Fundamentals of the Pulsed-Laser Technique for Single-Event Effects Testing

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Outline

- Basic Concepts

GOAL: to illustrate the basic characteristics of TPA and SPA SEE

- Case Studies
  - SEU Mapping
  - Sensitive Node Identification/Mitigation
  - Laser-Induced Latch-up Screening/Mitigation
  - Hardened Circuit Verification
  - Dynamic SEE Testing
  - Two-Photon-Induced SEE
- Conclusions/Questions

The Pulsed Laser is……..

A tool for *injecting charge* in a well-defined manner into semiconductor microelectronic and nanoelectronic structures

Has become: *indispensable* for Single-Event Effects characterization

Pulsed Laser SEE……..

- **<u>Above-band gap</u>** (*conventional, single-photon*) pulsed laser can inject:
  - a well-characterized quantity of charge
  - in a well-defined <u>*x-y* location</u>
  - with a well-defined charge-deposition profile
  - at a well-defined time
- **<u>Sub-bandgap</u>** (*two-photon*) pulsed laser can inject charge:
  - in a well-defined <u>*x-y-z* location</u>
  - at a well-defined time
  - and can propagate through silicon wafers
  - but is difficult to quantify

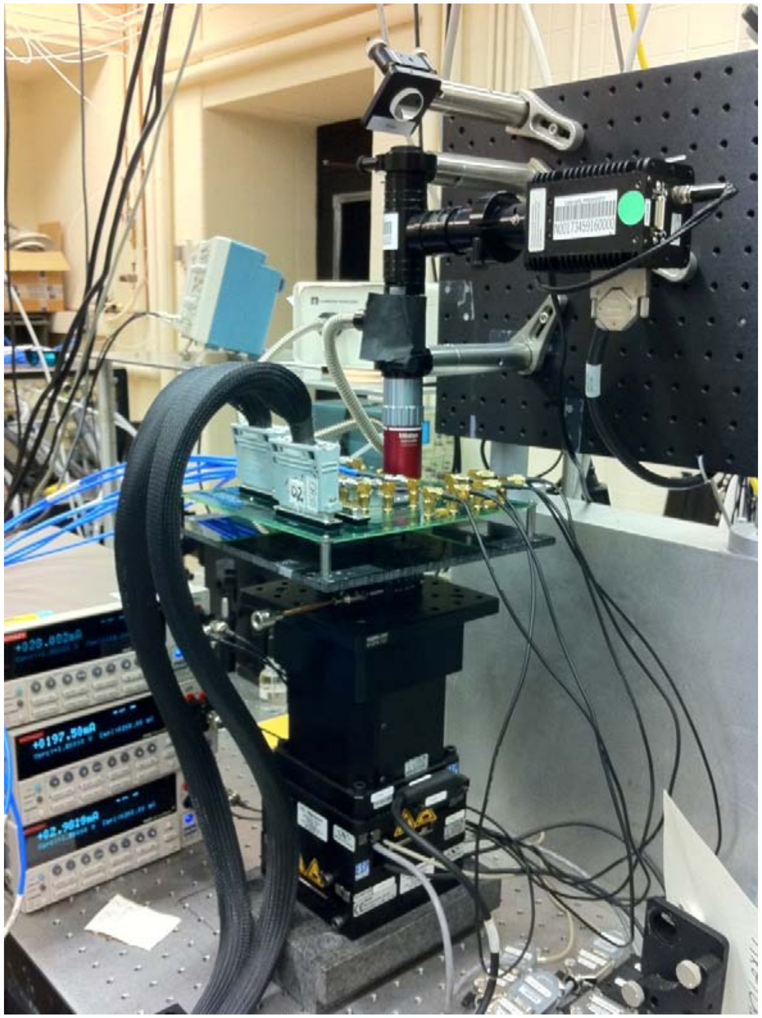
Laser SEE Experiments

TPA and SPA: TWO COMPLEMENTARY TECHNIQUES

- Neither is intended to replace heavy-ion irradiation
- TPA can not replace "conventional" (above band gap) SPA excitation

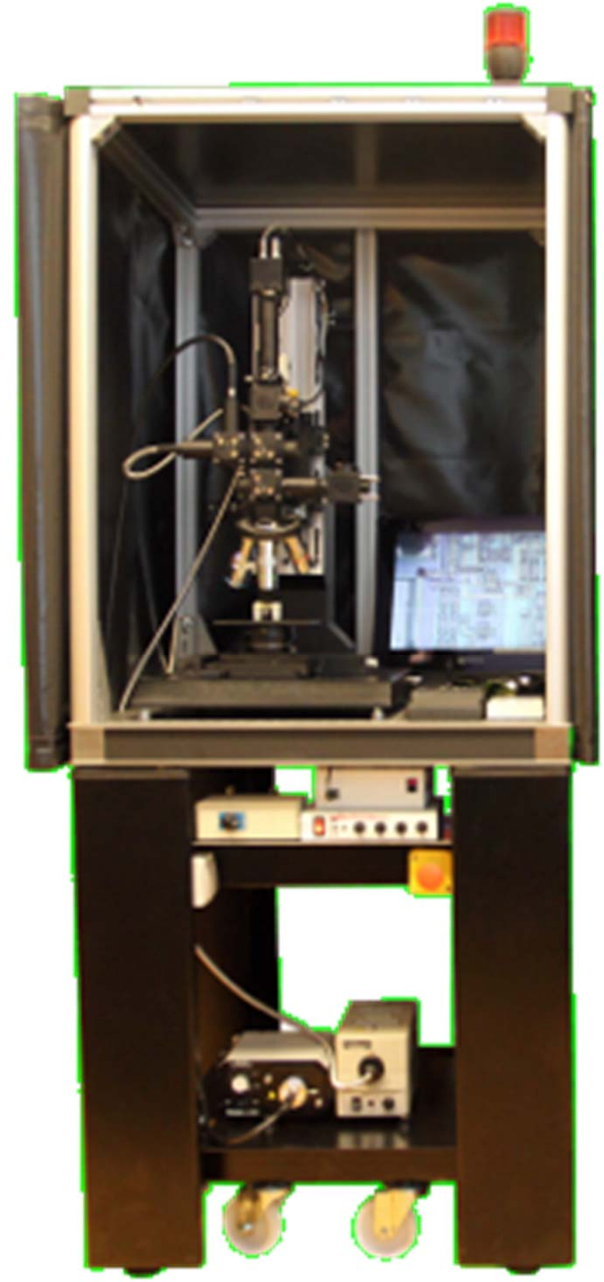
→ Two additional "Tools" in our "SEE Toolbox"

