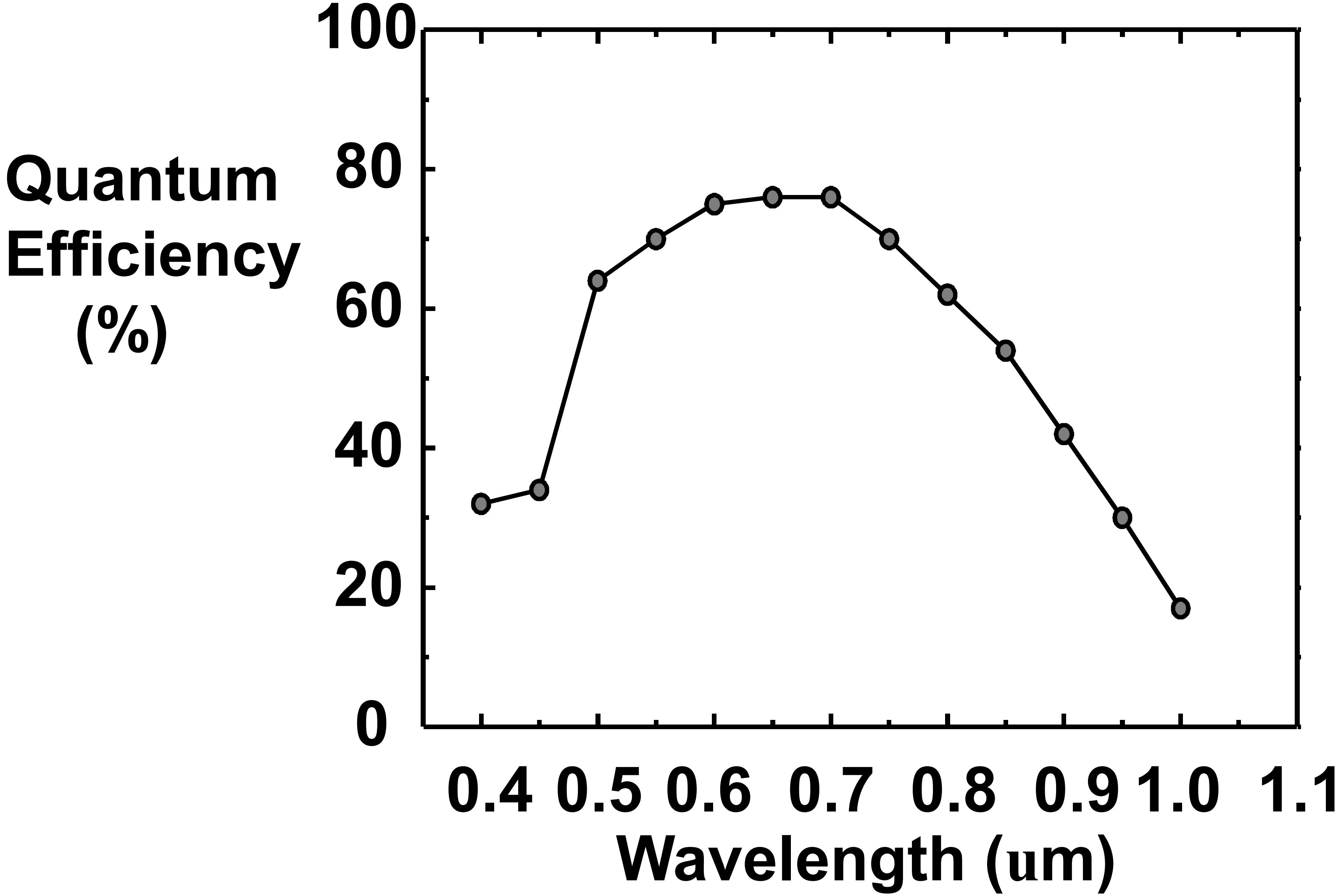
Silicon CCD Cameras

- **Cameras commercially available from several sources**

http://www.photomet.com/

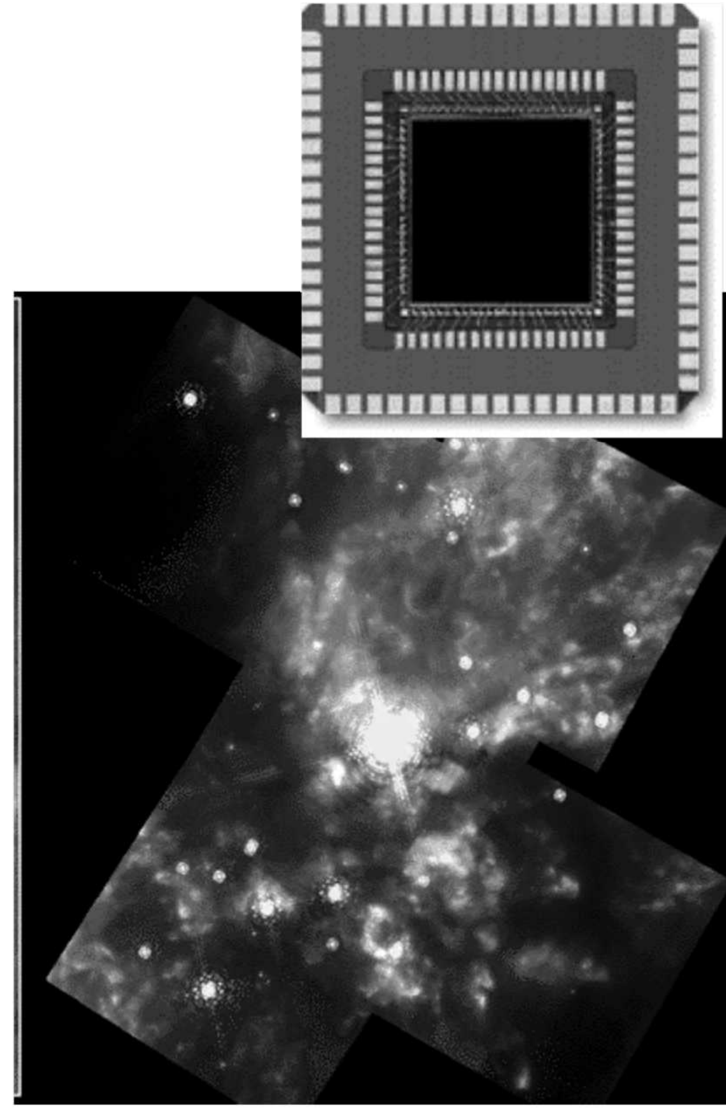
- **Arrays made by many companies (e.g. Tektronix, Kodak, Thompson, etc.)**
- **Mature manufacturing technology**
- **Cooling can be Peltier, liquid/Peltier, or LN_2**

