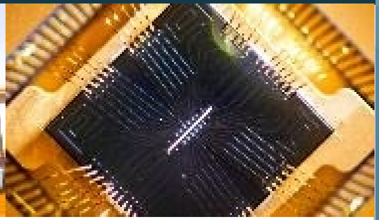
SAND2021-14486PE

Sandia National Laboratories

VISIBLE LIGHT LASER VOLTAGE PROBING
ADVANTAGES AND DRAWBACKS TO NEAR INFRARED PROBING

NATIONAL SECURITY PROGRAMS





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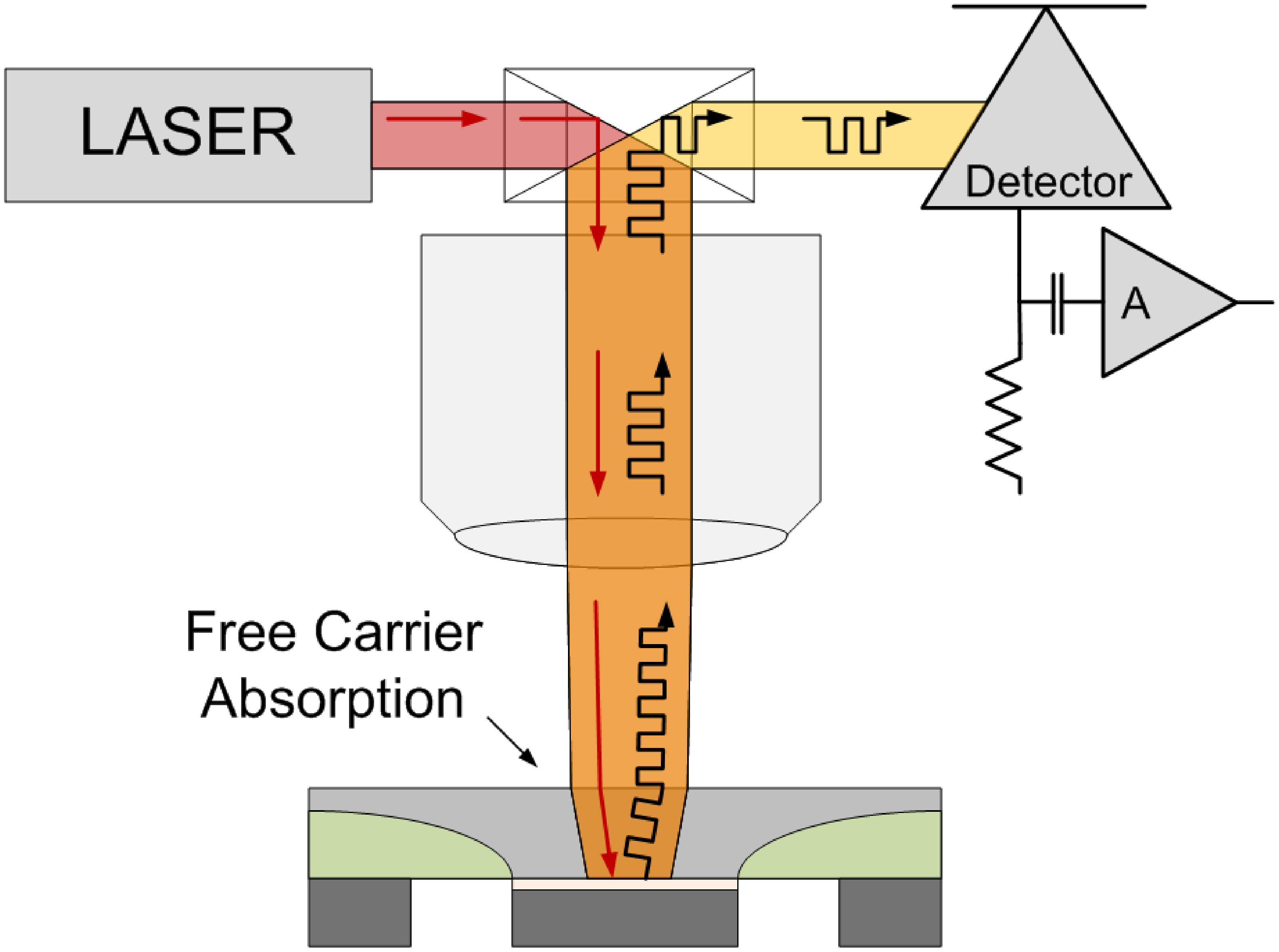
OUTLINE

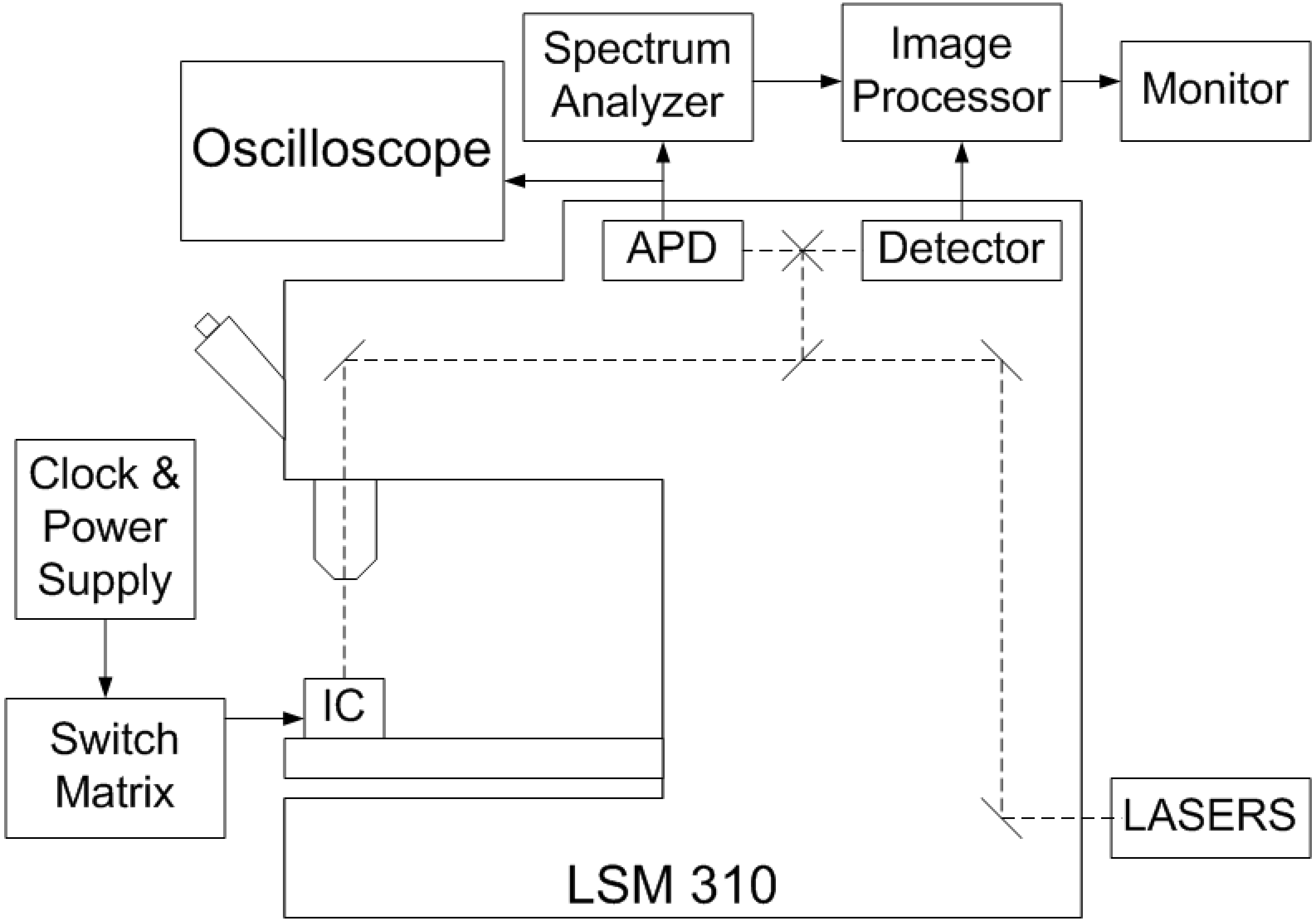
- Describe fundamentals of LVP
- Discuss resolution limitations of conventional LVP
- Discuss resolution improvements of Visible LVP
- Discuss advanced sample preparation for Visible LVP
- Comparison and contrast of Visible LVP vs. Conventional LVP