Pulsed Laser-Induced SEE Experiment

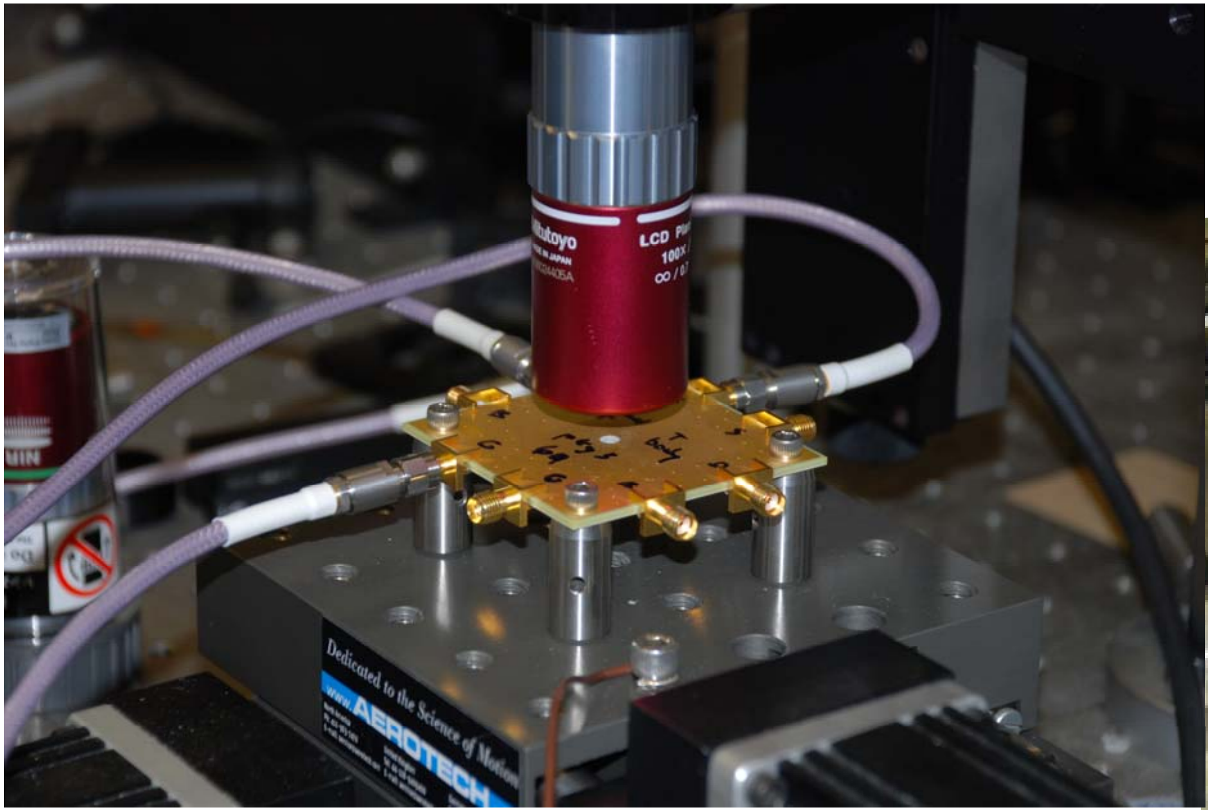


NRL Laser SEE Laboratory

PULSCAN equipment

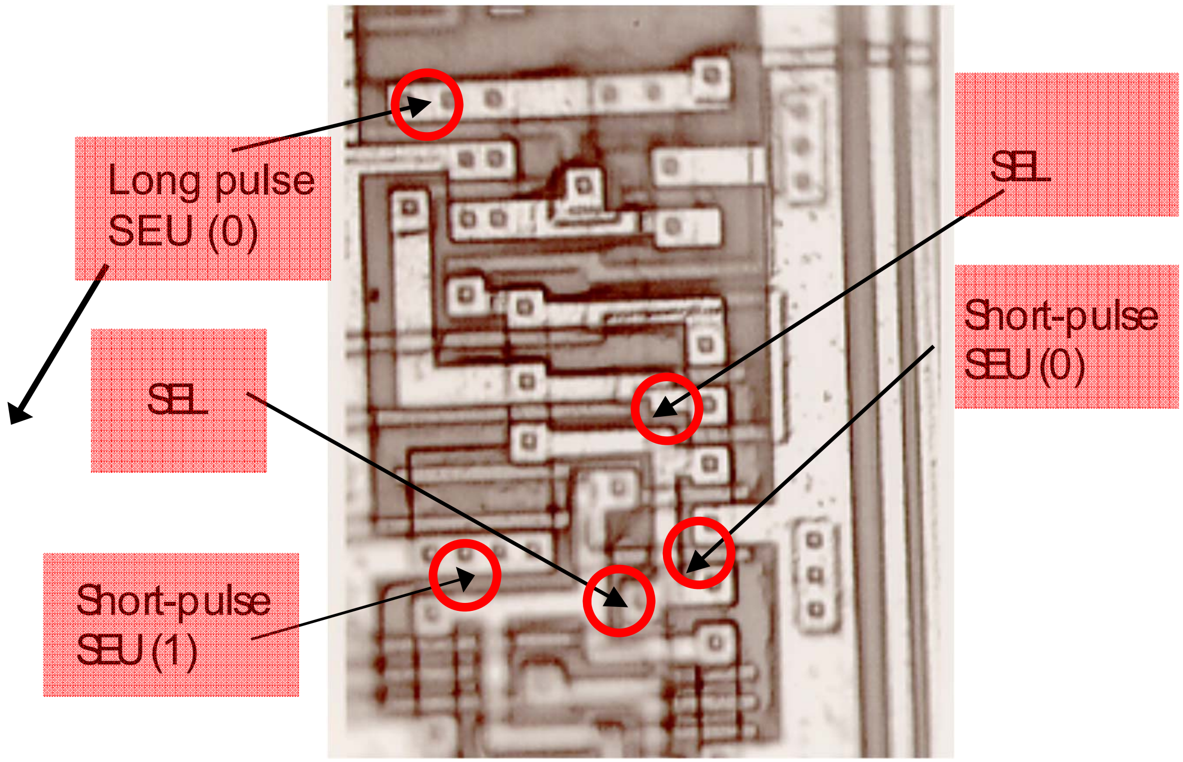


Pulsed Laser-Induced SEE Experiment



SEE Evaluation of COTS Parts

- pulsed laser interrogation permits ***detailed spatial evaluation*** of SEE that is not possible with broad-beam HI irradiation

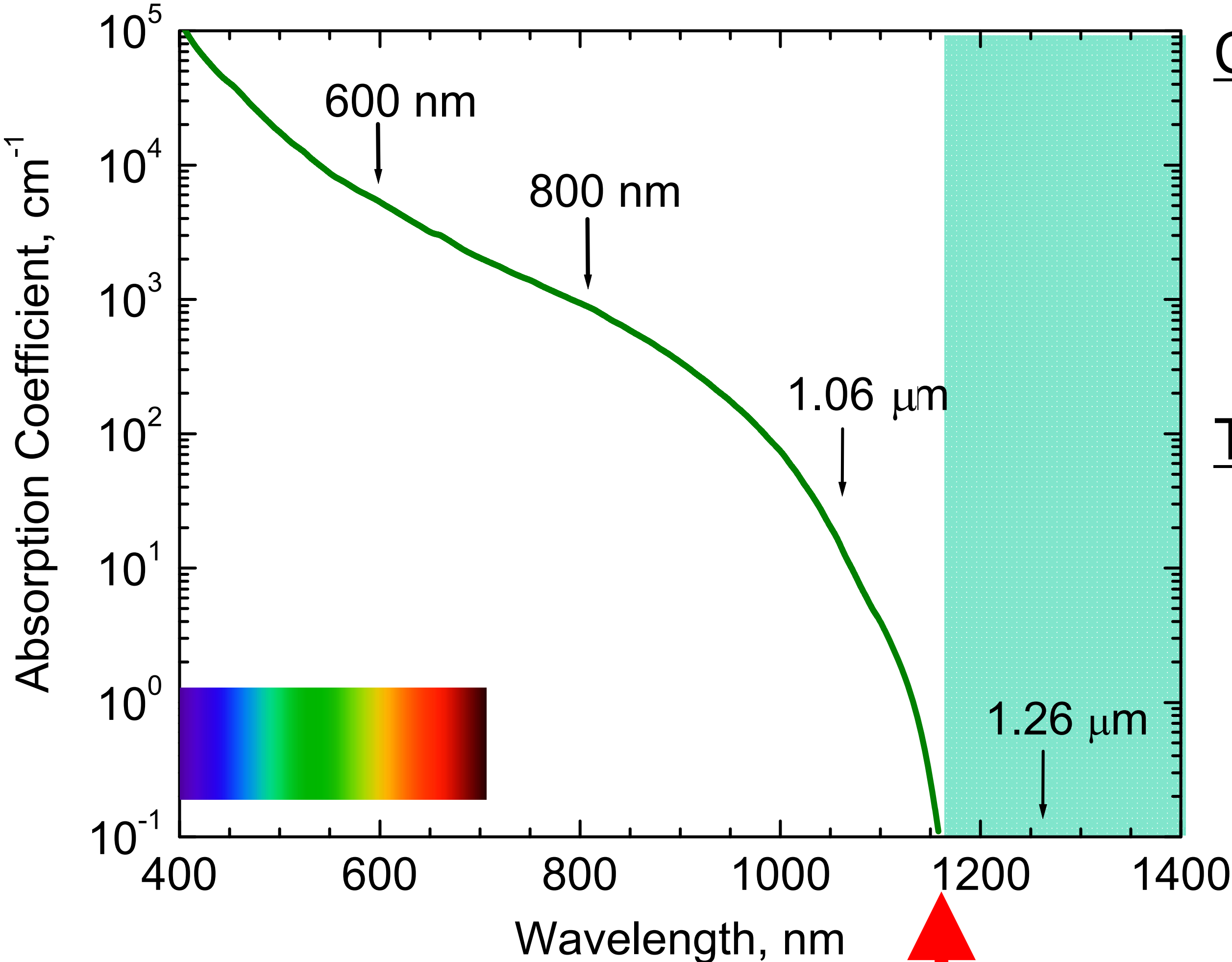


If performed with broad-beam heavy ion irradiation you may or may not be able to separate out these different effects

*Buchner, et al., TNS, **46**, 1445 (1999).*

Laser-Induced SEE Experiment:
Optical Excitation of Carriers

Optical Absorption Spectrum of Silicon



Band Edge (around 1.1 □m in Silicon)

Conventional:

λ < 1.1 μm

Above band gap

Single-photon absorption

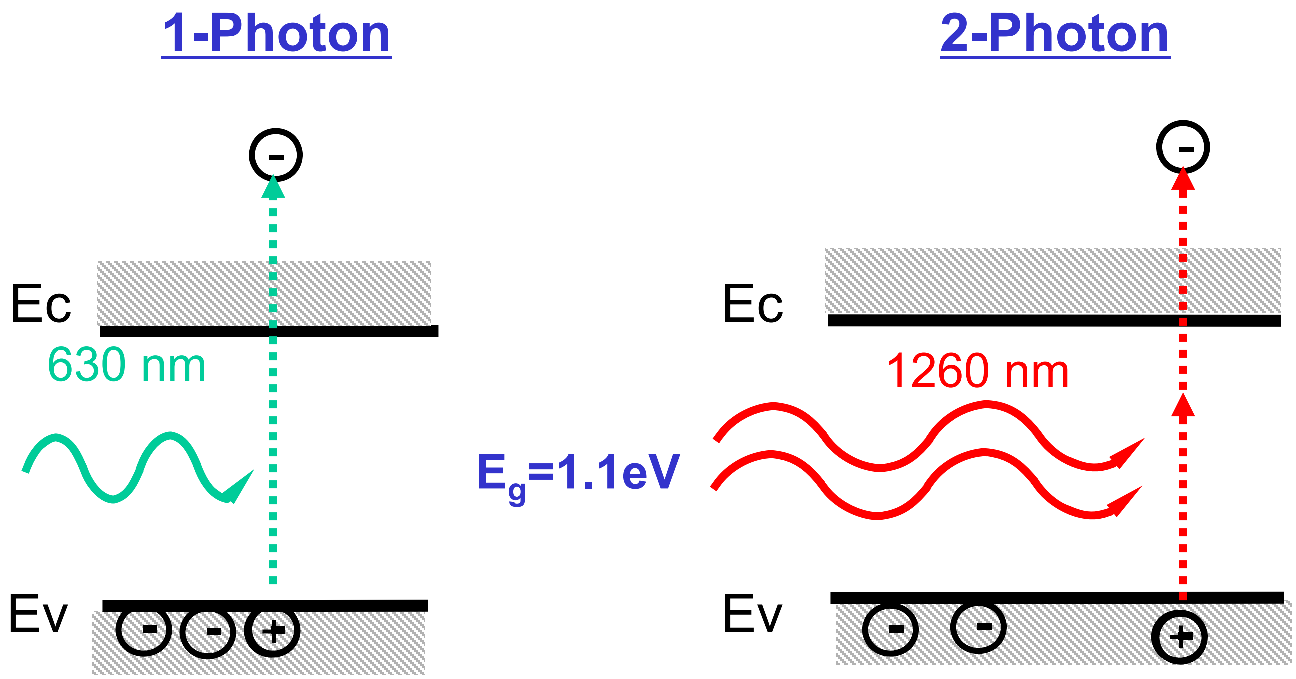
Two Photon:

λ > 1.1 μm

Sub-bandgap

Two-photon or multiphoton absorption

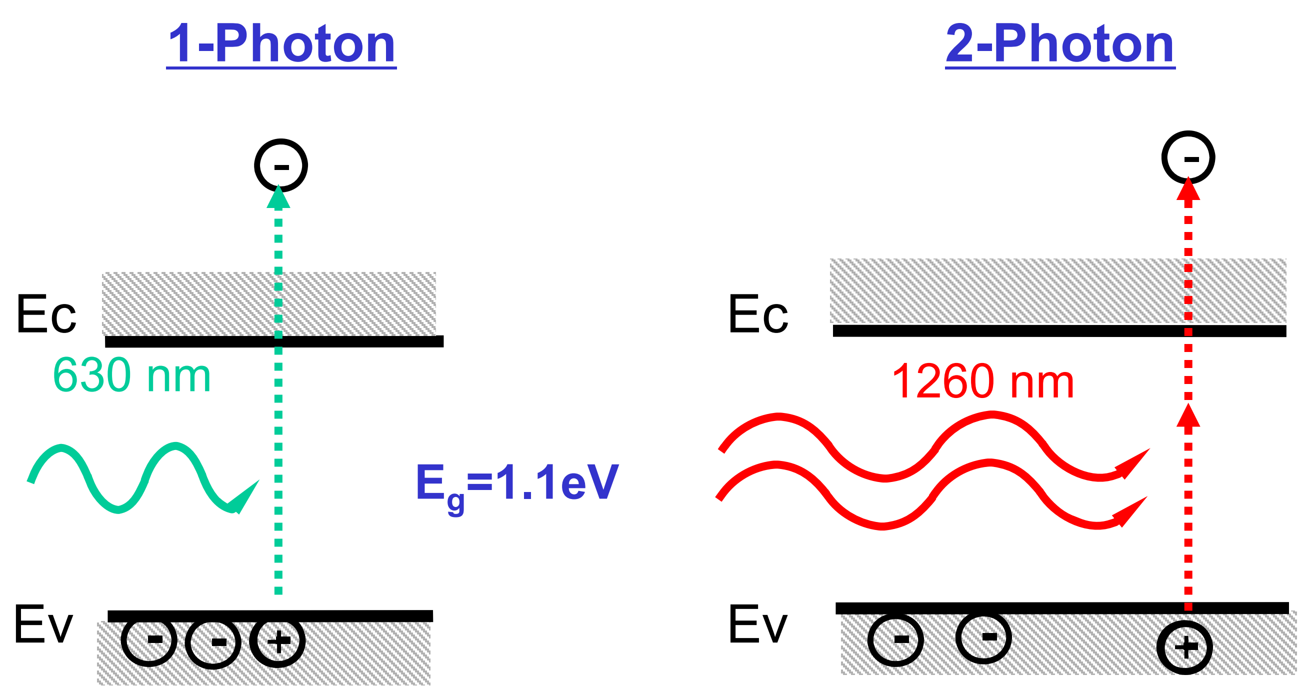
Optical Excitation of Carriers in Silicon



- *Single photon absorbed*
- *By the material (silicon)*
- *Creates a single e-h pair*

- *Two photons absorbed*
- *By the material (silicon)*
- *Simultaneously*
- *Creates a single e-h pair*

Optical Excitation of Carriers in Silicon



- ***NOTE: End result of excitation is identical***
- ***The material does not know the difference***

Optical Excitation of Carriers

Pulse Propagation Equation:

$$\frac{dI(r,z)}{dz} = -\left(\alpha I(r,z) + \beta_2 I^2(r,z)\right) - \sigma_{ex} N I(r,z)$$

Linear Absorption (Single-Photon, Beer's Law)

Nonlinear Absorption (Two-Photon)

Free-Carrier Absorption

Optical Excitation of Carriers

Carrier generation equation:

$$\frac{dN(r,z)}{dt} = \frac{\alpha I(r,z)}{\hbar\omega} + \frac{\beta_2 I^2(r,z)}{2\hbar\omega}$$

Linear Absorption
(Single-Photon, Beer's Law)

Nonlinear Absorption
(Two-Photon)

Optical Excitation of Carriers

Carrier generation equation:

$$\frac{dN(r,z)}{dt} = \frac{\alpha I(r,z)}{\hbar\omega} + \frac{\beta_2 I^2(r,z)}{2\hbar\omega}$$

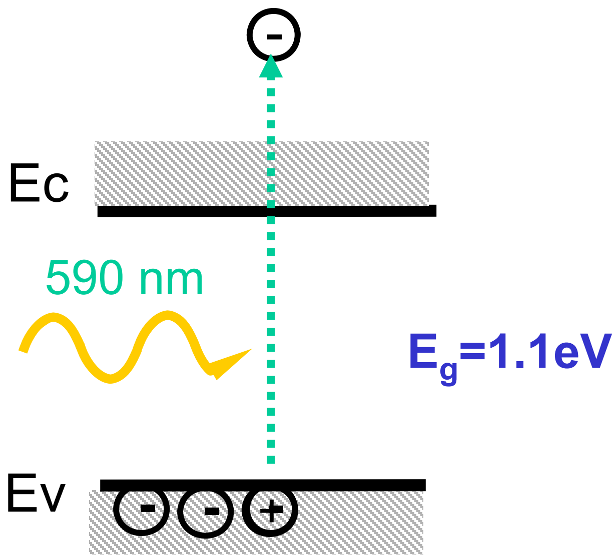
Carrier Generation:

$$N_{1P}(z_m) = \frac{\alpha}{\hbar\omega}\exp(-\alpha z_m)\int_{-\infty}^{\infty} I(t)dt,\ z_m \geq 0$$