Si - CCD Array QE

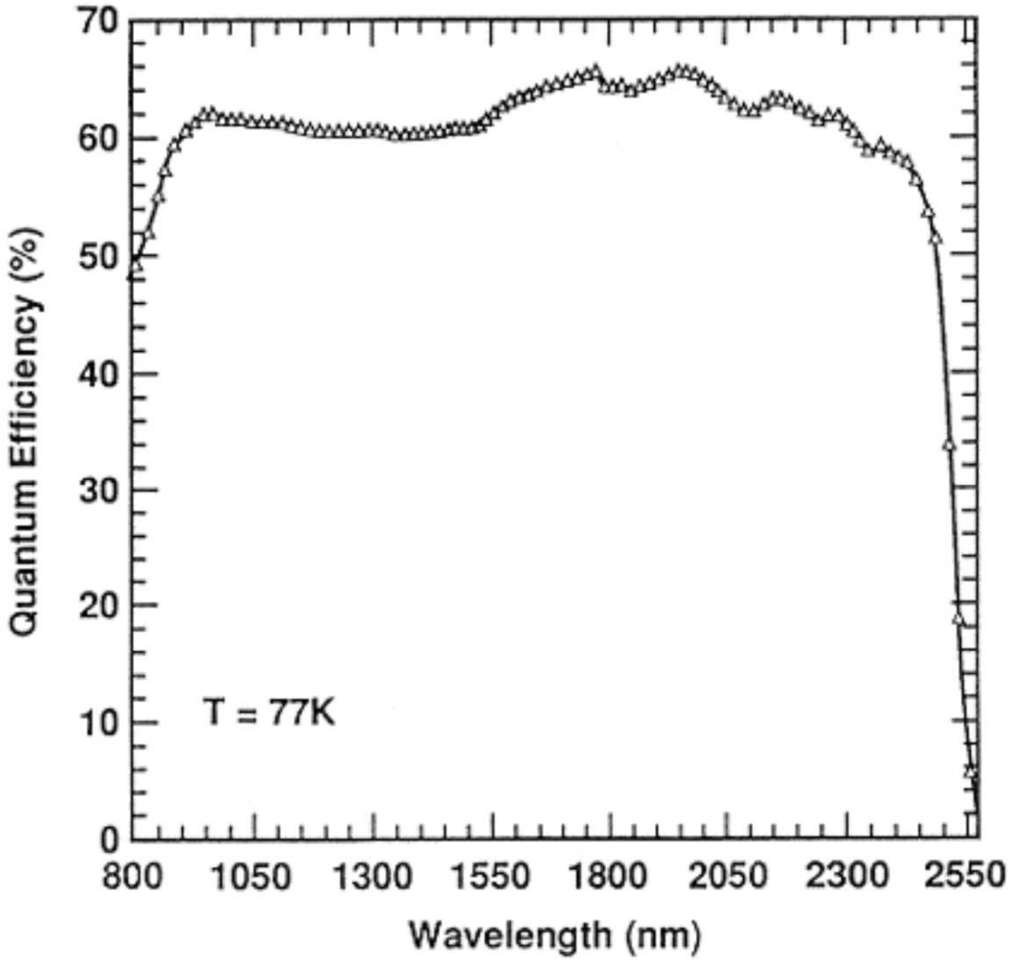


NICMOS Array

- **NICMOS - Near Infrared Camera Multi-Object Spectrograph**
- **256 by 256 pixel HgCdTe array**
- **Optimized for use between 800 & 2500 nm**
- **First Array with Si-CCD level performance in NIR**
- **Flown on Hubble Space Telescope - February 1997**



NICMOS Array Response

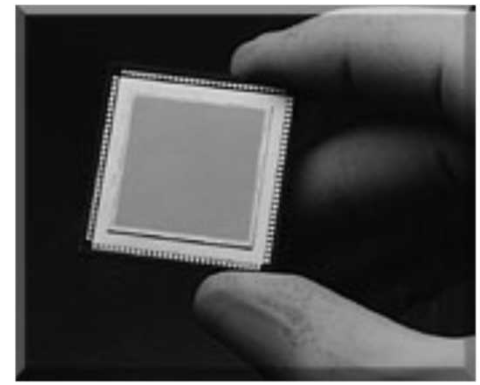


Read Noise (77 K) : <40 e^-

Dark Current (77 K): <1 e^-/s

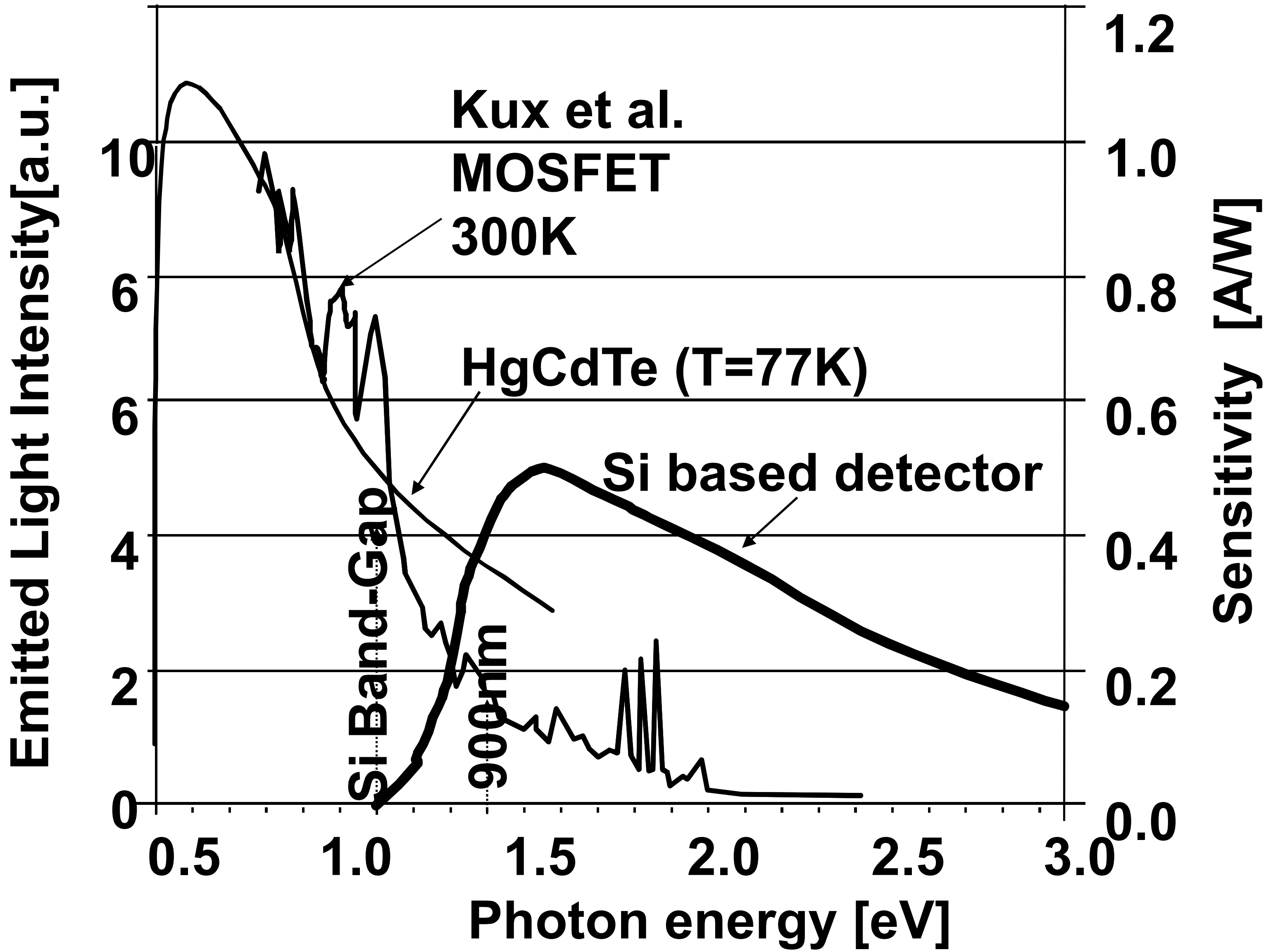
Other NIR Arrays

- **Other arrays are available with low noise NIR response:**
  - InSb (Indium Antimonide)
    - **64x64 to 1024x1024 pixel formats**
    - **Spectral response ~0.6 to 5 μm**
    - **Operating temperature 35 K**
    - **Infrared blocking more difficult**
  - PtSi (Platinum Silicide)
    - **256x256 pixel array format**
    - **Spectral range 1 to 5.7 μm**
    - **Operating temperature 79 K**