FUNDAMENTALS OF LVP

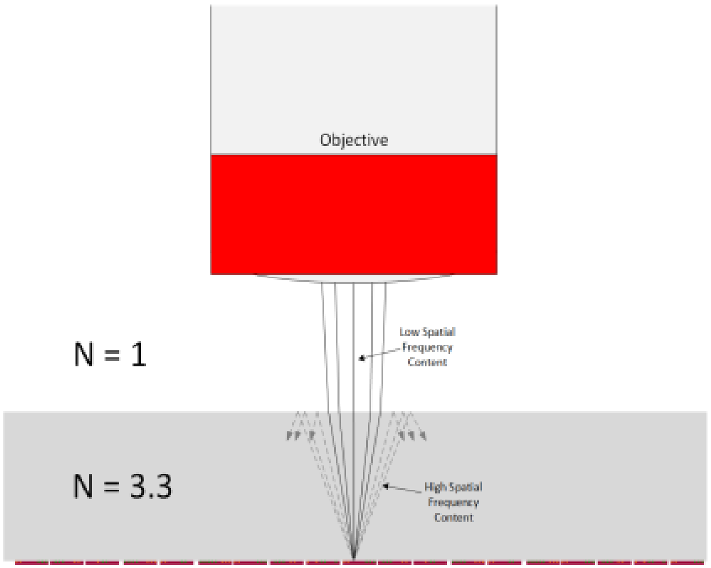
LVP BASICS

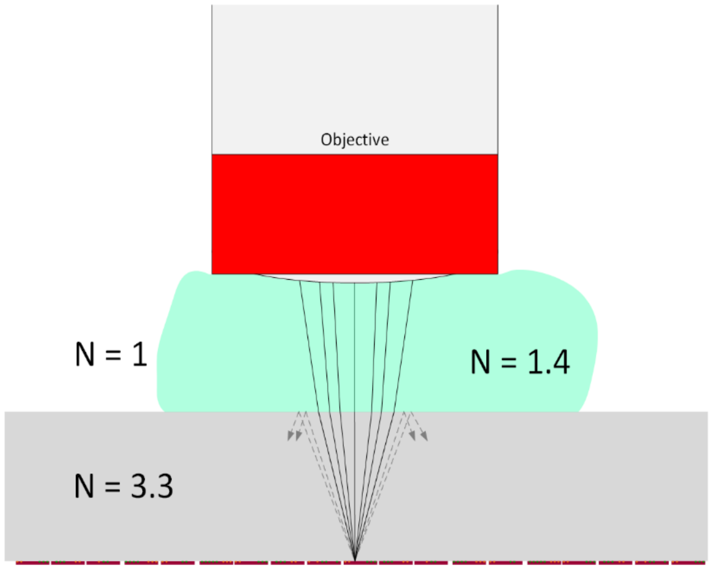


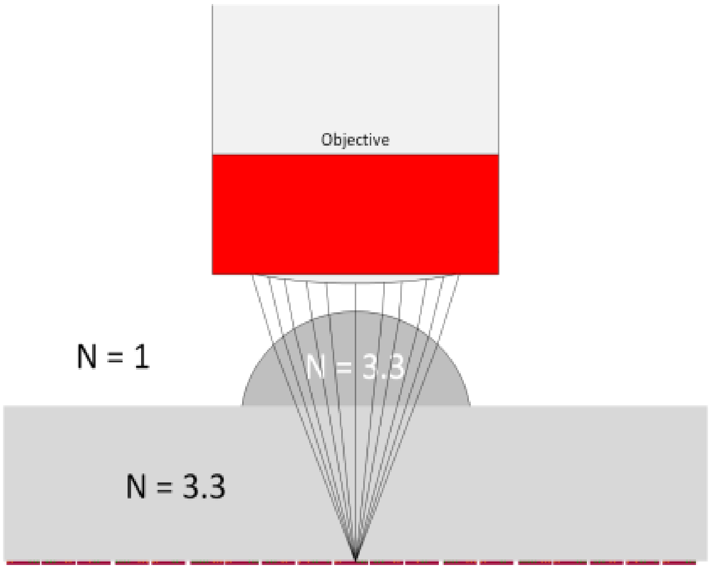
LVP FRAMEWORK



SOLID IMMERSION LENS (SIL)







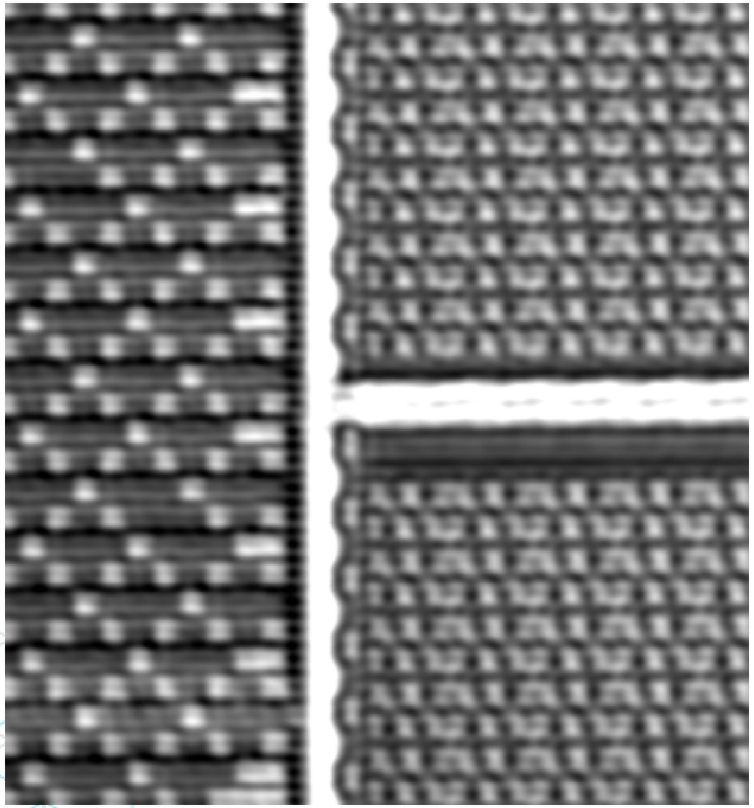
- Imaging through silicon with air gap
  - High spatial frequency components of light are trapped in Silicon from total internal reflection at the air/Si interface

- **Imaging through silicon using immersion microscopy**
  - **Replacing the air with oil increases the index of refraction and decreases the total internal reflection at the oil/Si interface**
  - **Consequently resolution improves**

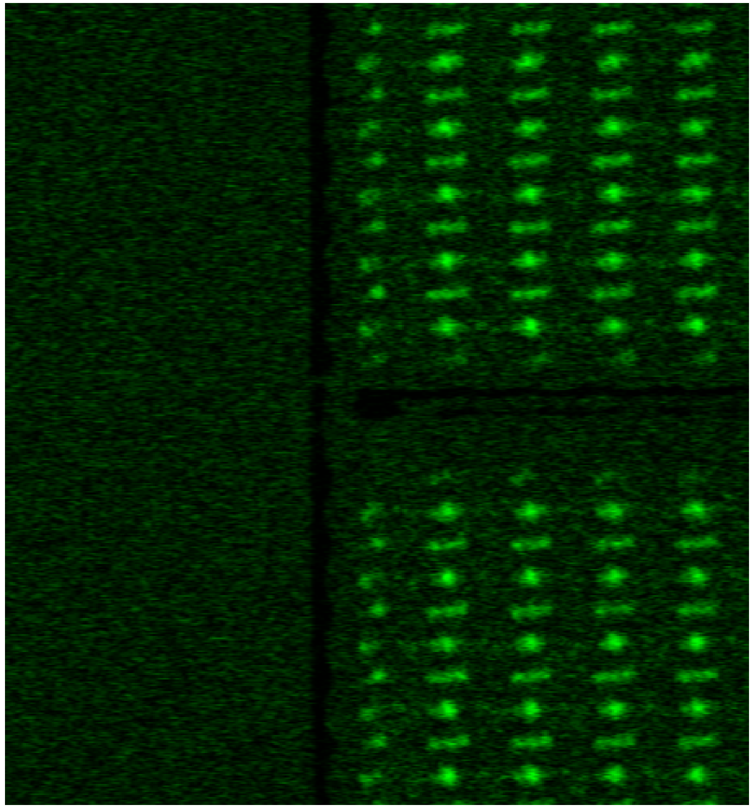
- **Imaging through silicon with a hemisphere**
  - **Using a silicon hemisphere that is in very close contact with the Silicon surface further decreases the total internal reflection at the air/Si interface**
  - **Resolution is further improved**
  - **The max resolution that one can get corresponds to a Numerical Aperture of the index of the silicon**

LASER VOLTAGE IMAGING (LVI)

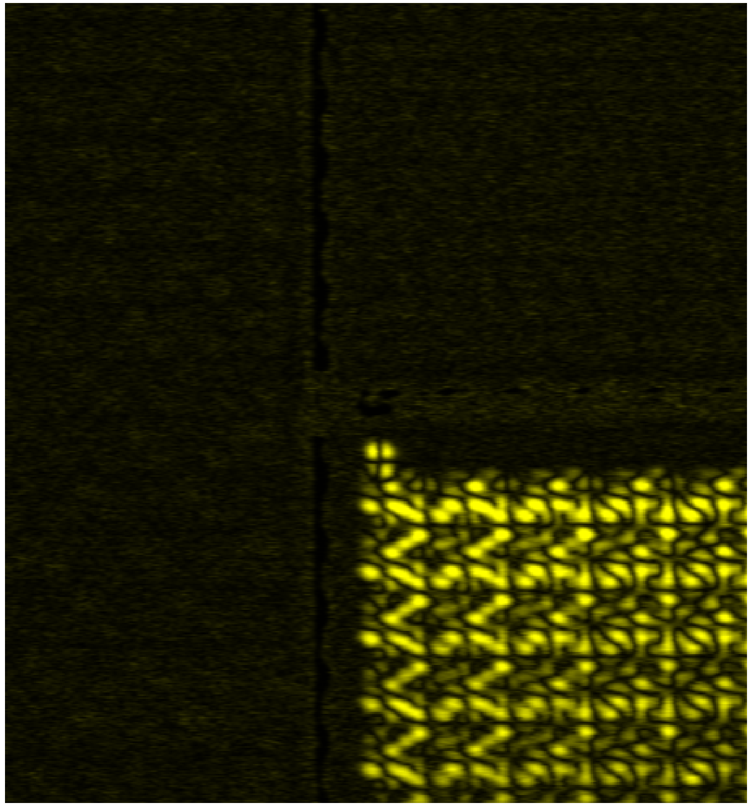
Reflected Light Image



LVI at 50 MHz



LVI at 25 MHz



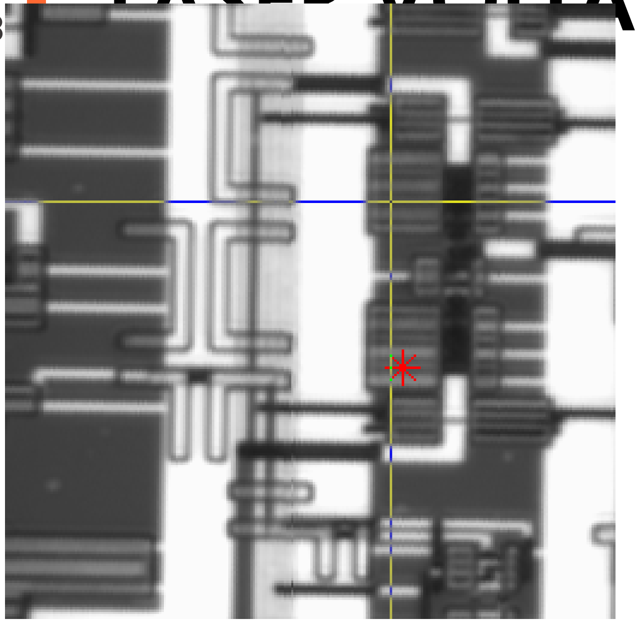
1319 nm Laser 3.3 NA SIL

Laser Voltage Images are made by running periodic data through a chip, analyzing the LVP signal with a zero spanned spectrum analyzer set to video output and the fundamental harmonic of the periodic frequency, and feeding the video output into the digitizer