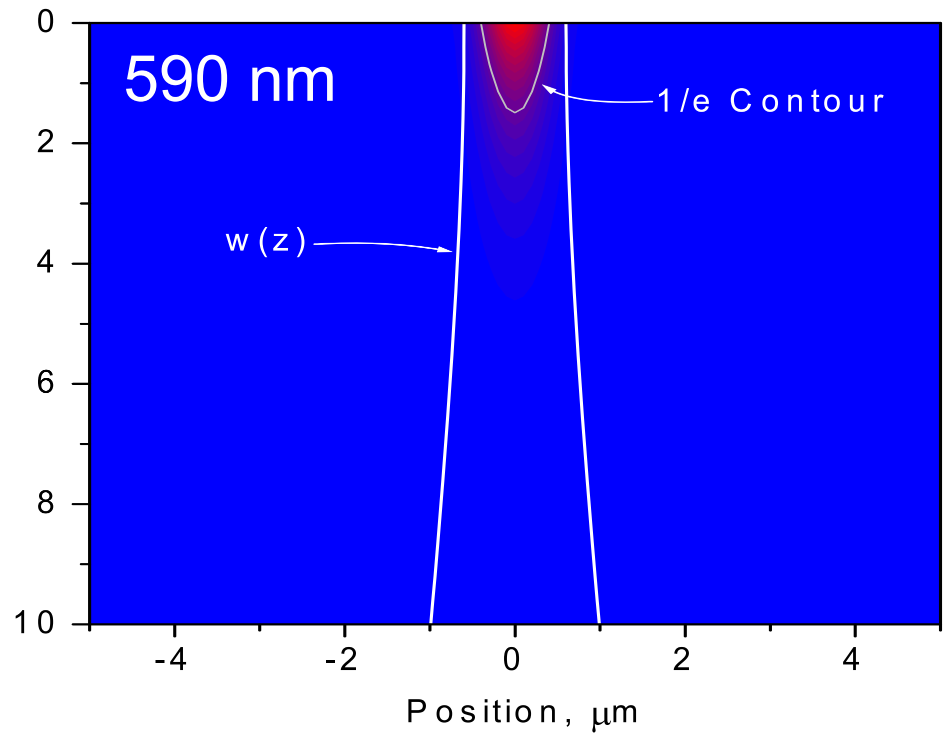
Beer' s Law

Linear (Single-Photon) Optical Absorption

1-Photon



- ***Single photon absorbed***
- ***Creates a single e-h pair***



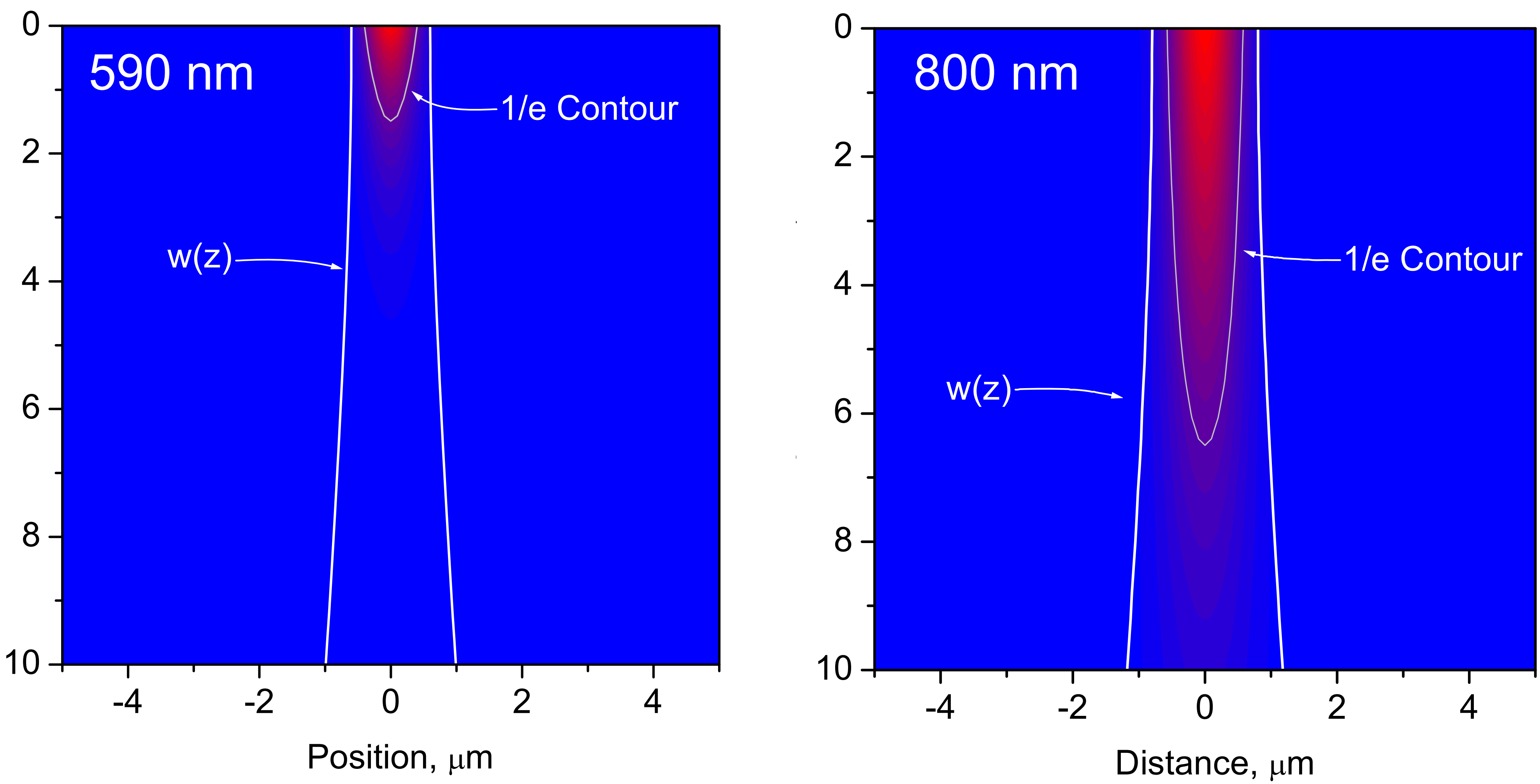
$$I(r,z) = I_o e^{-\alpha z}$$

$$N(r,z) \propto I(r,z)$$

Carrier Density Distribution

Above-Band-Gap Single Photon Absorption

$$I(r,z) = I_o e^{-\alpha z}; \quad N(r,z) \propto I(r,z)$$



Carrier Density Distribution

1/e Optical Penetration Depth

What is meant by:

- "*Penetration Depth*"?
- "*Skin Depth*"?

➔ 1/e depth

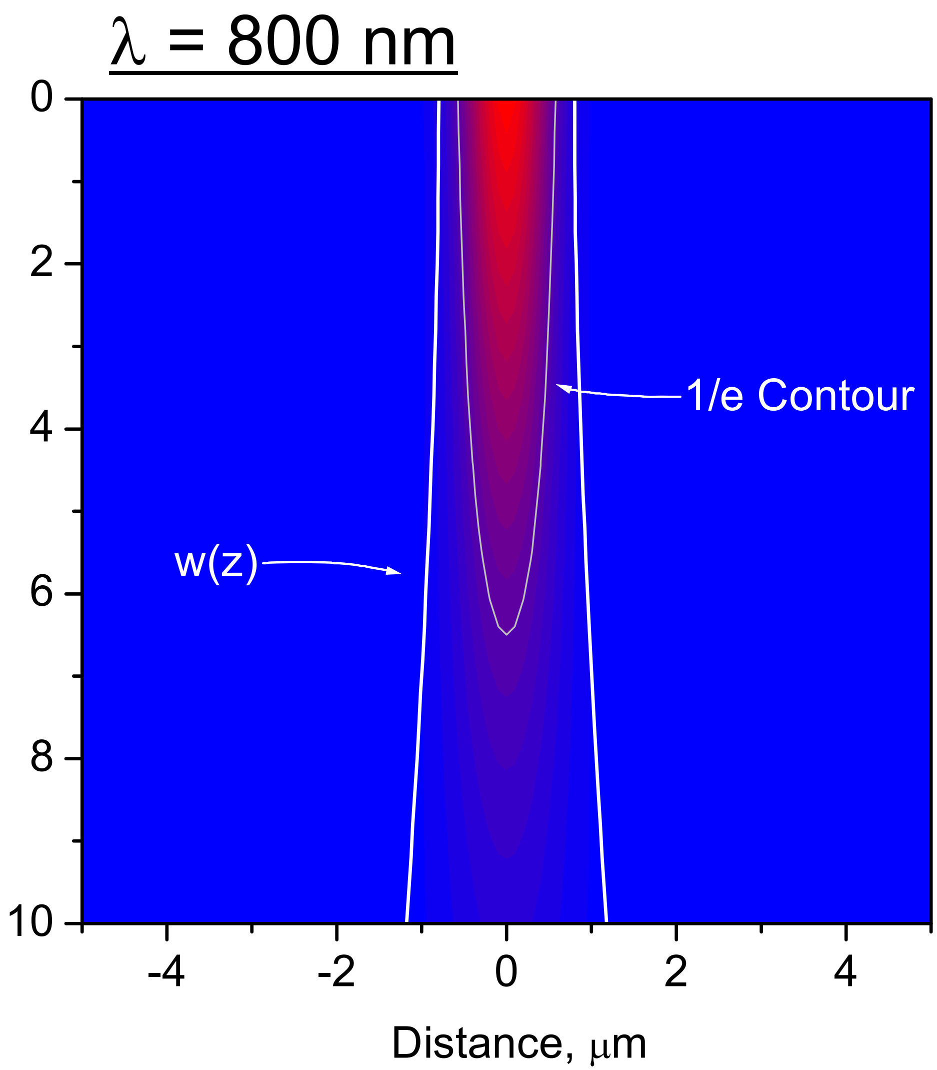
$$I_{1/e} = 0.368 I_o$$

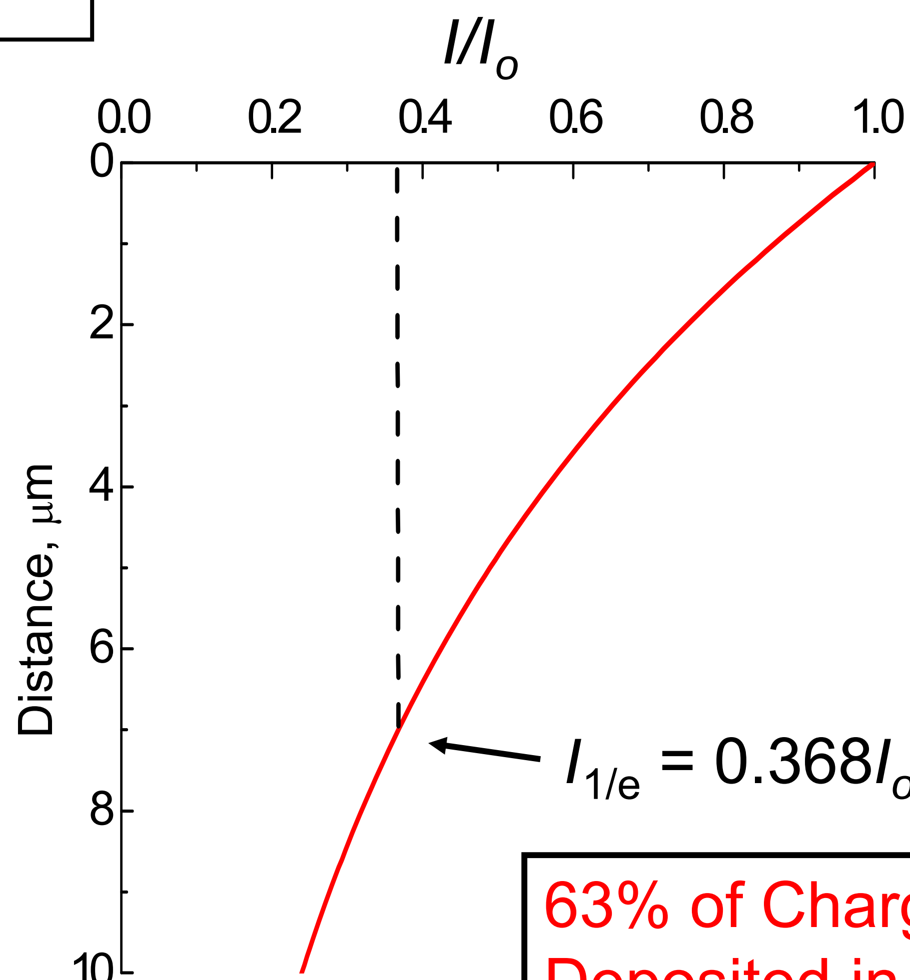
Depth at which the optical irradiance has fallen to 36.8% of its initial value ➔ 63% of Charge Deposited in 1/e depth