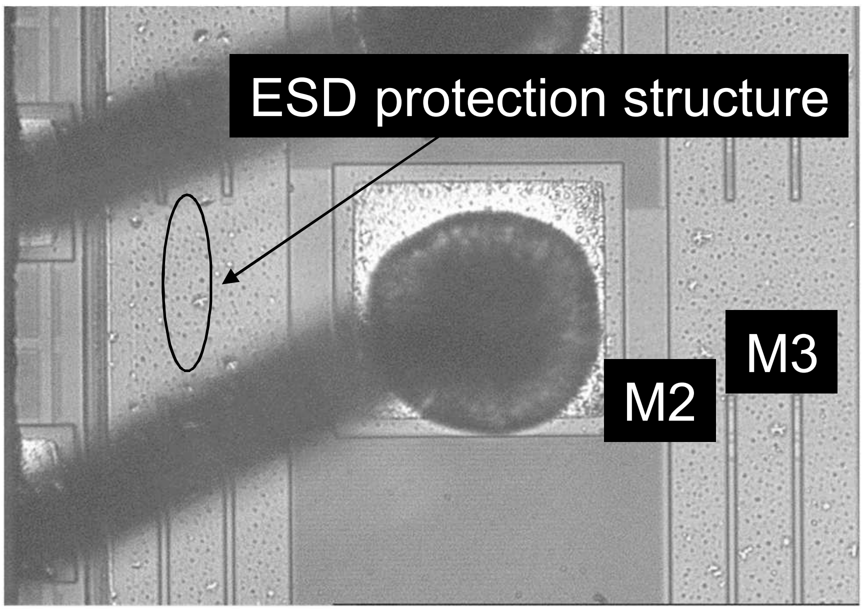
http://www.sbrc.com/

PEM

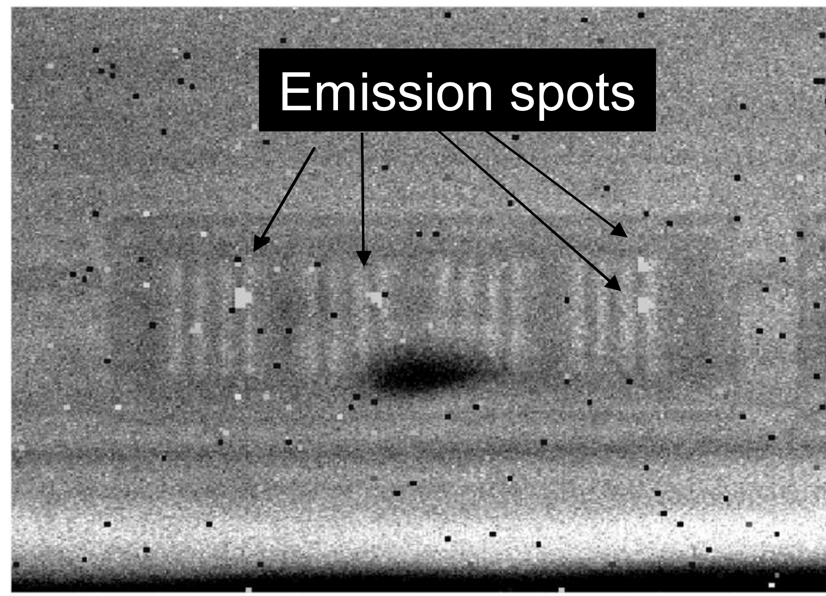

Kux et al.
MOSFET
300K
HgCdTe (T=77K)
Si based detector
Si Band-Gap
900nm
Emitted Light Intensity[a.u.]
10
6
6
4
2
0
Sensitivity [A/W]
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Photon energy [eV]

PEM

Frontside illuminated image



Backside PEM (Si CCD detector)



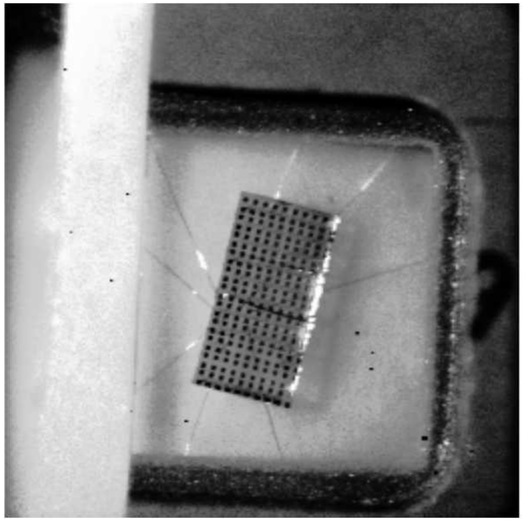
d_{Si}=150µm, $n_{substrate}=1x10^{19}cm^{-3}$