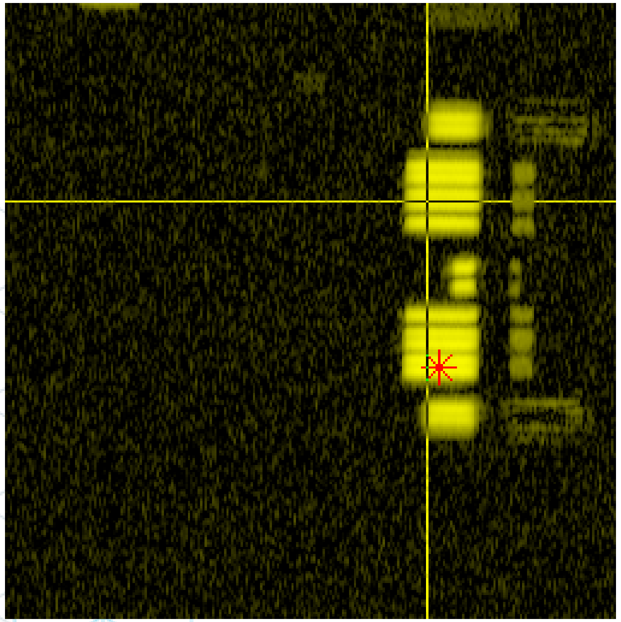
3 mW Incident Power, 156 µW Reflected Power

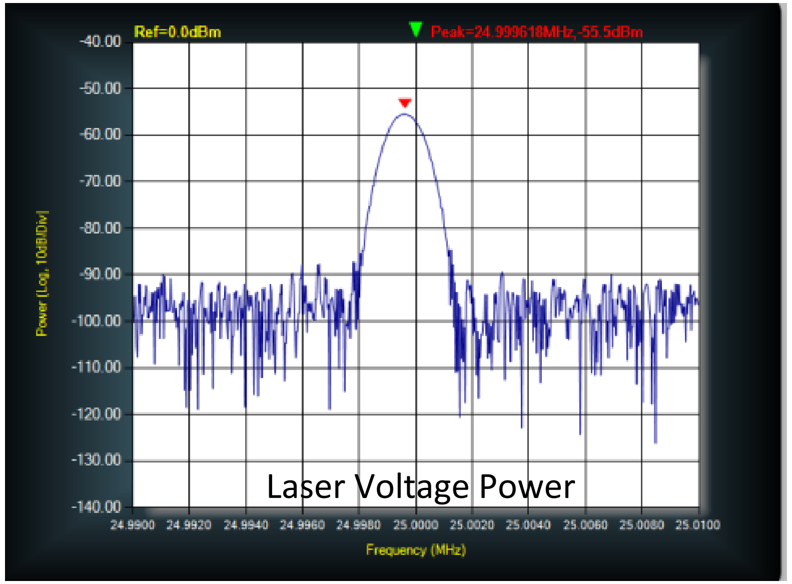
LASER VOLTAGE PROBING

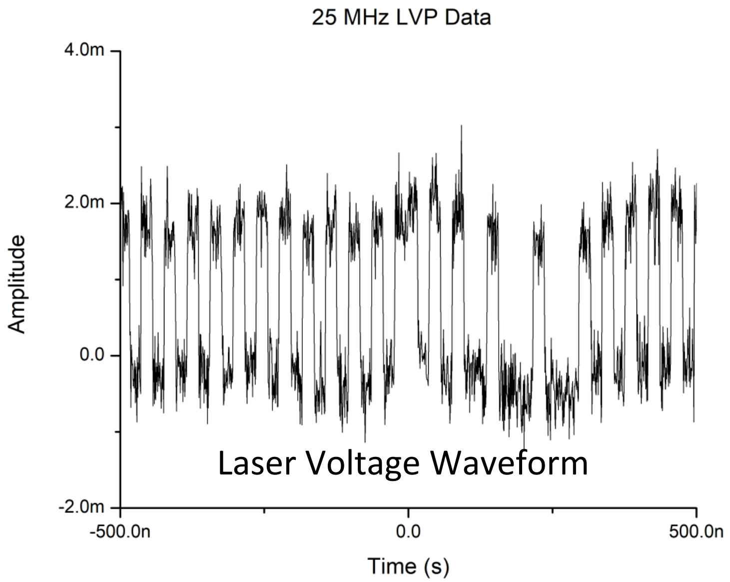
Reflected Light Image



Laser Voltage Image





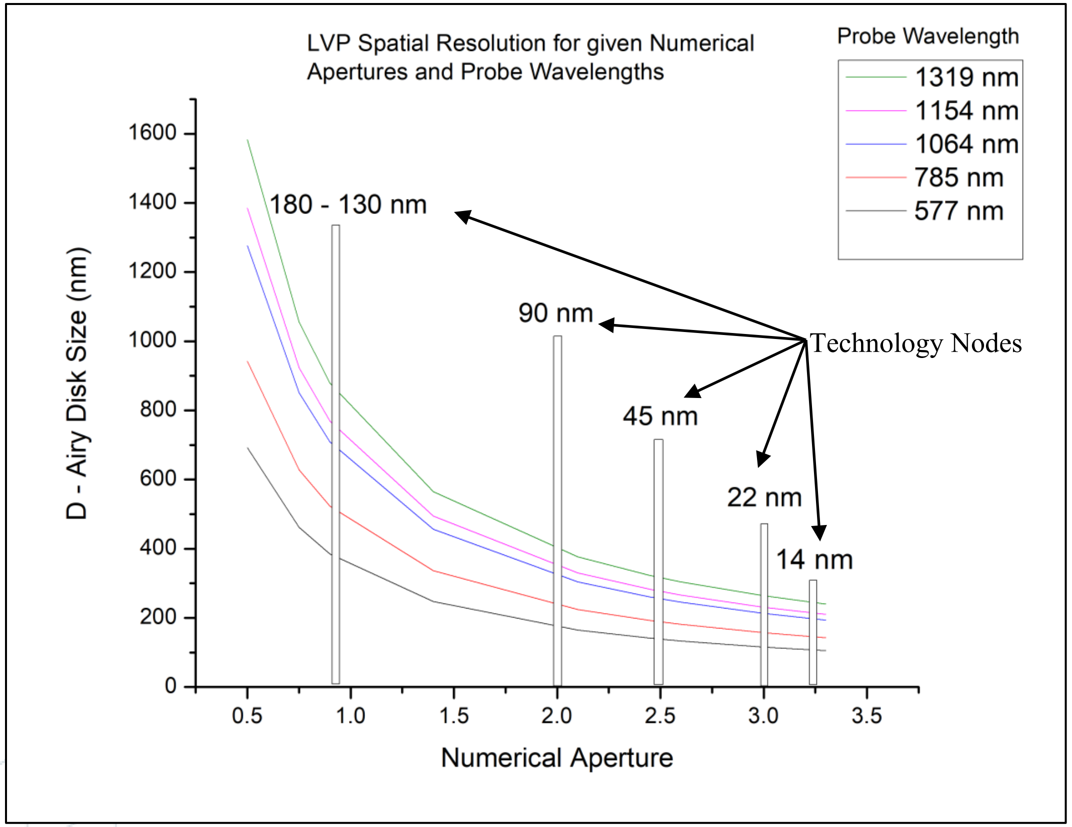


- **Laser Voltage Signal**
  - **The part of the optical return signal that carries the waveform of interest**
  - **This signal is typically very weak**
    - **Here it is quite strong ~ -55 dBm**
    - **Typical signals range from -90 dBm (picoWatts) to -60 dBm (nanoWatts)**
- **Noise**
  - **Everything that is not the Laser Voltage Signal**

- **Laser Voltage Probing**
  - **The Laser Voltage Signal is visible on narrow spanned spectrum analyzers**
  - **This signal is drowned out by noise on wideband scopes**
  - **Consequently, LVP waveform acquisition requires a reliable trigger and averaging**