Carrier Density Distribution

1/e Optical Penetration Depth

$$\boxed{I(r,z) = I_o e^{-\alpha z}}$$





63% of Charge Deposited in 1/e depth

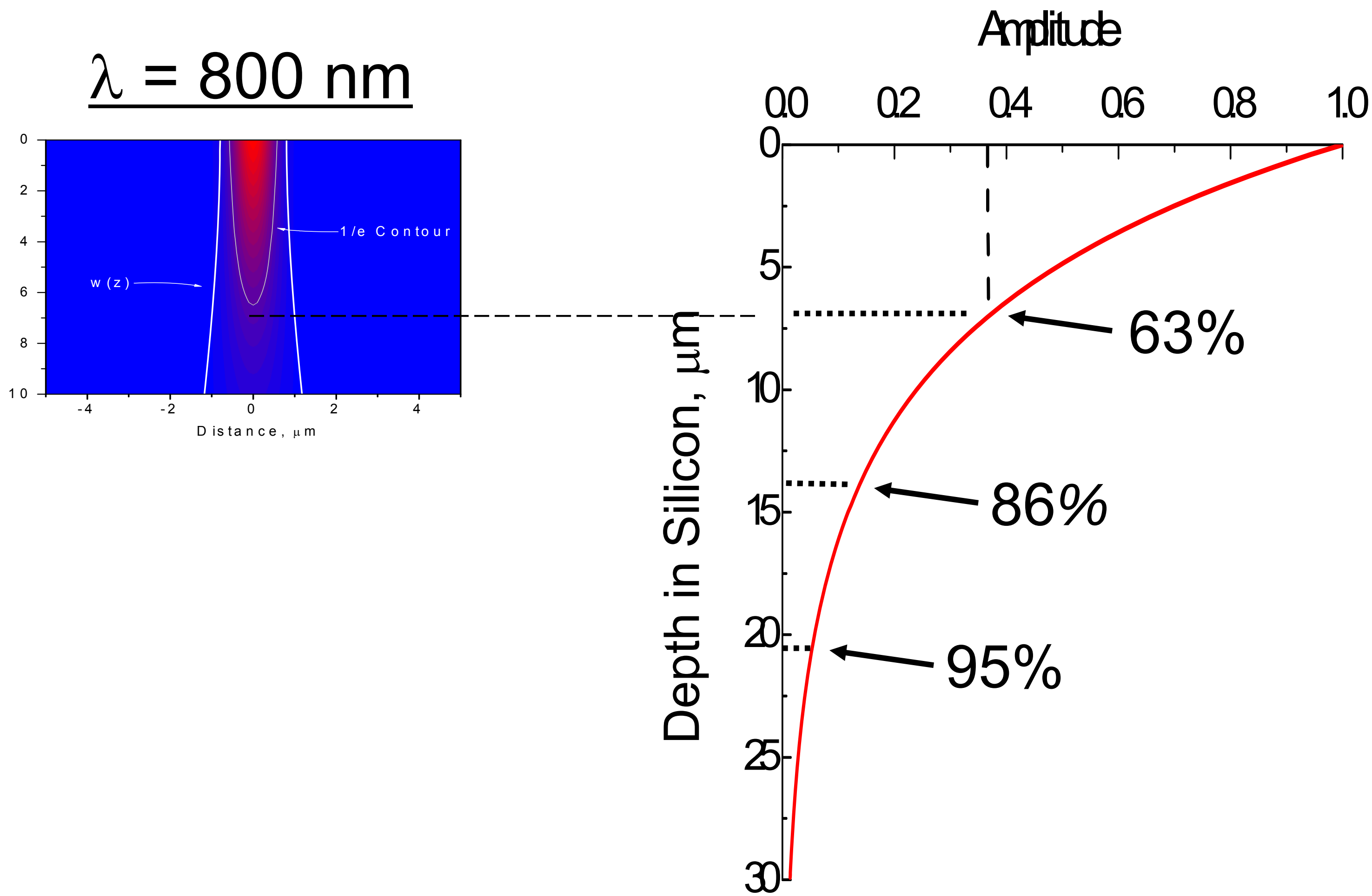
Carrier Density Distribution

1/e Optical Penetration Depth

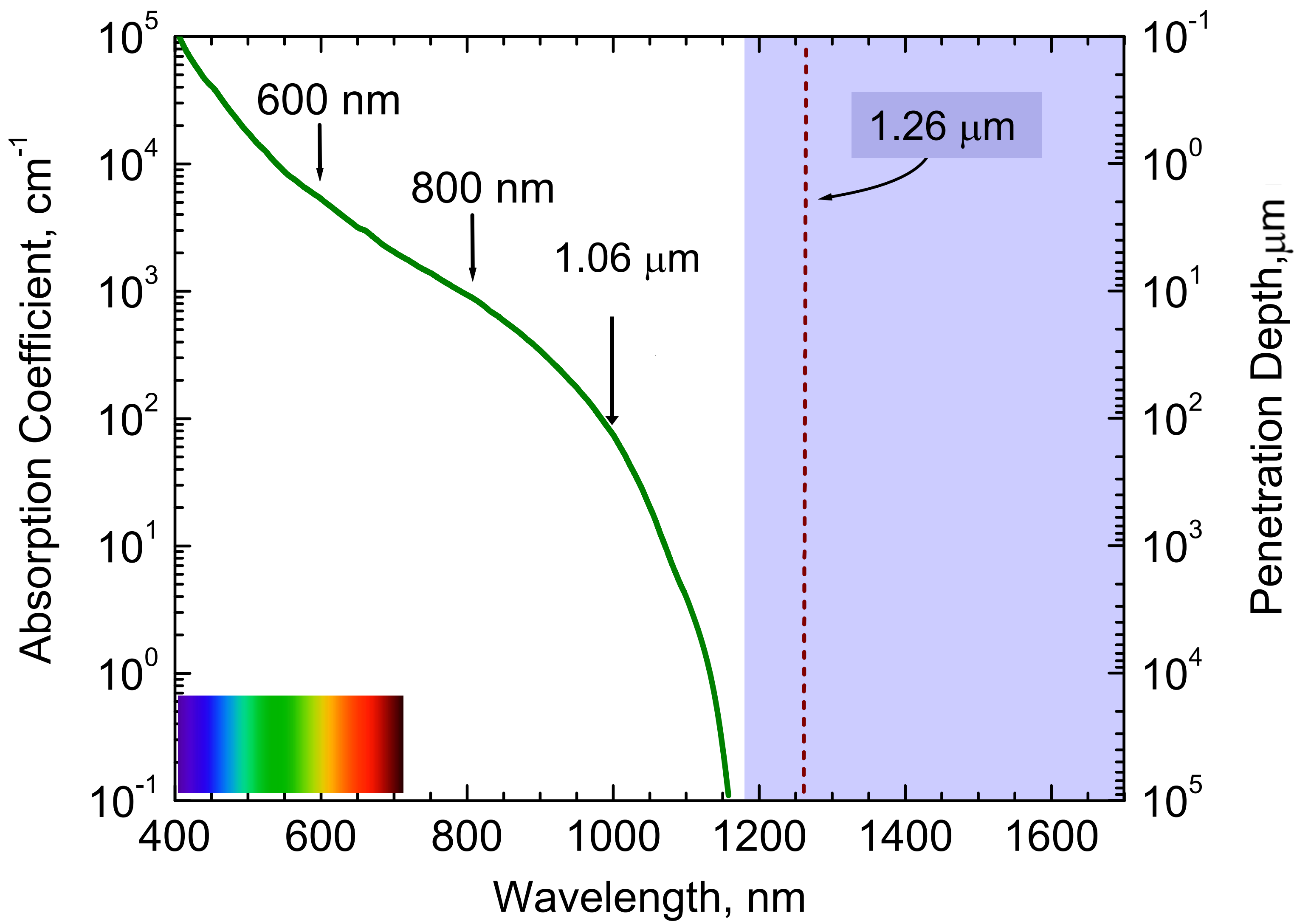
$$I(r,z) = I_o e^{-\alpha z}$$

$$N(r,z) \propto I(r,z)$$

λ = 800 nm



Nonlinear (Two-Photon) Optical Absorption



NRL Laser Single-Event Effects

13 Years of TPA SEE

Subbandgap Laser-Induced Single Event Effects: Carrier Generation via Two-Photon Absorption

Dale McMorrow, William T. Lotshaw, Joseph S. Melinger, Stephen Buchner, *Member, IEEE*, and Ronald L. Pease, *Senior Member, IEEE*

***Abstract*—Carrier generation based on subbandgap two-photon absorption is demonstrated and shown to be a viable alternative to the conventional single-photon excitation approach in laser-induced single event effects. The two-photon approach exhibits characteristics distinct from those of single-photon excitation, and may be advantageous for a range of single-event effect investigations. The charge track produced by two-photon absorption more closely resembles that of heavy-ion irradiation and, because the photon energy is subbandgap, backside injection through bulk silicon wafers is straightforward and three-dimensional mapping is possible.**

***Index Terms*—Error injection, multi photon absorption, optical propagation in absorbing media, silicon, single-event effects, single-event transients, two-photon absorption.**

I. Introduction

THE PULSED picosecond laser has become an important tool for the investigation and understanding of single-event effects (SEEs) in microelectronic circuitry [1]–[7]. In its present implementation, the pulsed-laser technique is based upon the excitation of carriers in a semiconductor material using tightly focused, above-bandgap optical excitation. Carrier generation is governed primarily by Beer's law

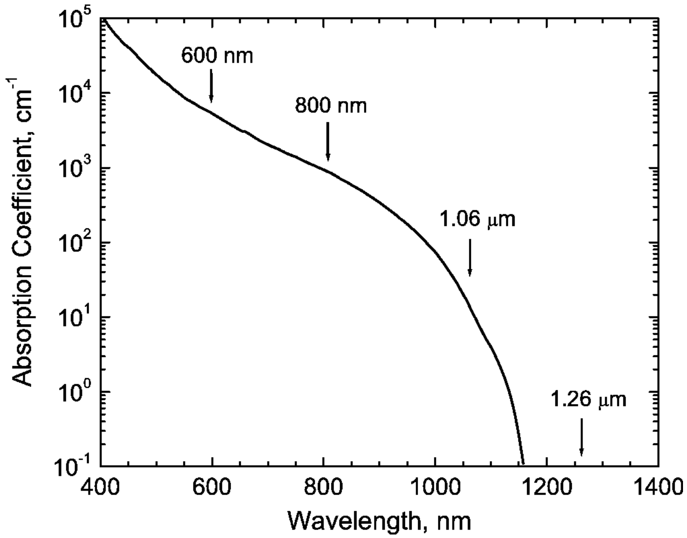


Fig. 1. Room temperature absorption spectrum of silicon in the visible and near-infrared region of the spectrum illustrating the common laser wavelengths used for above-bandgap single-event effects measurements and also that for the subbandgap experiment described here [8]–[11].