$I_{leakage}$=2µA, V=3.5V after electrical overstresss

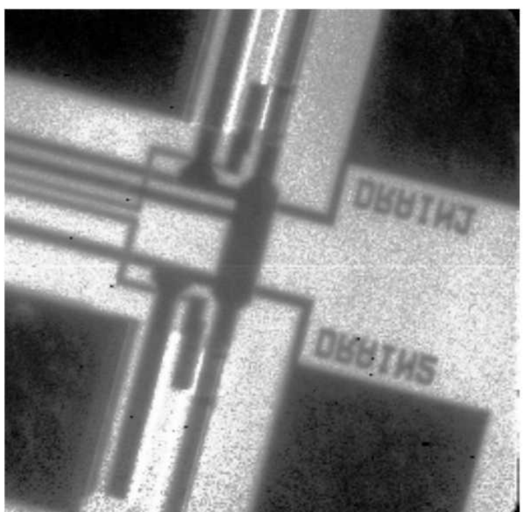
PEM

Backside illuminated images

X1

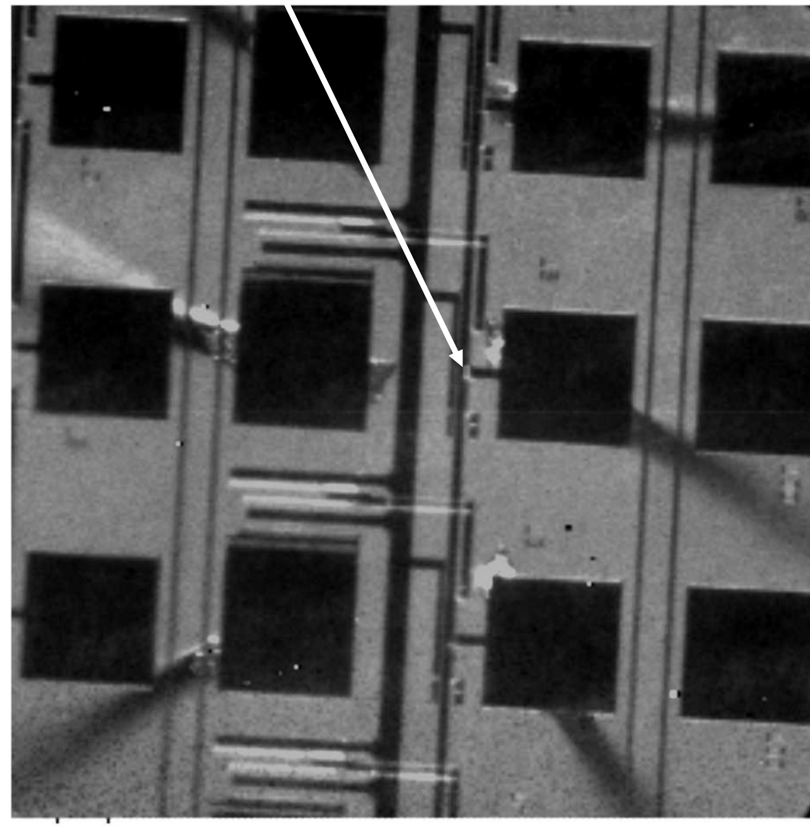


X50



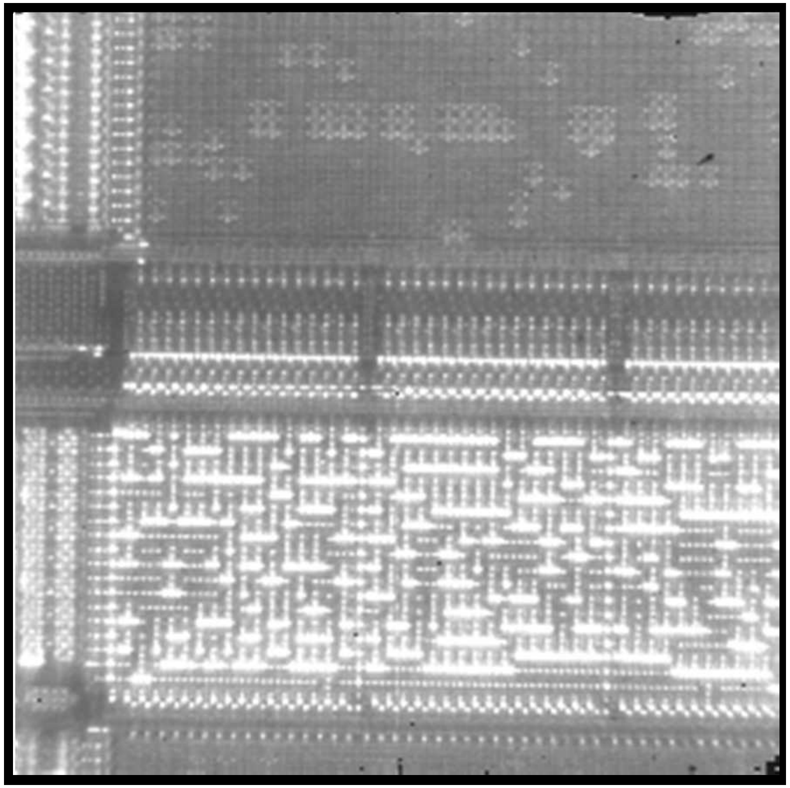
Backside emission signal: n-channel MOSFET

V_g=5V, V_{SD}=3.5V, I_{DS}=1.5mA, 10 sec integration time

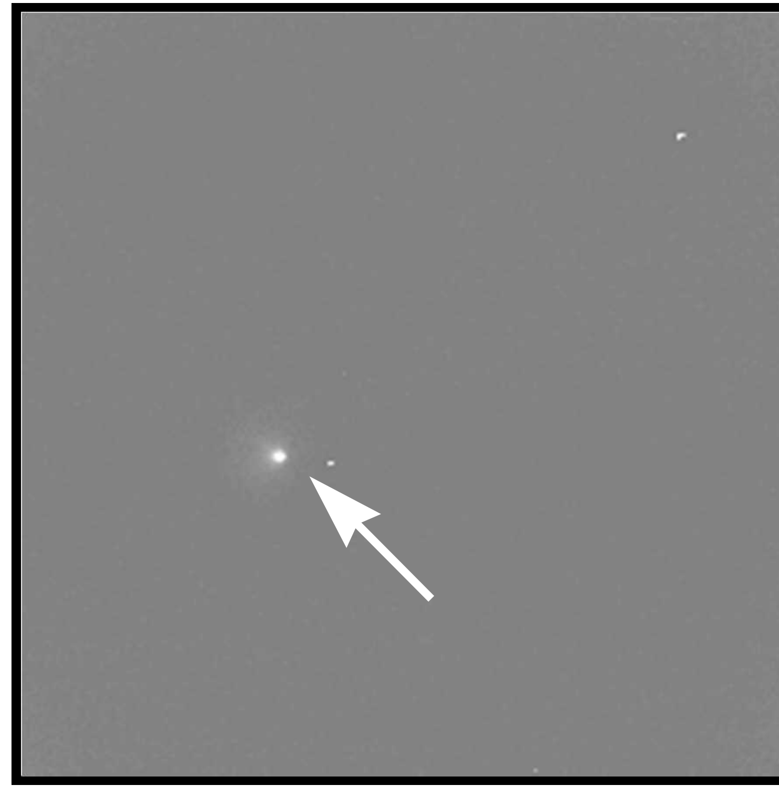


Backside emission microscopy with HgCdTe camera; Measurements performed by A. Zaplatin IR Labs