RESOLUTION LIMITATIONS OF CONVENTIONAL LVP

OPTICAL RESOLUTION



- Rayleigh Criteria

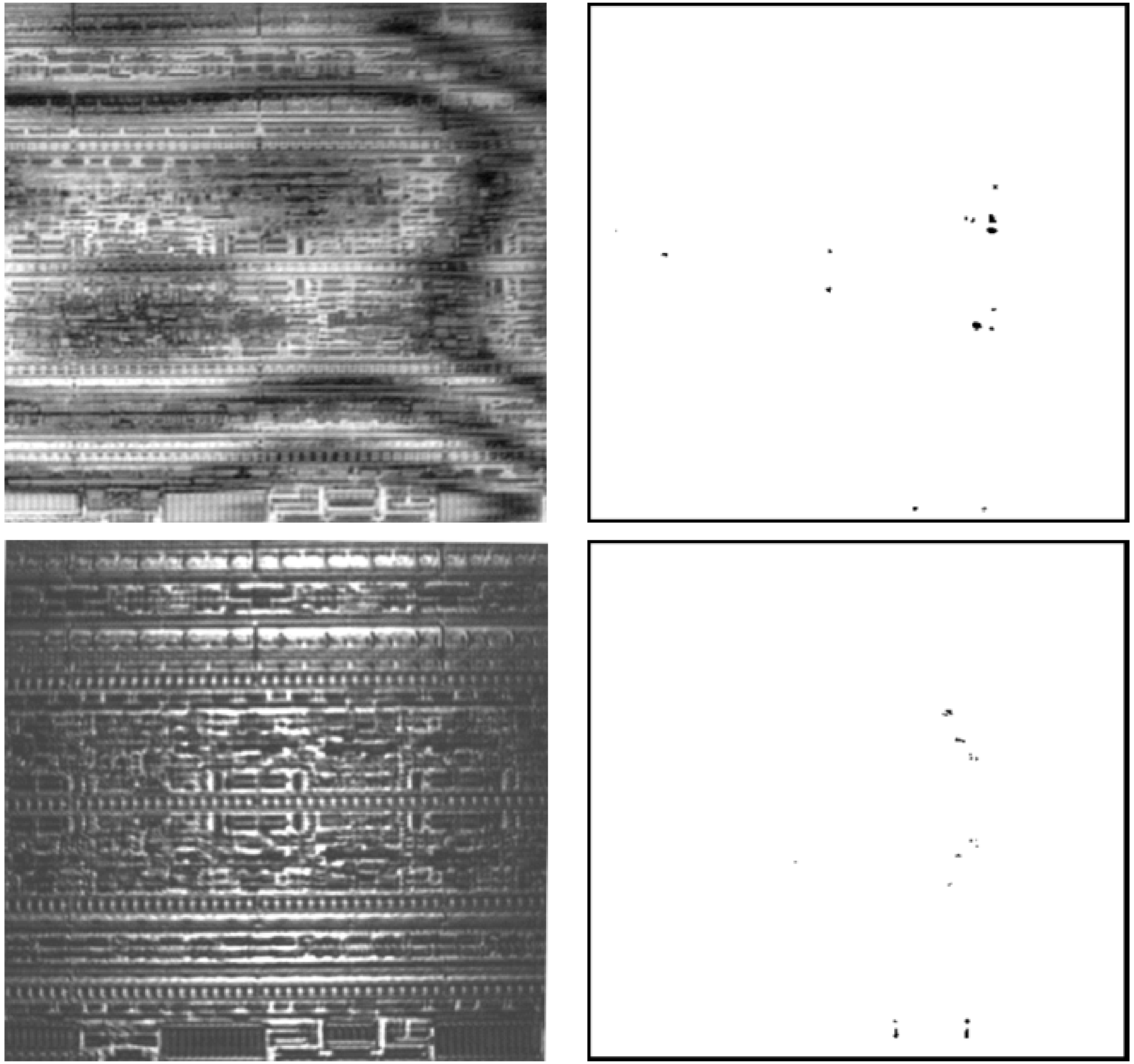
$$D = \frac{0.61\lambda}{NA}$$

- **Optical Resolution for Backside Silicon Imaging**
  - **Backside imaging historically utilizes the Silicon window where near IR light is largely transparent**
  - **Airgap objectives became largely ineffective a long time ago**
  - **Solid Immersion Lenses have reached their theoretical max**
  - **Wavelength is next to optimize**

MIX AND MATCH WAVELENGTH AND NA

633 nm

1320 nm



Reflected Light

LVI

Visible LVP
1.4 NA OIL

LVP
2.6 NA SIL

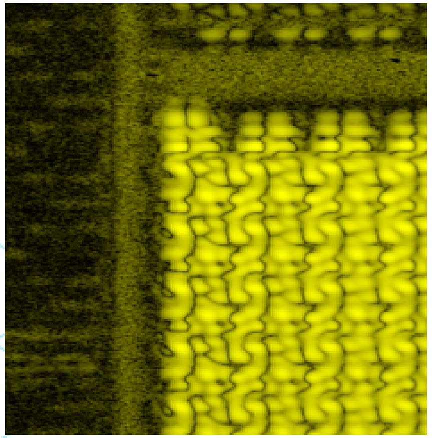
IR AND VISIBLE LVP

- IR
  - Advantages
    - Silicon Transparency
    - Straightforward backside sample preparation
  - Limitations
    - Long wavelength spatial resolution
    - Resolution enhancements becoming difficult
- Visible light advantages
  - Shorter wavelengths / Enhanced spatial resolution
  - Increased thinning possible
  - New resolution enhancement realm
- Why does spatial resolution matter so much?

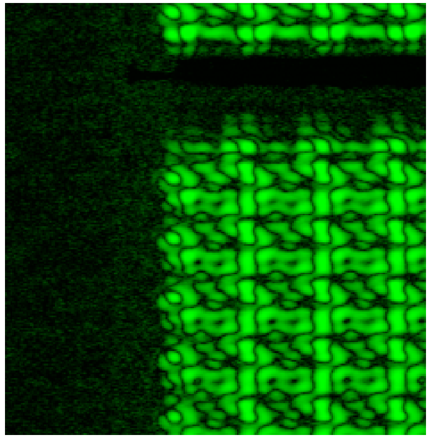
CONVENTIONAL IR LVP LIMITATIONS

- Cross-Talk
  - Spot size of probe is so large that it overlaps two different nodes of combinational logic