Nonlinear (Two-Photon) Optical Absorption

Carrier generation equation:

$$\frac{dN(r,z)}{dt} = \cancelto{0}{\frac{\alpha I(r,z)}{\hbar\omega}} + \boxed{\frac{\beta_2 I^2(r,z)}{2\hbar\omega}}$$

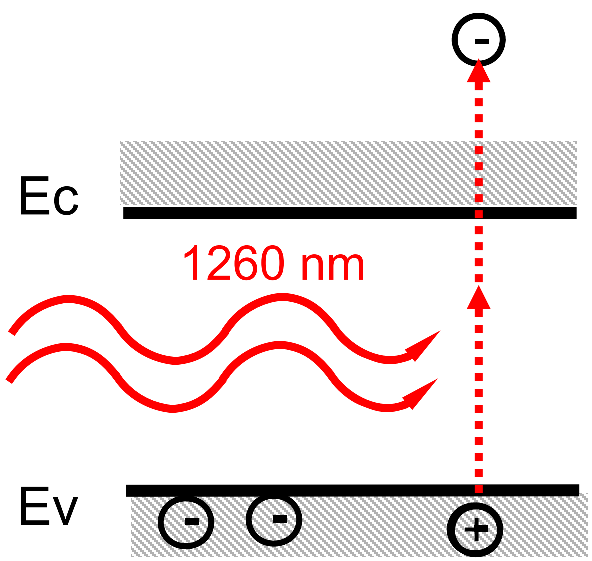
Nonlinear Absorption
(Two-Photon)

Nonlinear (Two-Photon) Optical Absorption

Carrier generation equation:

$$\frac{dN(r,z)}{dt} = \frac{\alpha I(r,z)}{\hbar\omega} + \boxed{\frac{\beta_2 I^2(r,z)}{2\hbar\omega}}$$

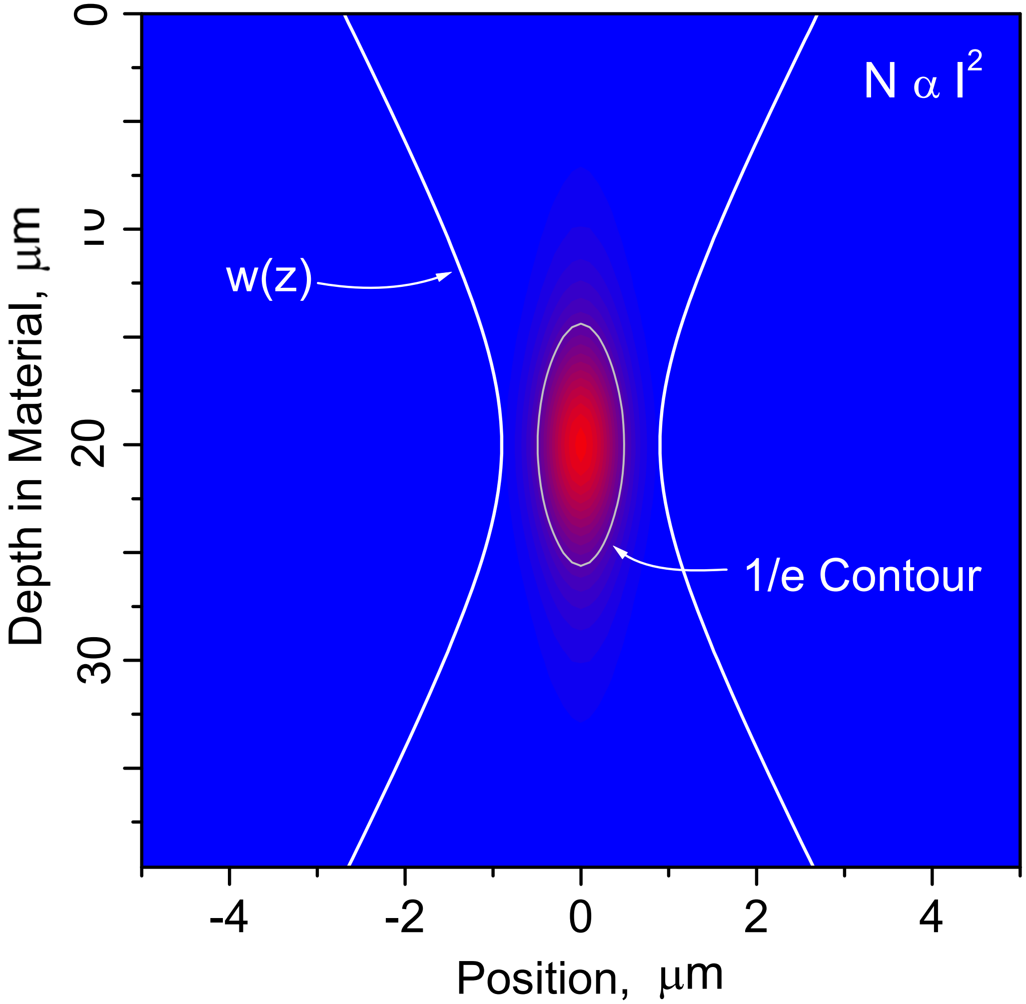
- Carriers are generated by nonlinear absorption at high pulse irradiances by the *simultaneous absorption of two photons*



- ***Two photons absorbed***
- ***By the material (silicon)***
- ***Simultaneously***
- ***Create a single e-h pair***

Two-Photon Absorption SEE Experiment

“Zeroth” Order TPA Carrier Distribution

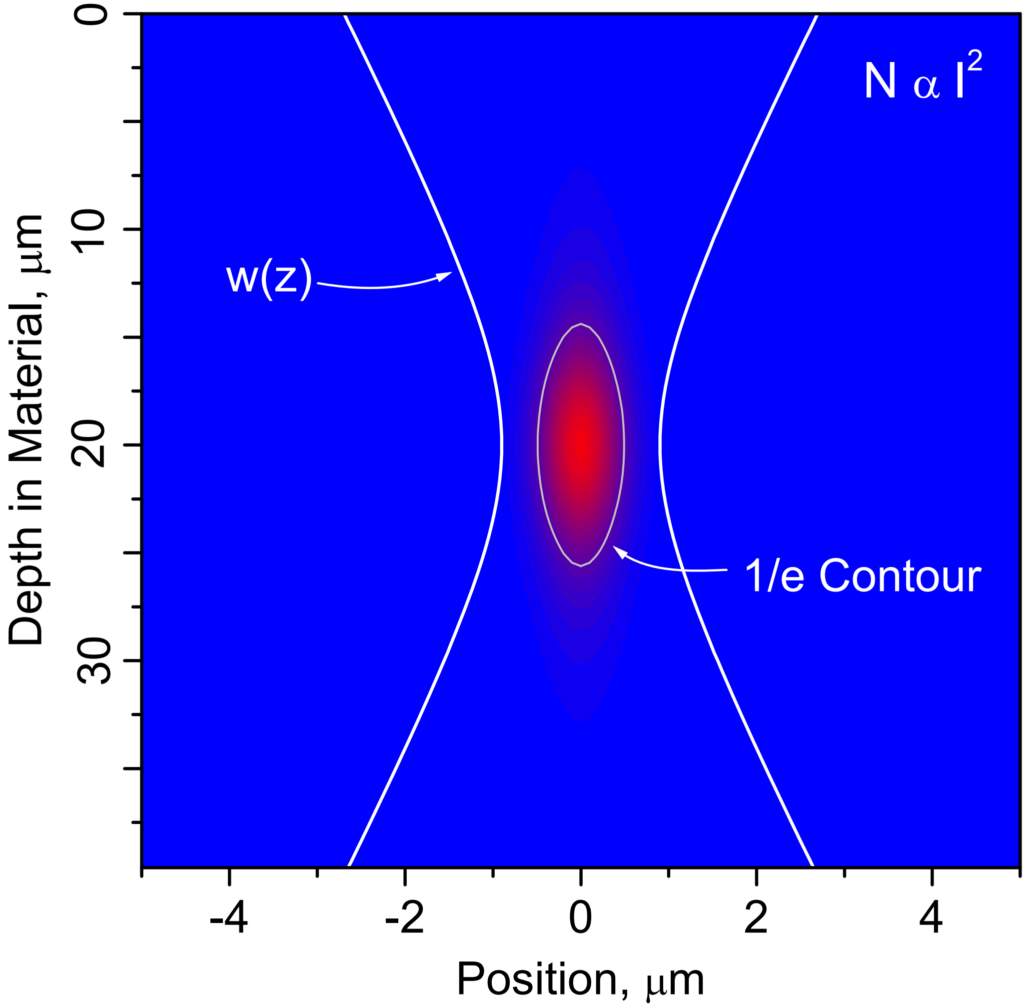


- Carriers are highly concentrated in the ***high irradiance region*** near the focus of the beam
- Because of the lack of exponential attenuation, carriers can be ***injected at any depth*** in the semiconductor material
- This permits <u>***3-D mapping***</u> **and** <u>***backside illumination***</u>