Backside Analysis: Gate Oxide Breakdown



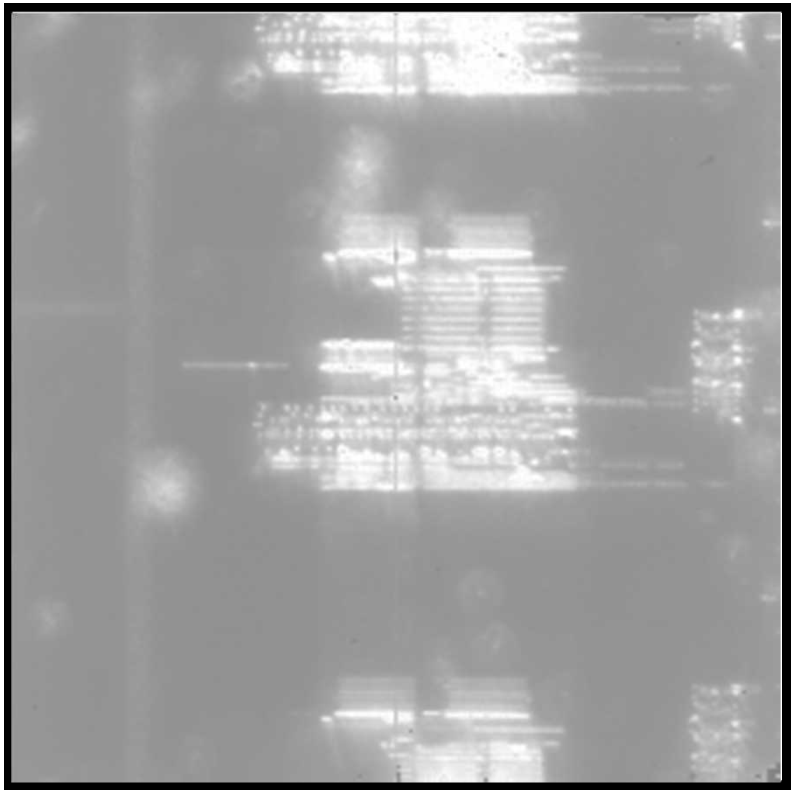
Reflected Image



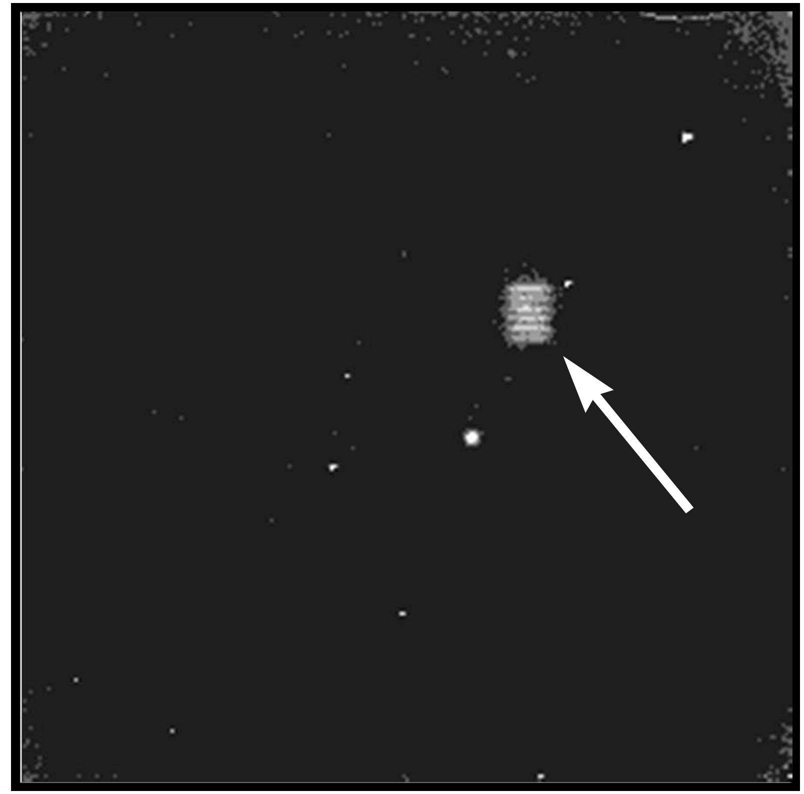
Emission Image

1.5 sec. exposure, I_{DD} = 1.47 mA

Backside Saturation Emission



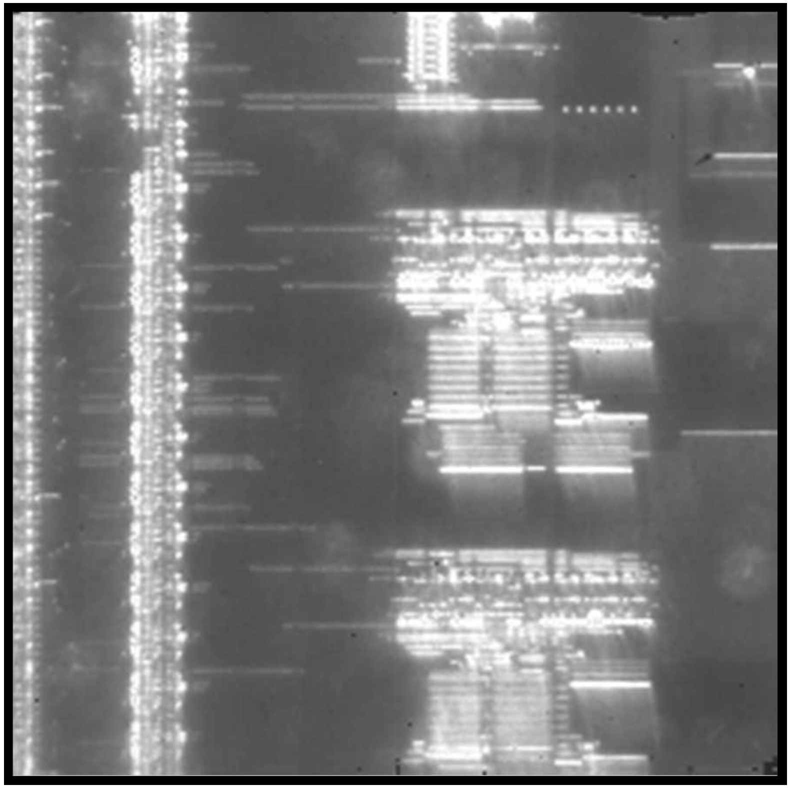
Reflected Image



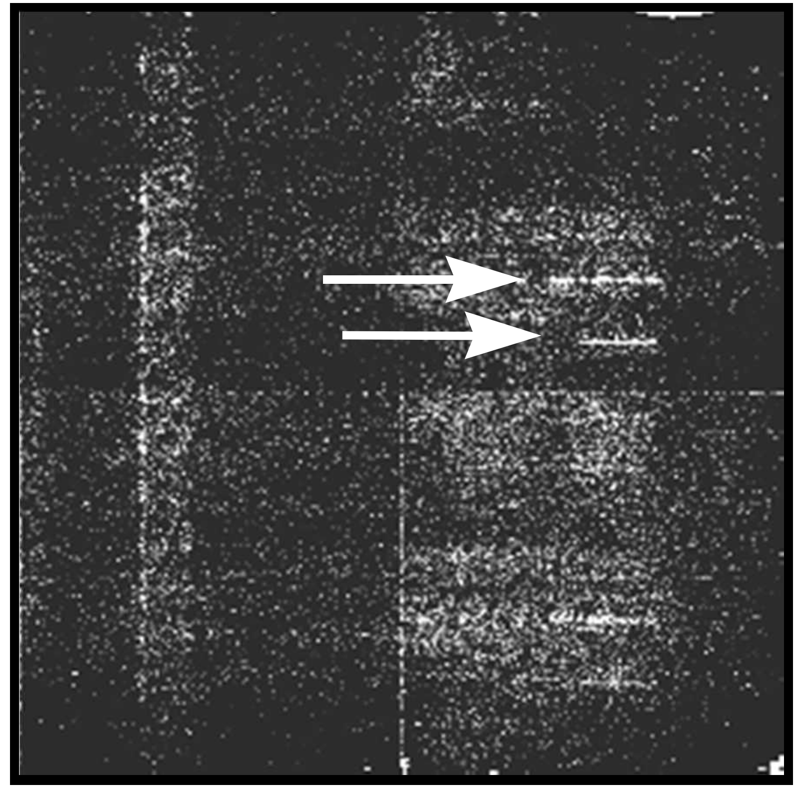
Emission Image

Full thickness die, 10 sec. exposure, I_{DD} = 225 μA

Backside Defect Detection



Reflected Image



Emission Image

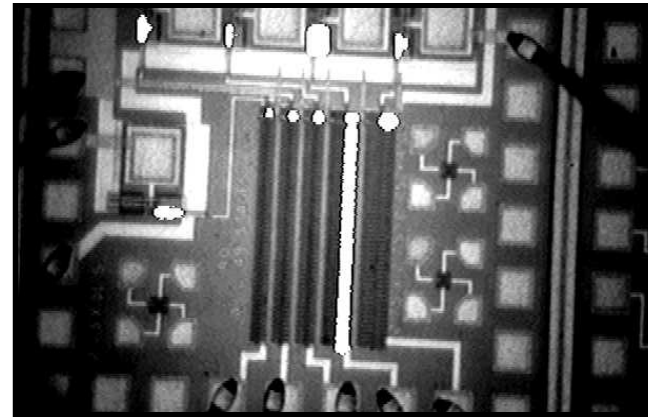
Full thickness die, 200 sec. exposure
I_{DD} = 200 μA

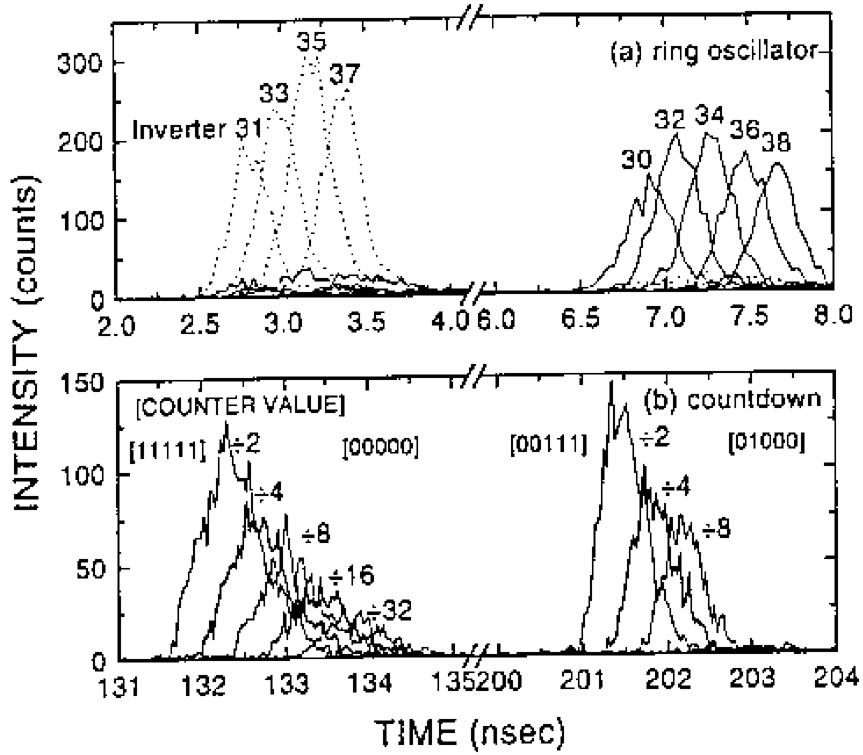
PEM Conclusions

- Physics suggests stronger light emission in NIR than at visible wavelengths