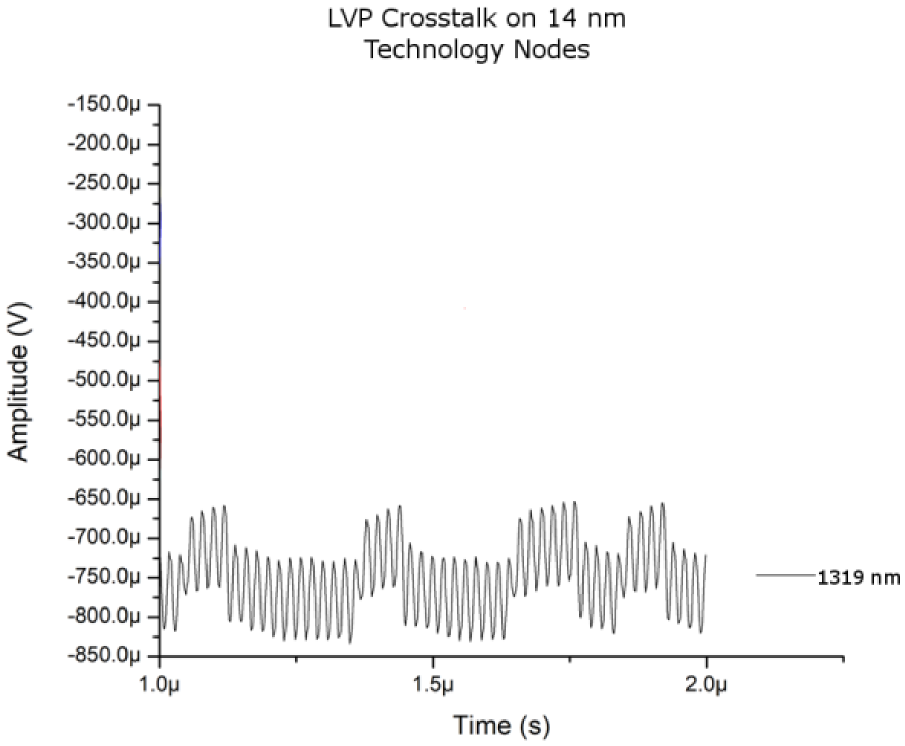
14 nm LVI, 1319 nm, 3.3 NA SIL



25 MHz Data

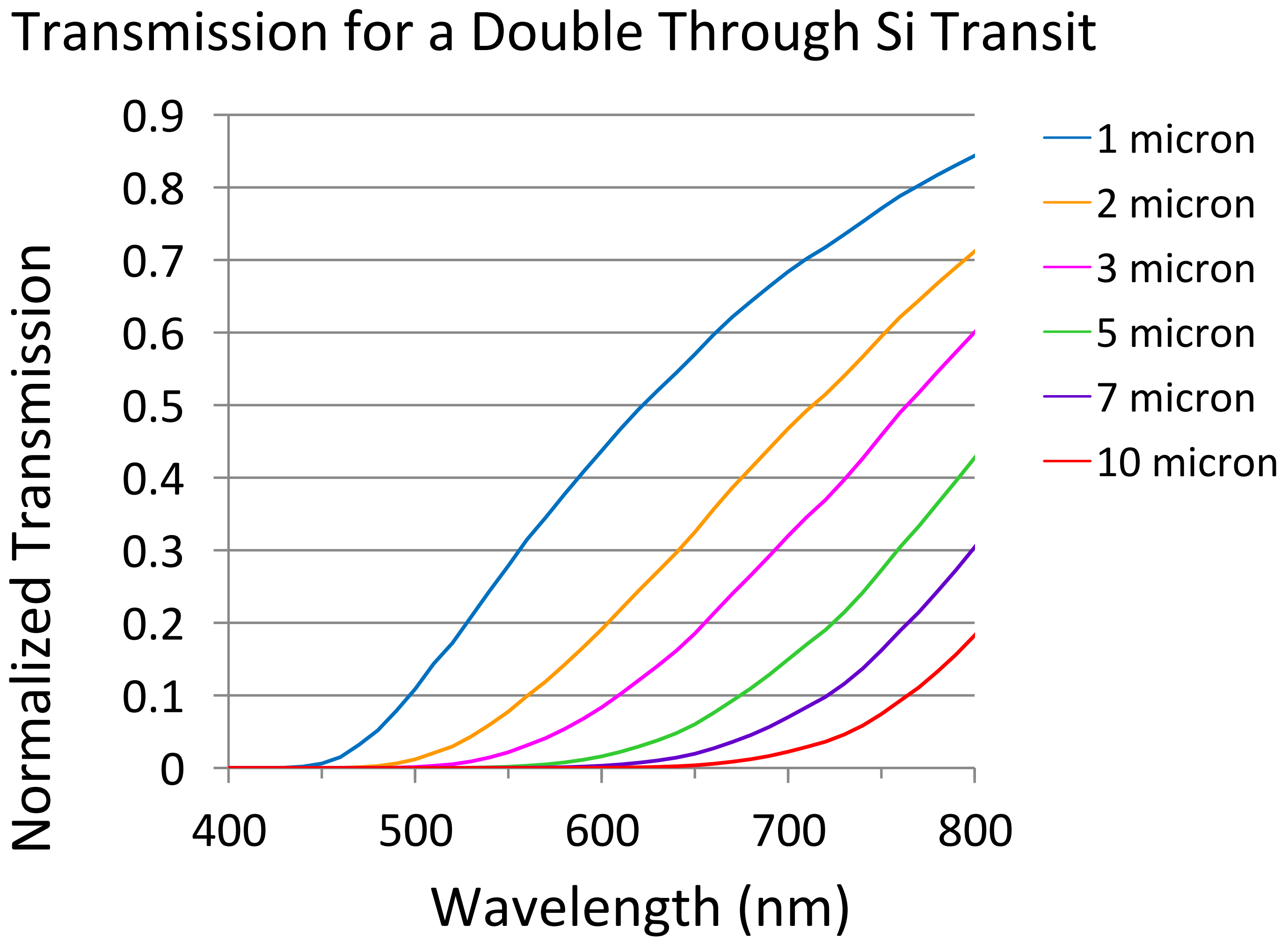


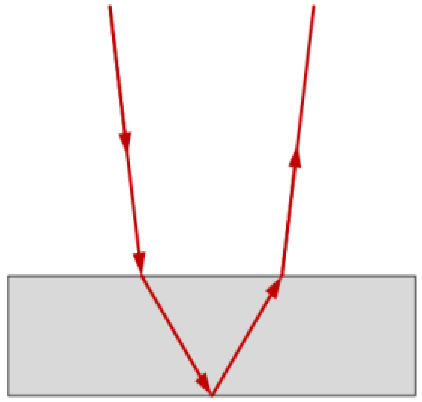
50 MHz Clock



ADVANCED SAMPLE PREPARATION FOR VISIBLE LVP

VISIBLE LIGHT TRANSMISSION





Raw data from: PVEDUCATION.ORG – Optical Properties of Silicon
http://www.pveducation.org/pvcdrom/materials/optical-properties-of-silicon

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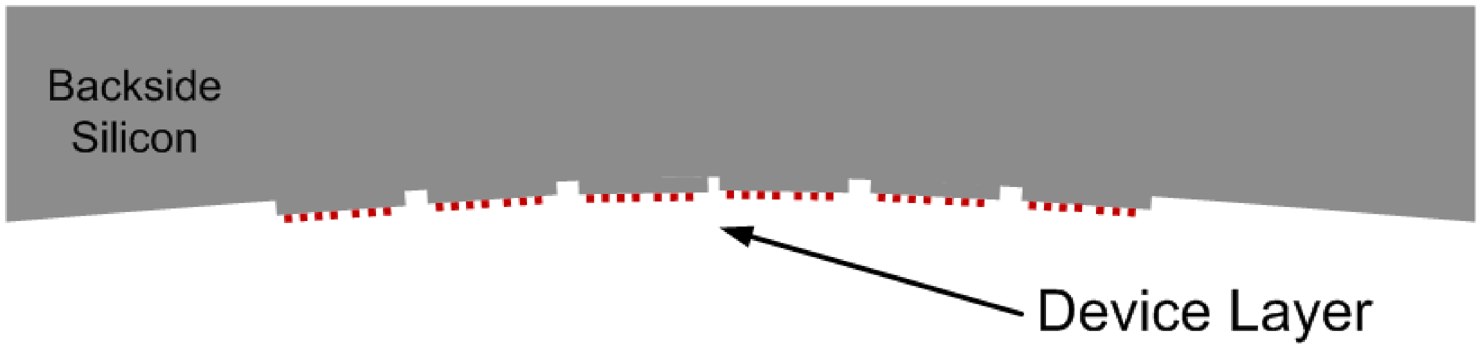
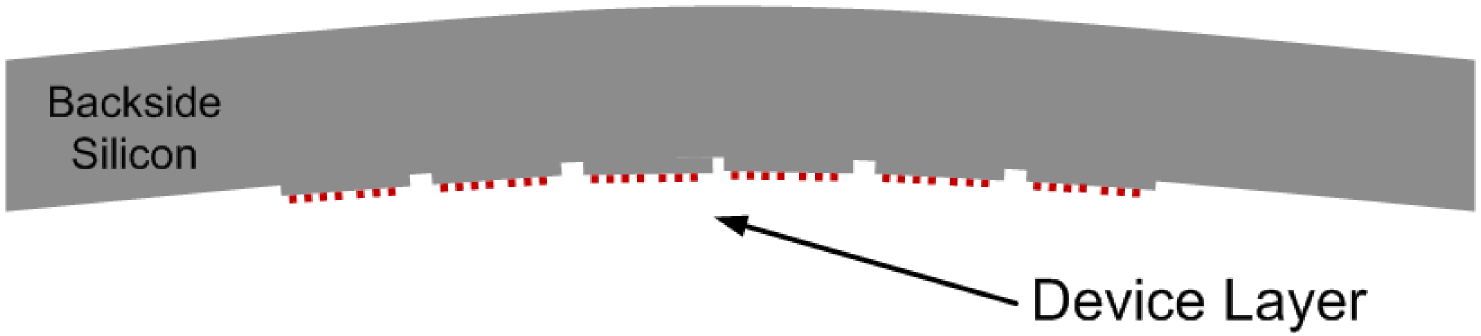
ADVANCED SAMPLE PREPARATION

Advantages of Conformal Backside Substrate Removal



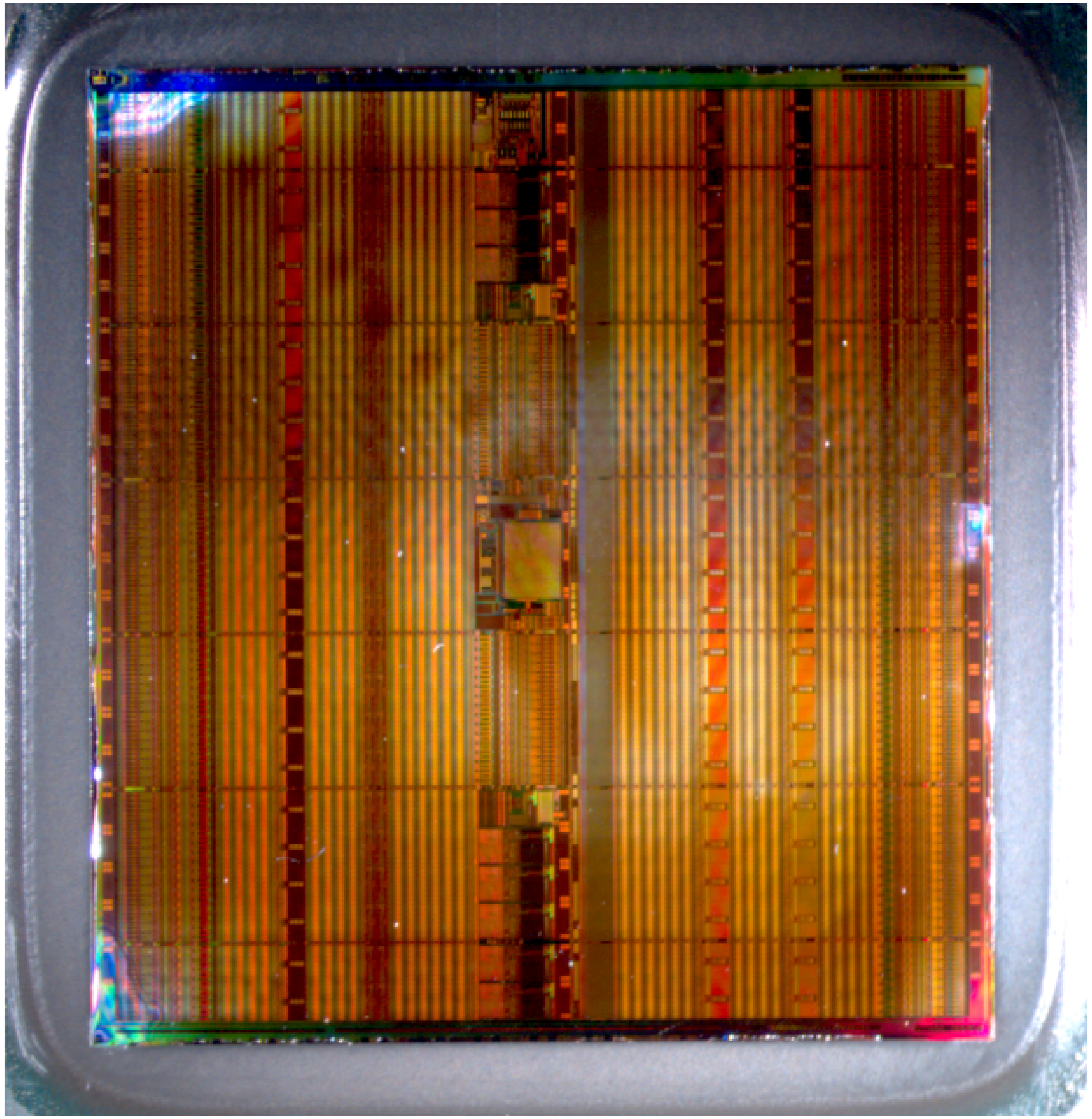
Lapping



Adaptive Milling

Improved Ultra-Thinning

- **Xilinx Virtex 4 LX-25**
  - **~ 3 µm remaining Silicon**
    - **Still Functional**
  - **Prepared on Variomill**