McMorrow, et al., TNS 2002

Two-Photon Absorption SEE Experiment

"Zeroth" Order TPA Carrier Distribution

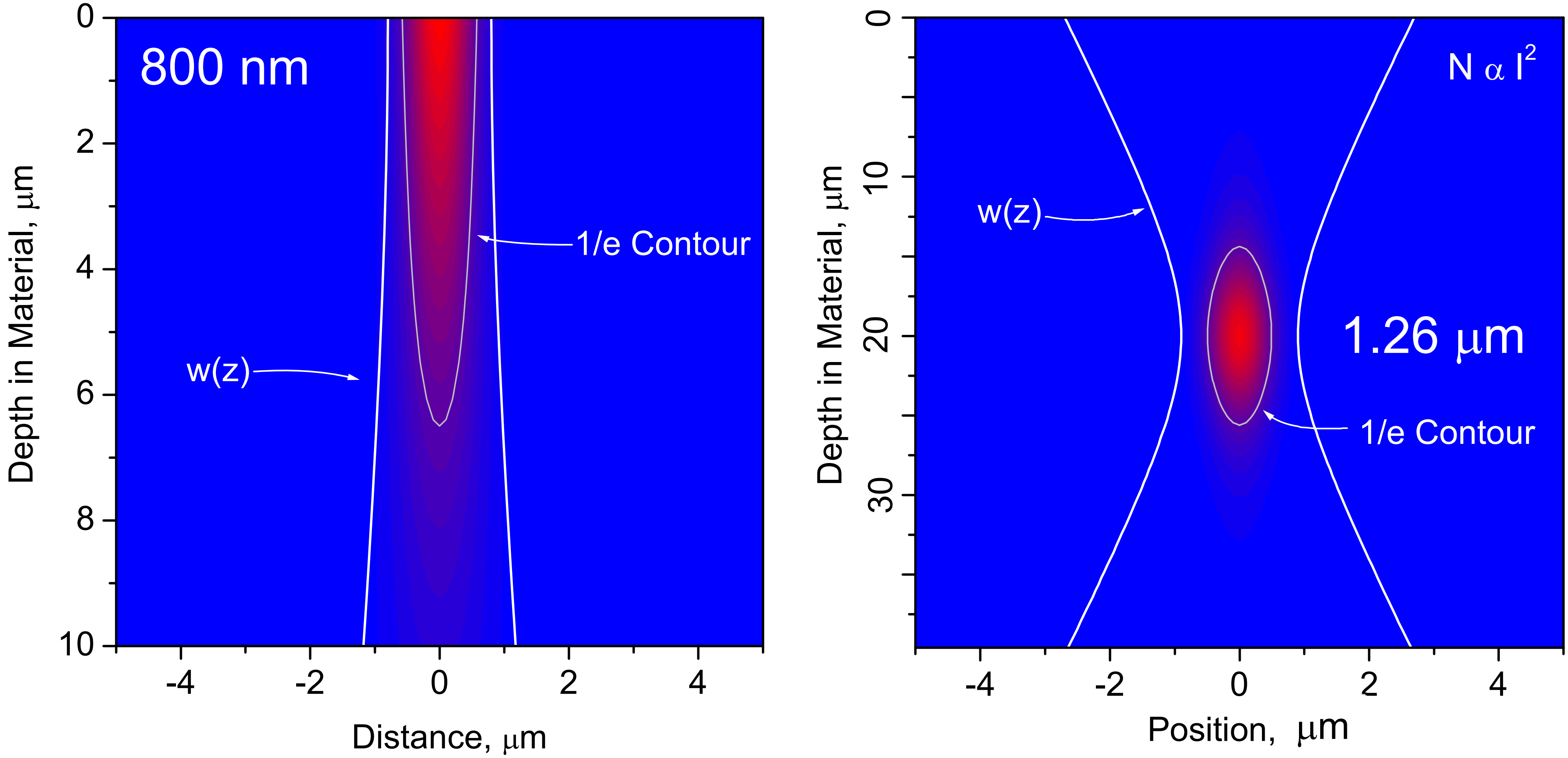


Two-Photon Absorption:

- Efficient only in the high-irradiance region near the focus of the beam
  - Tight focus
  - Short pulse (~120 fs)
  - High pulse energy (~1 nJ)