- Technology to detect NIR emission now available
- Head to head comparison of visible and NIR cameras proved NIR emission is stronger
- Similar signal to noise images can be acquired with up to 1000 times shorter exposures

PICA

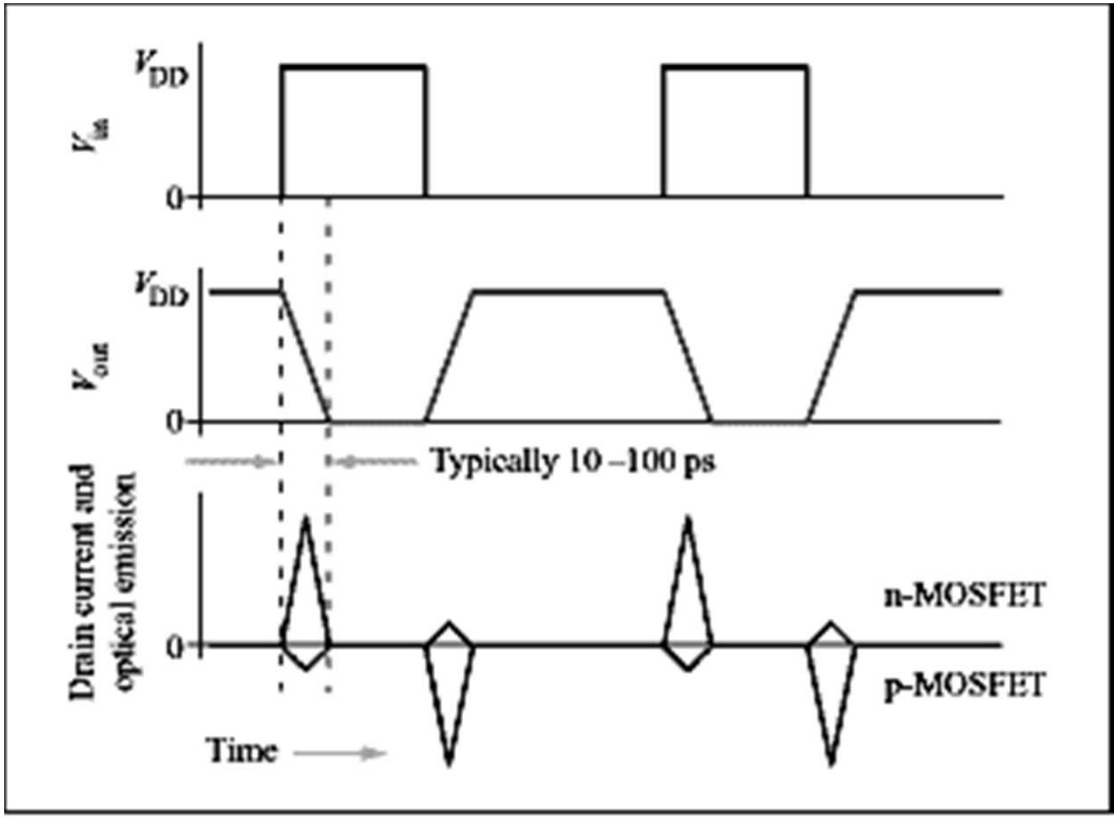
- **Picosecond Imaging Circuit Analyzer (PICA)**
  - **Kash & Tsang, IBM**
- **Working gates emit light during switching**
- **Emission is strongest when gate voltage is half of the drain voltage - the midpoint of the logic transition**
- **PICA uses a strobed, intensified data collection to gather spatial and time information**
- **The use of optical information emitted from IC makes PICA non-invasive**