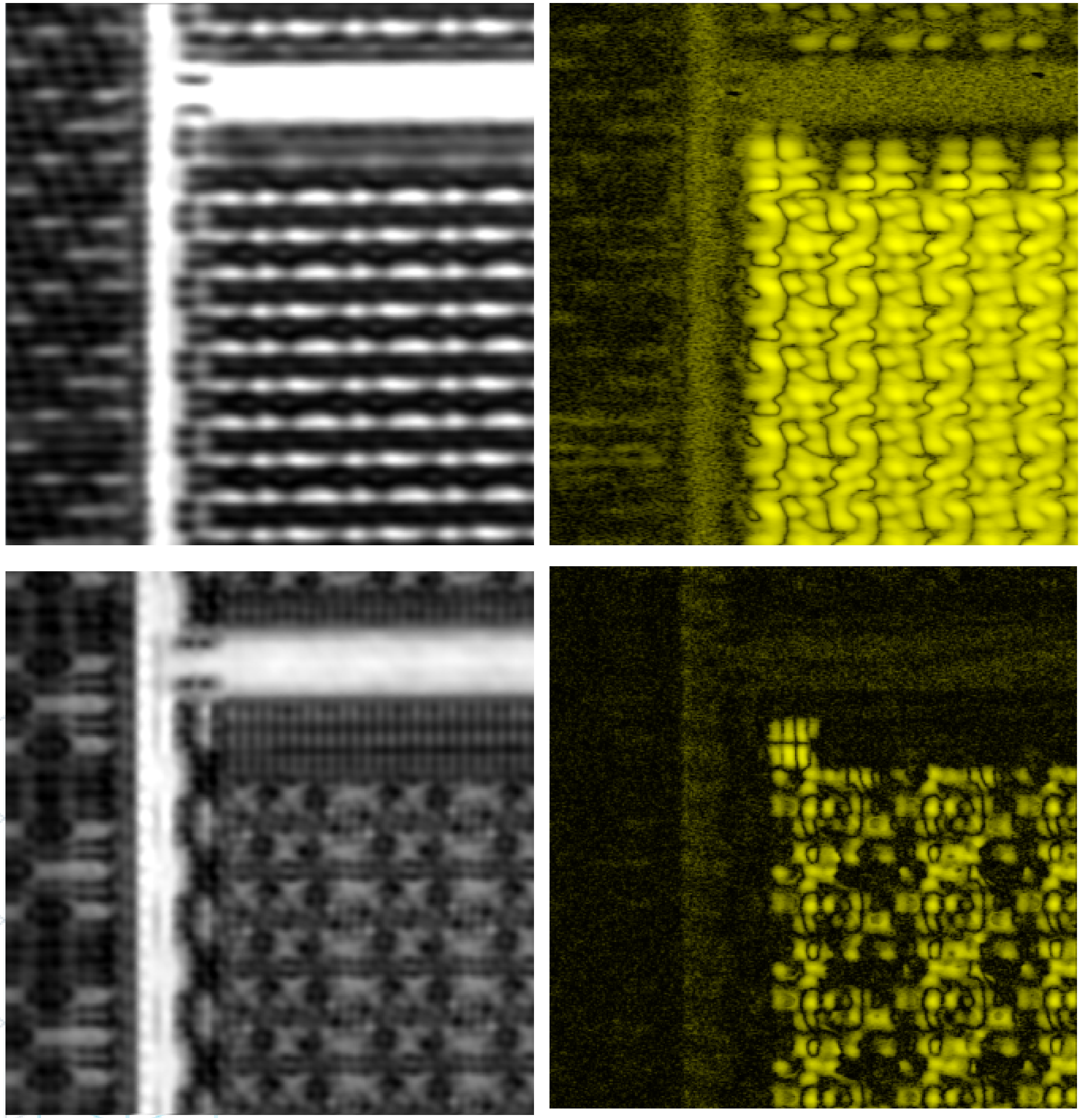


VISIBLE LVP VS. CONVENTIONAL IR LVP

VISIBLE LVP VS. CONVENTIONAL IR LVP

1319 nm 3.3 NA SIL

785 nm 3.0 NA SIL



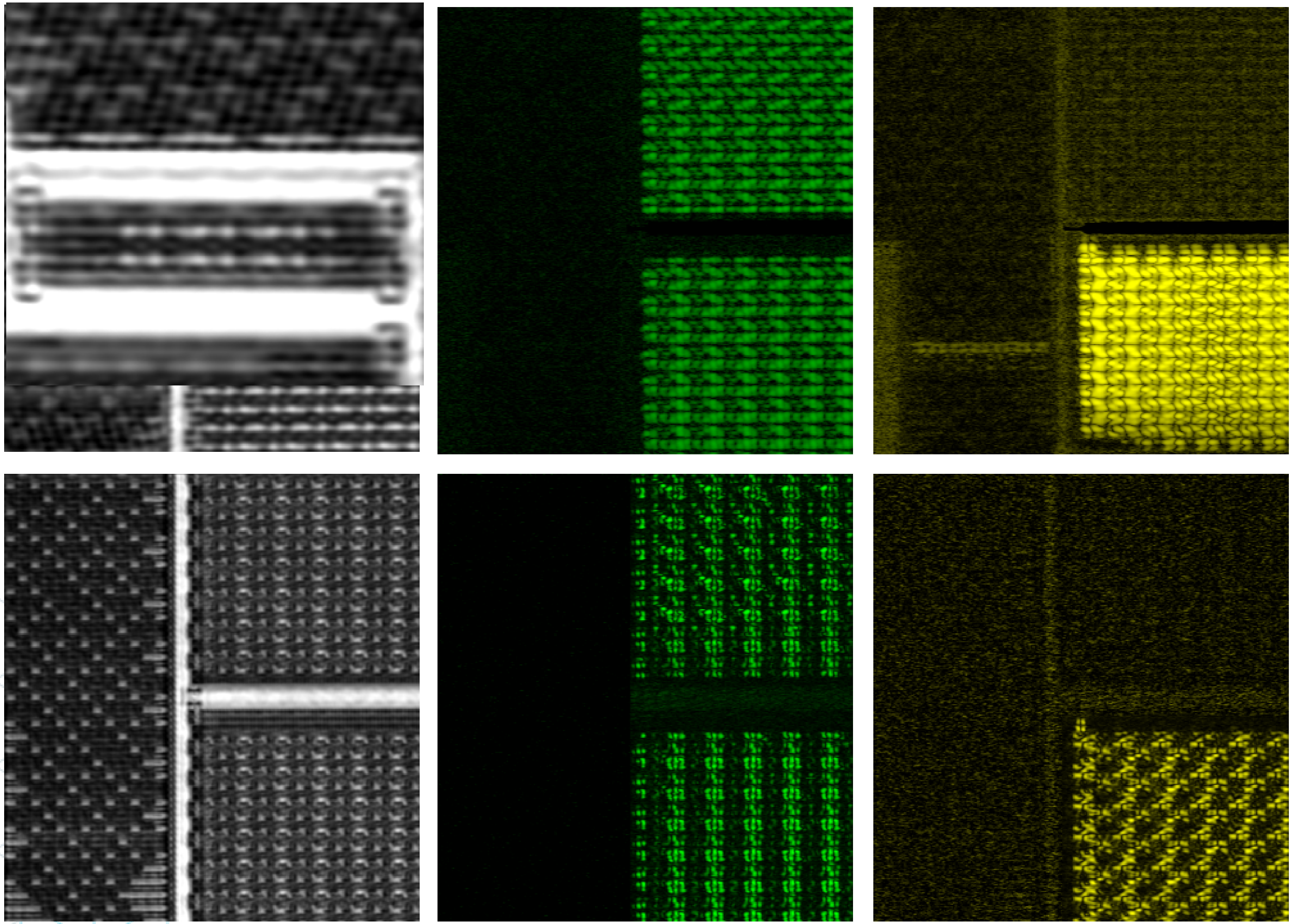
Reflected Light LVI

- Significant improvement in Spatial resolution
- Using visible spatial resolution improves ability to localize logic within highly optimized cells

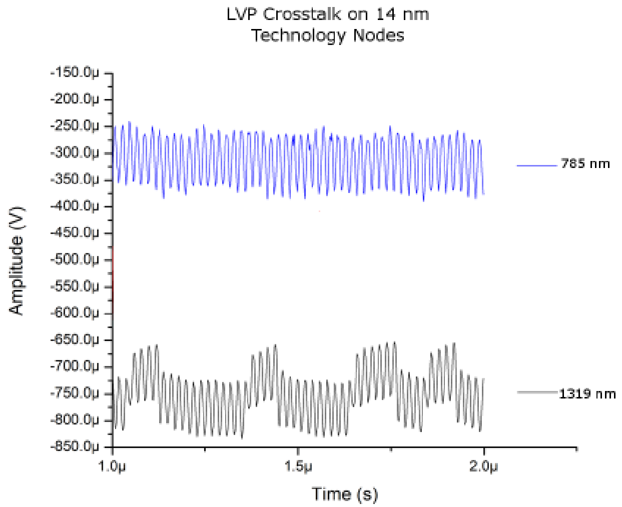
VISIBLE LVP VS. CONVENTIONAL IR LVP CROSSTALK

1319 nm 3.3 NA SIL

785 nm 3.0 NA SIL

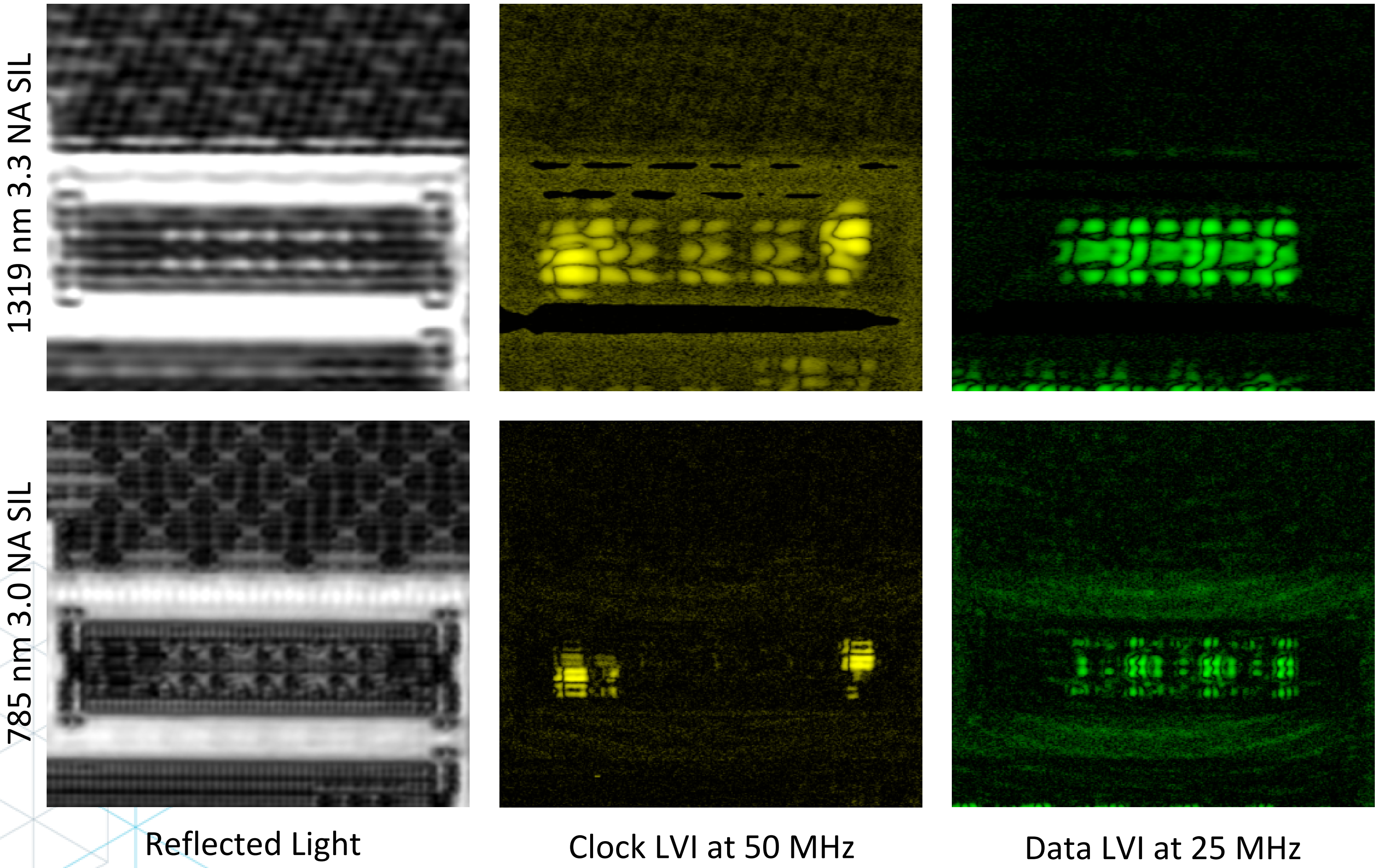


Reflected Light | Clock LVI at 50 MHz | Data LVI at 25 MHz



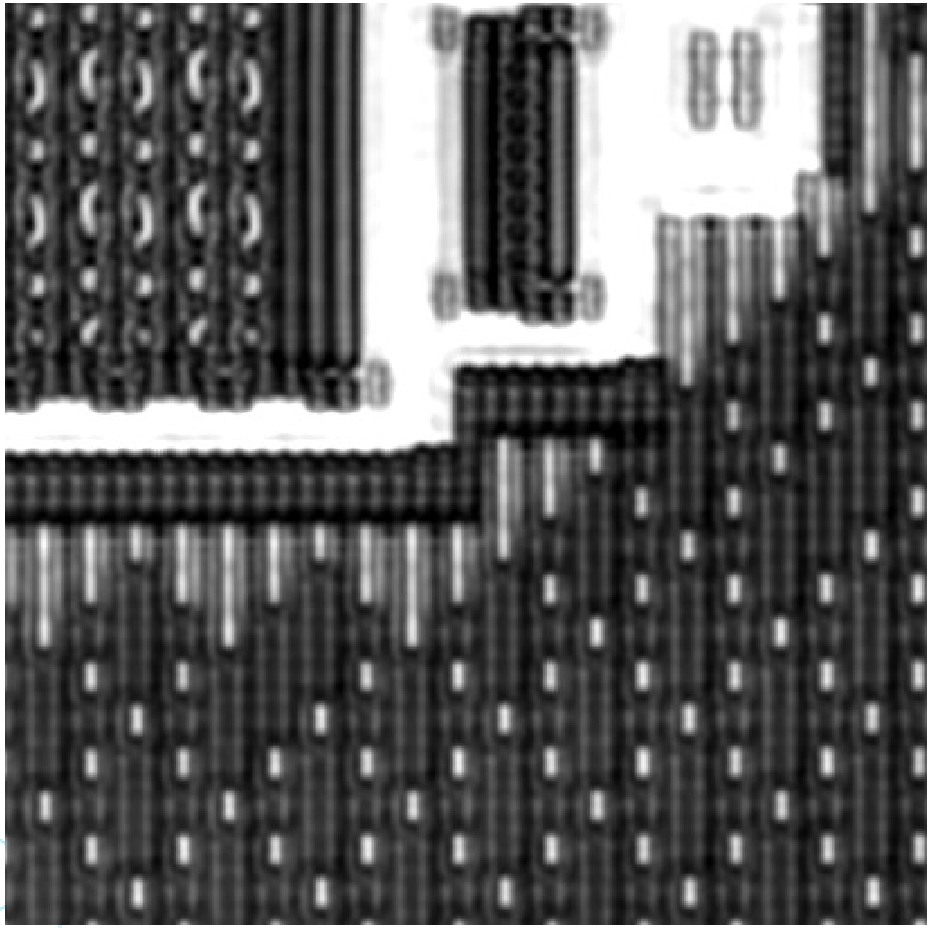
- Near complete removal of crosstalk on 14 nm logic when using visible light

VISIBLE LVP VS. CONVENTIONAL IR LVP

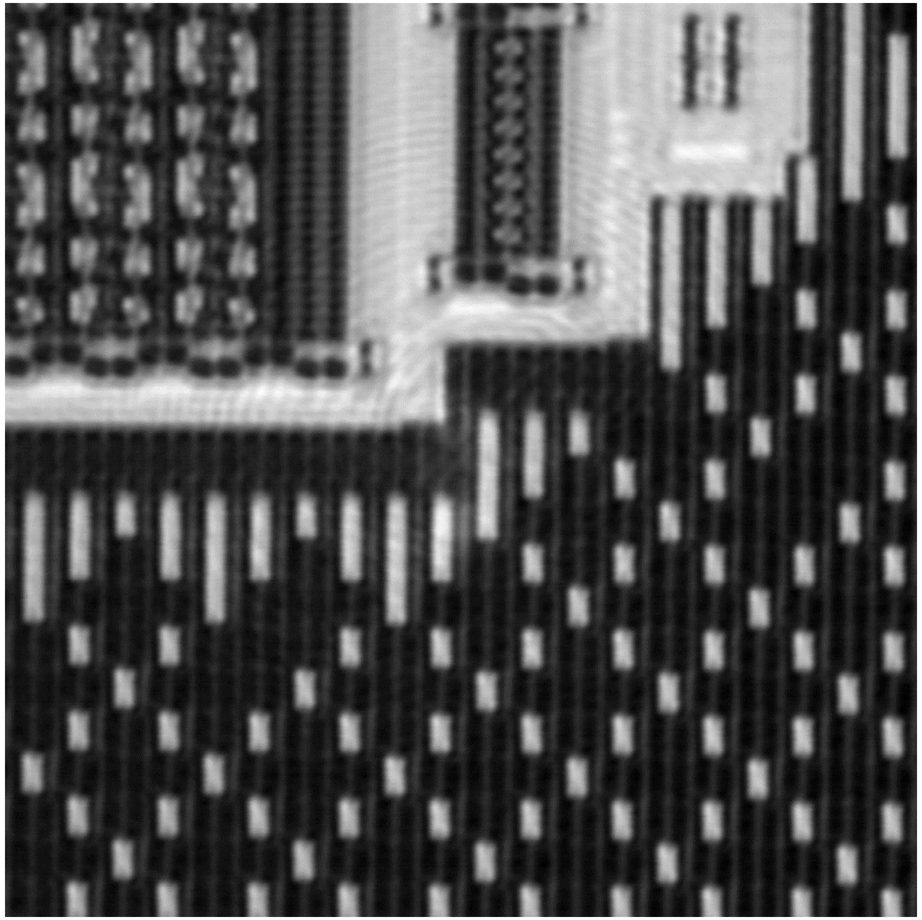


- IR LVP
  - Better SNR
    - Notice the regions between the end logic that are running close to periodic data
    - The IR LVP picks it up
- Visible LVP
  - Better Resolves the logic
    - PFET and NFET are probe-able
  - Reduced SNR