J.A. Kash and J. C. Tsang

PICA Signals

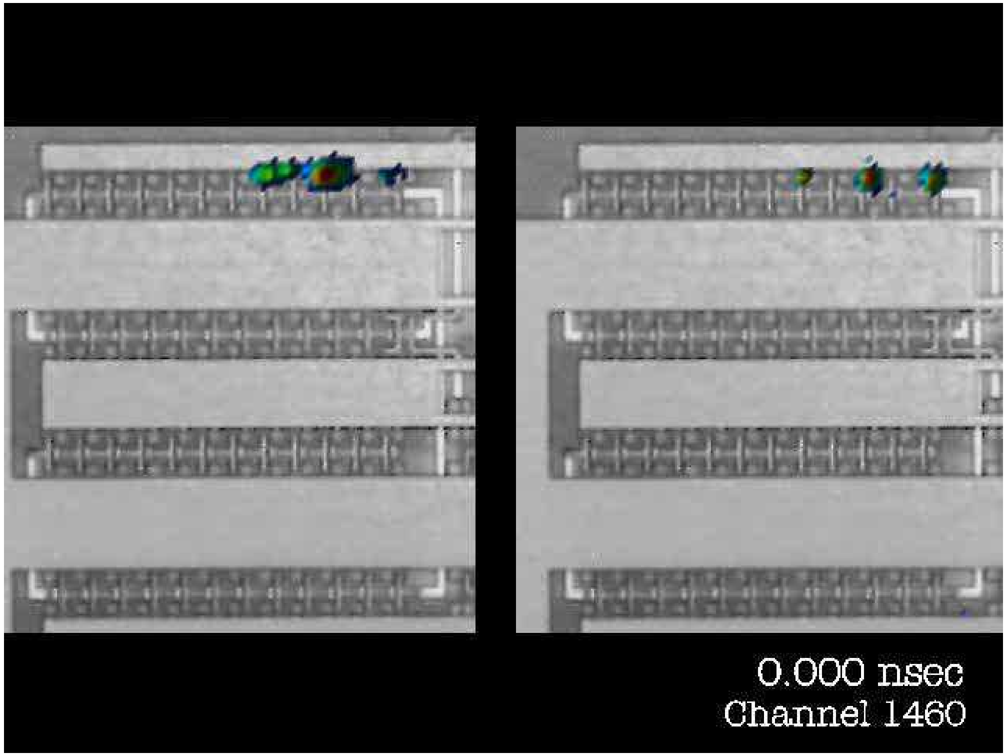


Schematic of the relationship between electrical and hot-carrier-induced optical emission waveforms for a CMOS inverter.

J.C. Tsang, J.A. Kash, and D.P. Vallet

PICA Ring Oscillator Movie

- Only a few "switching" transistors
- Timing and location information
- 20+ hours to acquire



Courtesy of Dave Vallet, IBM

Single Point PICA

- Traditional PICA technique
  - Collect all data from field of view (parallel acquisition)
  - Requires 2-D intensified array camera
  - Collection efficiency and photon flux yield long data acquisition times
    - But you get timing information from every transistor in the field of view
- Single point PICA
  - Position single photodetector over transistor of interest
  - Photodetector can be extremely fast and sensitive to IR light
    - More detector choices than in traditional PICA
    - IR-sensitive detectors better for backside applications
  - Issues
    - Positioning detector
    - High NA lenses for resolution and collection efficiency
      - Need solid immersion lenses for resolution

Magnetic Field Analysis

- Use *B* fields from local currents
  - Biot-Savart law

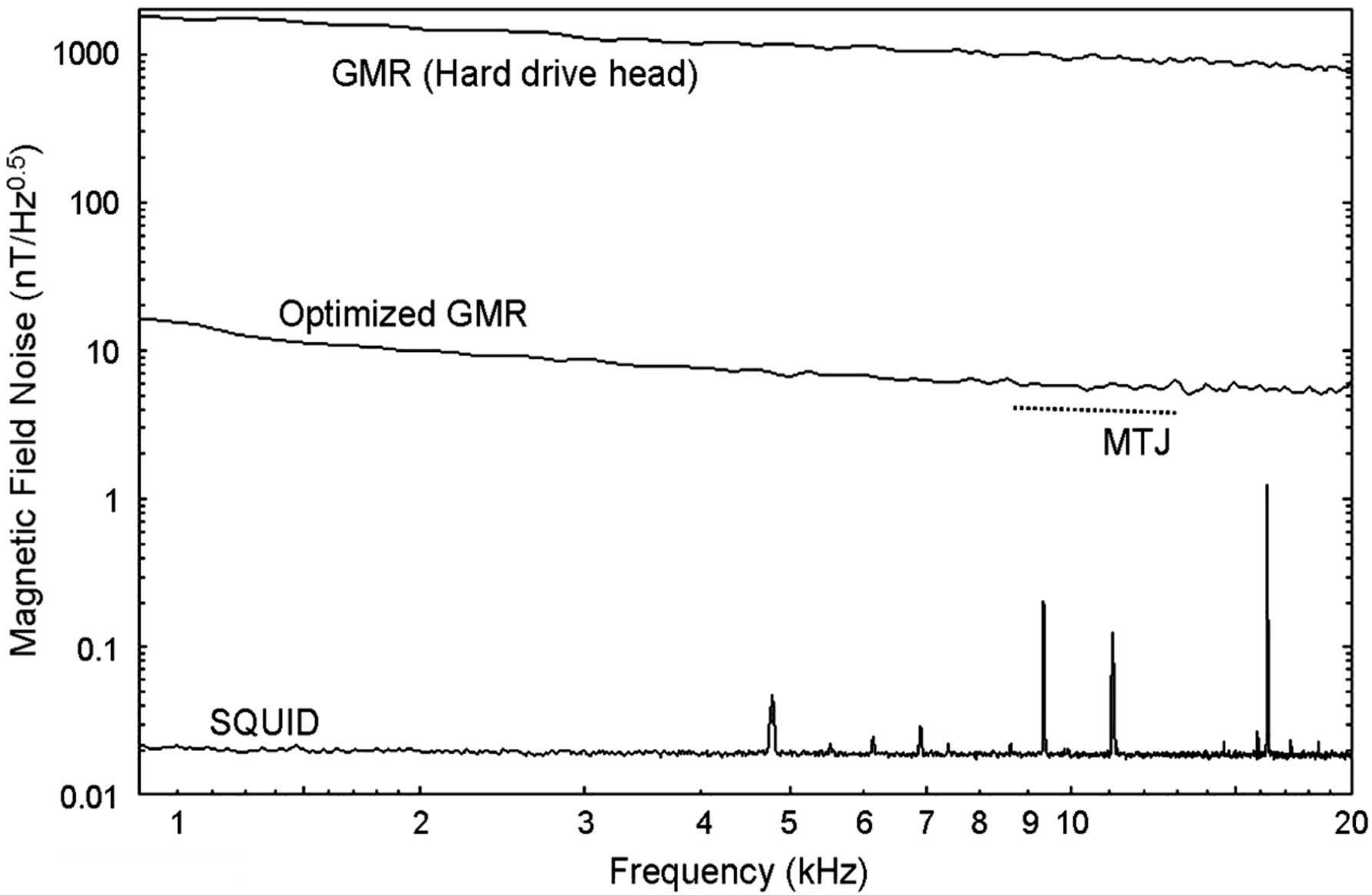
$$\vec{B} = \frac{\mu_o I}{2\pi r}\hat{\phi}$$