THE VERY BEST SPATIAL RESOLUTION HAS TO OFFER



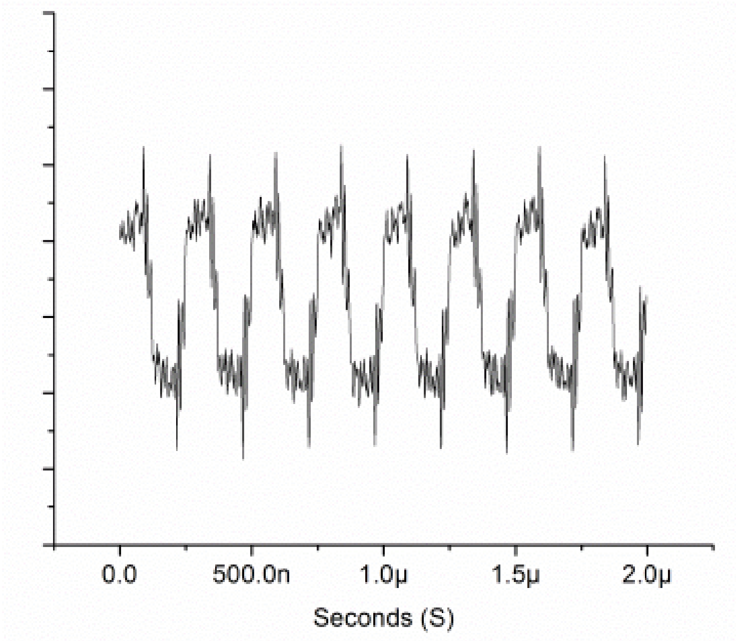
785 nm 3.0 NA reflected light on 14 nm



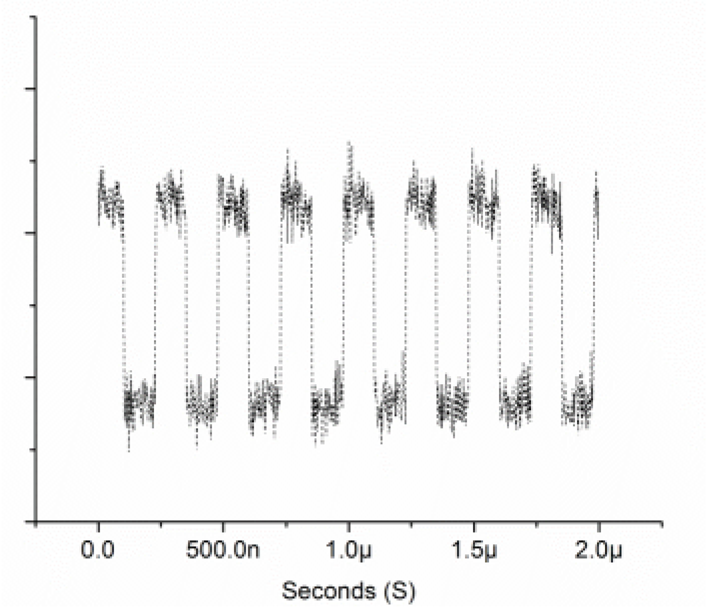
577 nm 3.2 NA SIL reflected light on 14 nm

WAVEFORM DEFORMATION

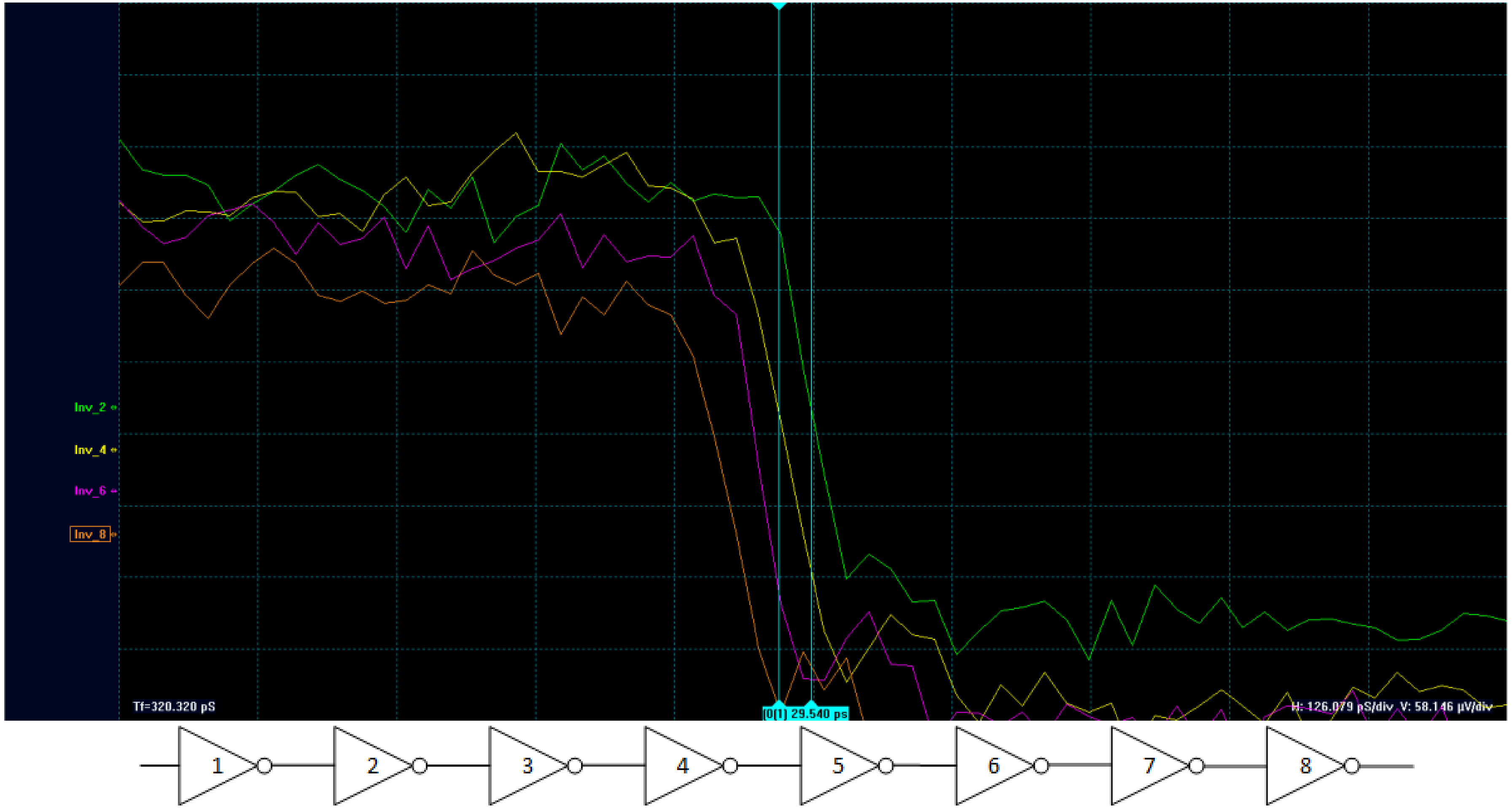
- Visible Light Waveform
  - Highly logic dependent
  - Loading of the logic with E-H pairs generated in silicon causes transistor to work harder to switch states
  - Distorted rise and fall times



- IR Waveform
  - Very little if any distortion of waveform
  - Ideal for analog applications



VISIBLE VS. IR – TIMING SKEW



- Skew measurements are used to diagnose timing violations
  - Depending on the logic, visible probing can greatly affect the rise and fall times of probed logic
  - This can make timing skew measurements using visible light less desirable/precise
    - Especially when measuring skew between logic that is not identical

VISIBLE LVP VS. CONVENTIONAL IR LVP

- Visible Light
  - Advantages
    - Shorter wavelengths / Enhanced spatial resolution
    - Decreased Crosstalk
    - Improved combinational logic and scan chain debug
  - Limitations
    - Difficult Sample Prep
    - No good for analog
      - Creation of too many hole-pairs in substrate
    - Loading of signal in digital logic
      - Deformation of waveform
      - Decreased desirability on timing skew measurement

- IR
  - Advantages
    - Silicon Transparency
    - Straightforward backside sample preparation
    - Excellent SNR options
    - Proven, robust technology
      - Timing skew
  - Limitations
    - Long wavelength spatial resolution
    - Resolution enhancements becoming difficult
    - Crosstalk is a problem at advanced technology nodes

CONCLUSIONS

- Where one technology falls short, another takes its place
  - Visible LVP is used by every bleeding edge chip maker in the world
  - Most are well past 14 nm and looking at sub-10 nm nodes
  - Appears to be what industry is behind for the foreseeable future
  - Currently at 785 nm probe with 5 μm RST samples
  - Future at 577 nm probe with 1 μm RST samples
    - Testing samples this thin typically requires cooling
- There is a place for Conventional IR LVP
  - It is not going away
  - Has many larger node applications
  - Still has small node applications, but it is increasingly limited