  - *B* fields can penetrate overlying layers
    - Enables non- or minimally invasive backside and multilayer samples
- Now a standard approach for PCBs and ICs
- Quantitative current and depth measurement

Detectors for Magnetic Field Analysis

- Three basic detectors
  - MFM (magnetic field microscopy)
    - AFM based approach
    - μA demonstrated over very small fields of view
  - SQUID (superconducting quantum interference device)
    - Most sensitive (lowest noise floor)
    - Geometry and cooling can be a challenge
  - Magnetoresistive sensors: GMR and MTJ
    - Reduced sensitivity, but better spatial resolution
      - Can be used in “cavities”
    - GMR (giant magnetoresistance)
      - Easier to manufacture (“tape heads”)
    - MTJ (magnetic tunnel junction)

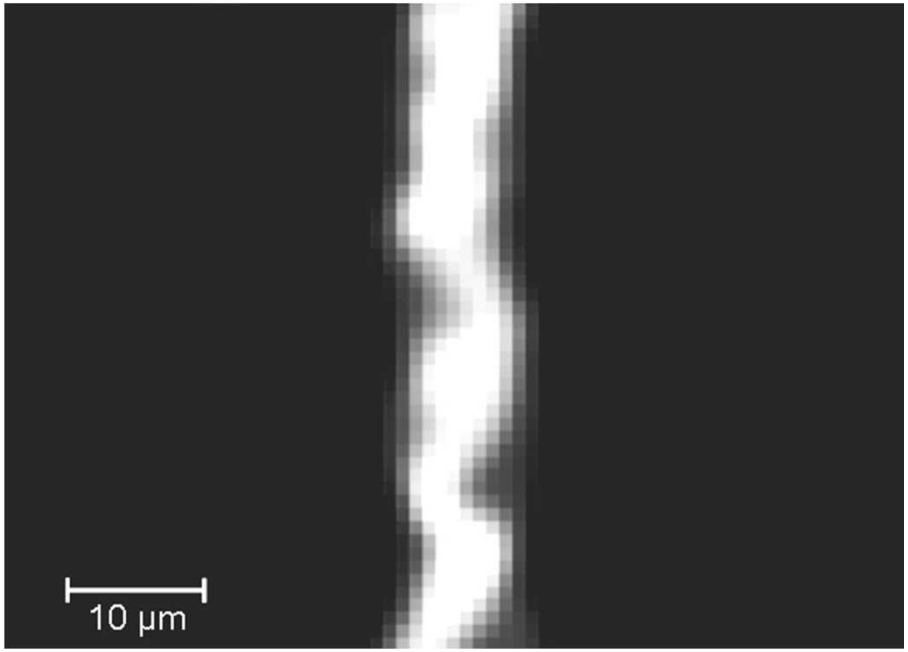
Detector Noise vs. Frequency



S.I. Woods, A. Orozco and L.A. Knauss

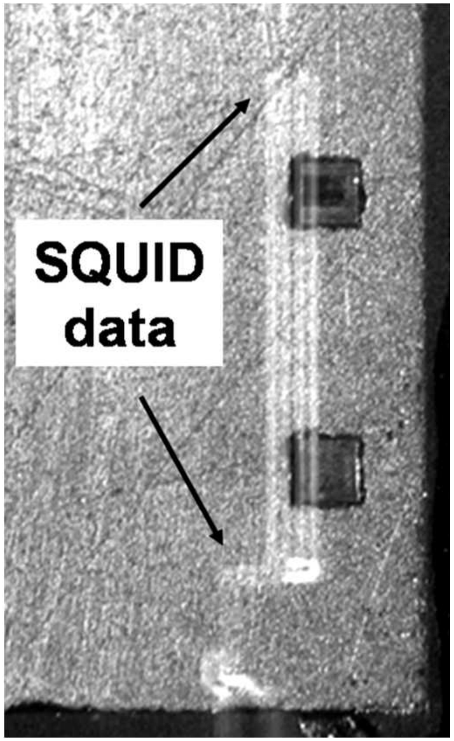
Optimized GMR Example

- High spatial resolution with GMR detector
- Similar image with normal GMR head would require 300 μArms

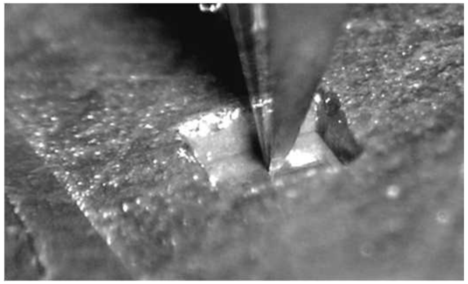


2 μArms

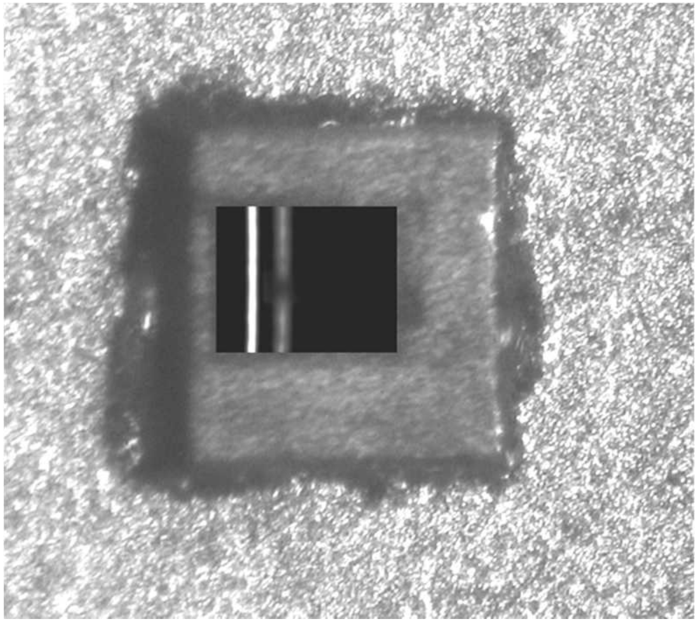
SQUID and GMR Complement



> 250 μm distance



GMR in local cavity 500x500x200 μm



GMR through 50 μm
Note 2 contrast levels for different metal levels

Summary

- Failure analysis now an enabler of technology
  - Reliability, performance, profitability
- Technology advances in IC processing require advances in FA
- Optical beam, photon emission, and magnetic imaging, with steady improvements, will continue to meet these needs

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<u>For PICA</u>

J.A. Kash and J. C. Tsang, "Dynamic Internal Testing of CMOS Circuits," *IEEE Electron Device Letters*, Vol. 18, pp. 330-332 (1997).

J.C. Tsang, J.A. Kash, and D.P. Vallet, "Picosecond Imaging Circuit Analysis", *IBM Journal of Research and Development*, V44, N 4, pp. 583-604, (2000).

References (con't)

<u>For Magnetic Analysis</u>

L.A. Knauss, et al. "Detecting Power Shorts from Front and Backside of IC Packages Using Scanning SQUID Microscopy", *ISTFA,* pp. 11-16. (1999).

B.D. Schrag, et al., "Quantitative Analysis and Depth Measurement via Magnetic Field Imaging", *EDFA Magazine*, November, Vol. 7, No. 4, pp. 24-31, (2005).

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