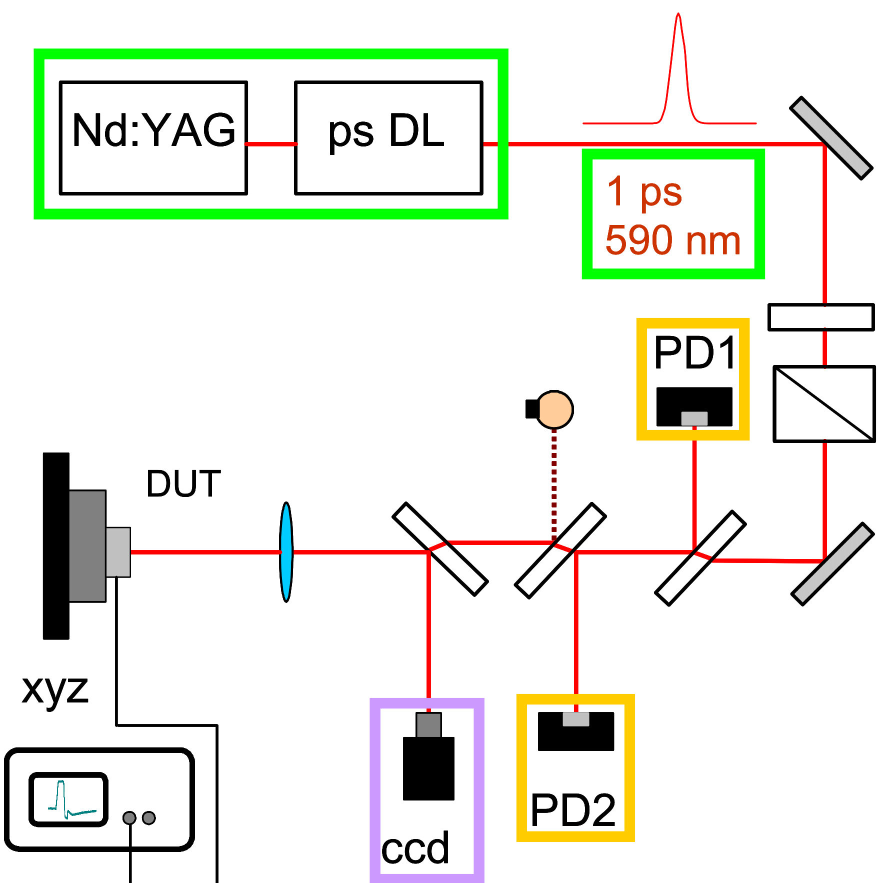
McMorrow, et al., TNS 2002

Carrier Density Distribution
Single Photon vs. Two Photon Absorption

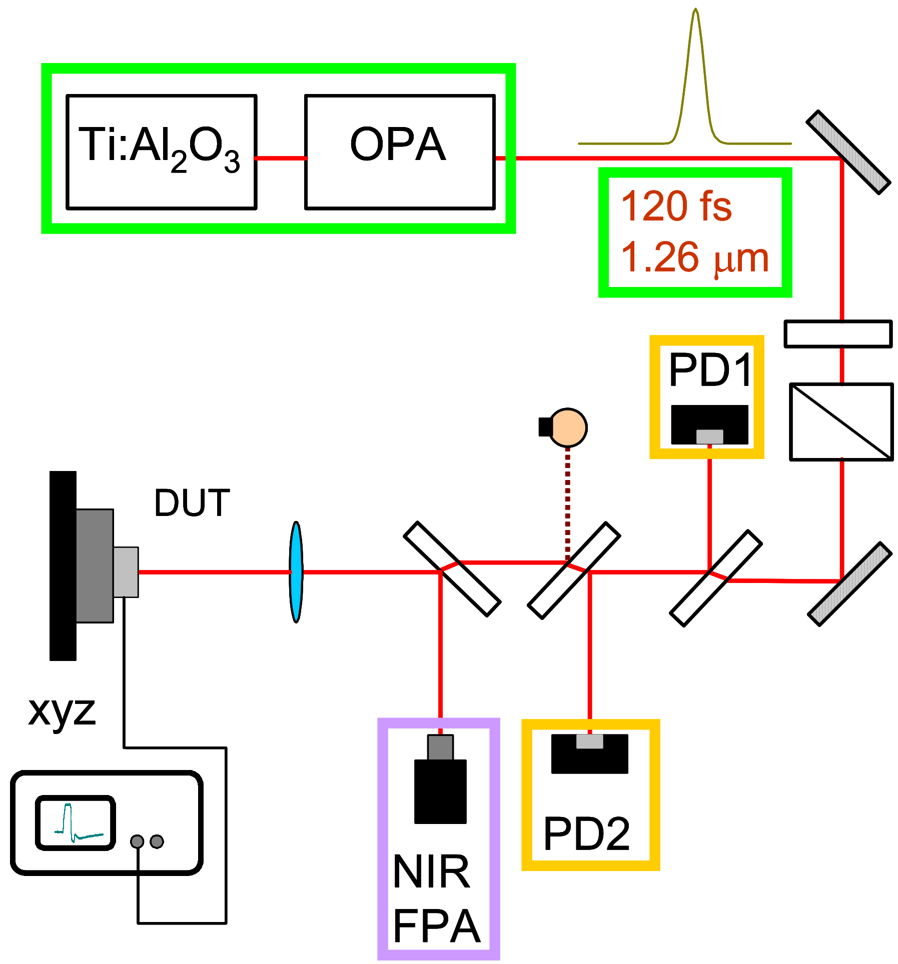


Pulsed Laser-Induced SEE Experiment

Above-Bandgap Single-Photon



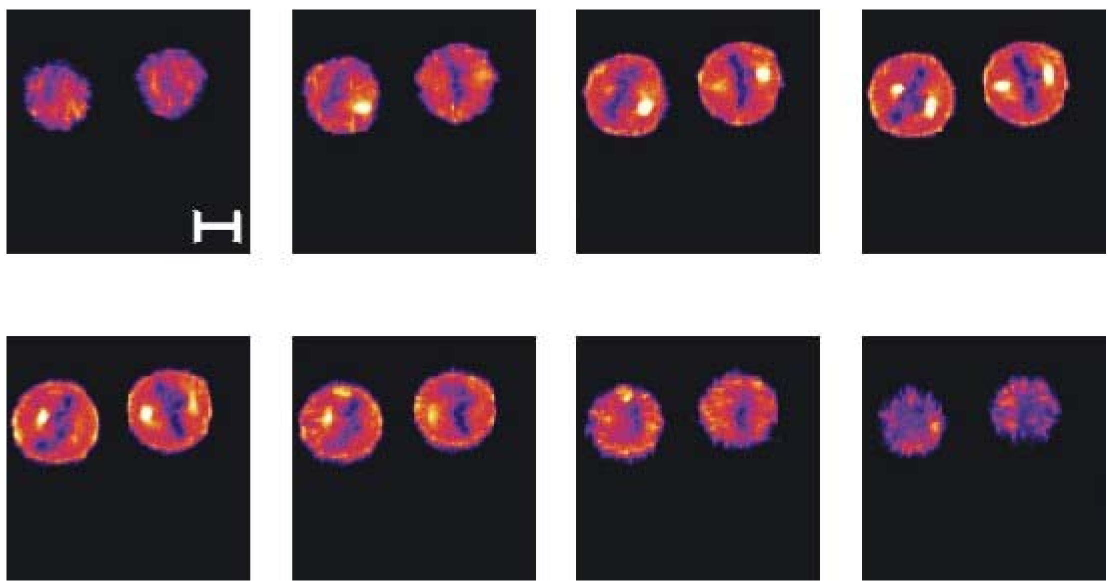
Sub-Bandgap Two-Photon



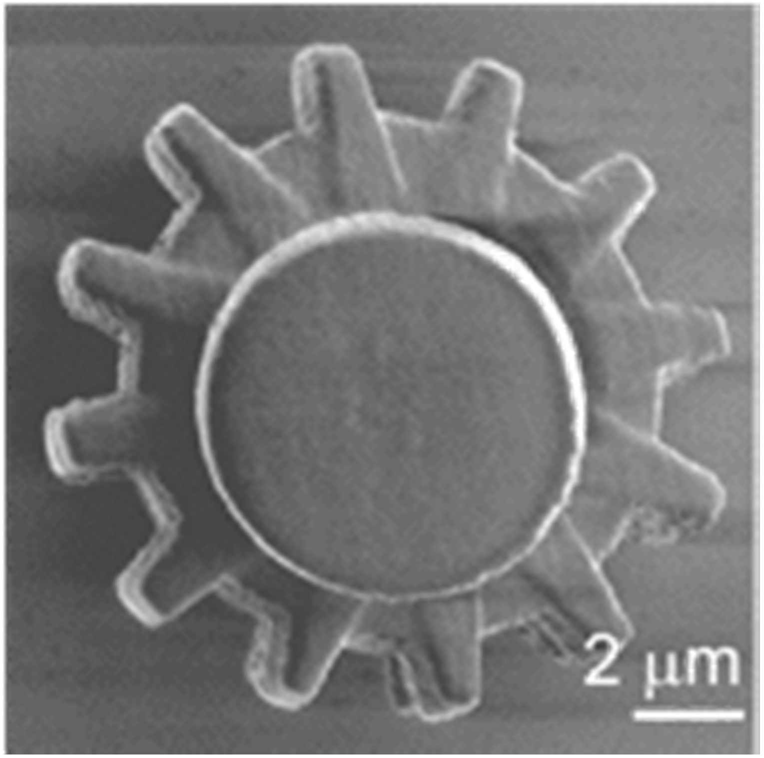
Two-Photon Absorption

M. Goppert-Mayer, "Ueber Elementarakte mit zweiQuantenspruengen", *Ann. Phys.*, vol. 9, pp. 273-294, 1931.

Other Applications of Two-Photon Absorption
Fluorescence Microscopy

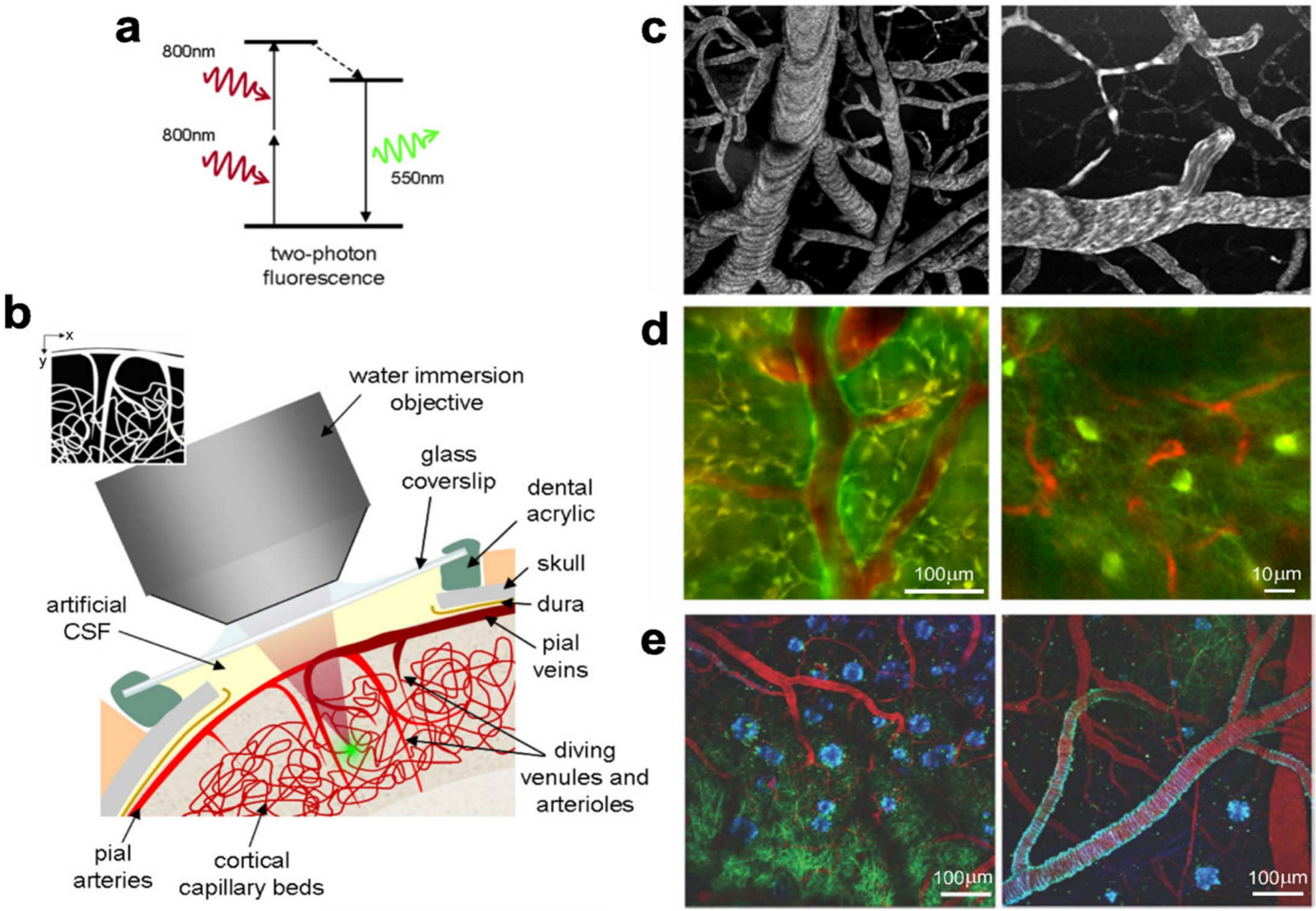


Other Applications of Two-Photon Absorption
Laser Manufacturing - MEMS



Other Applications of Two-Photon Absorption

Two-photon microscopy of in vivo brain function



After Wikimedia commons

Two-Photon Absorption SEE Experiment
What have we left out?

- Free Carrier Absorption
- Pump depletion
- Phase equation:

$$\frac{d\Phi(r,z)}{dz} = \beta_1 I(r,z) - \gamma_1 N(r,z)$$

  - β_1 is proportional to the real part of the nonlinear susceptibility ($\chi^{(3)}$)
  - γ_1 describes the refraction due to free carriers
  - Nonlinear refractive index changes

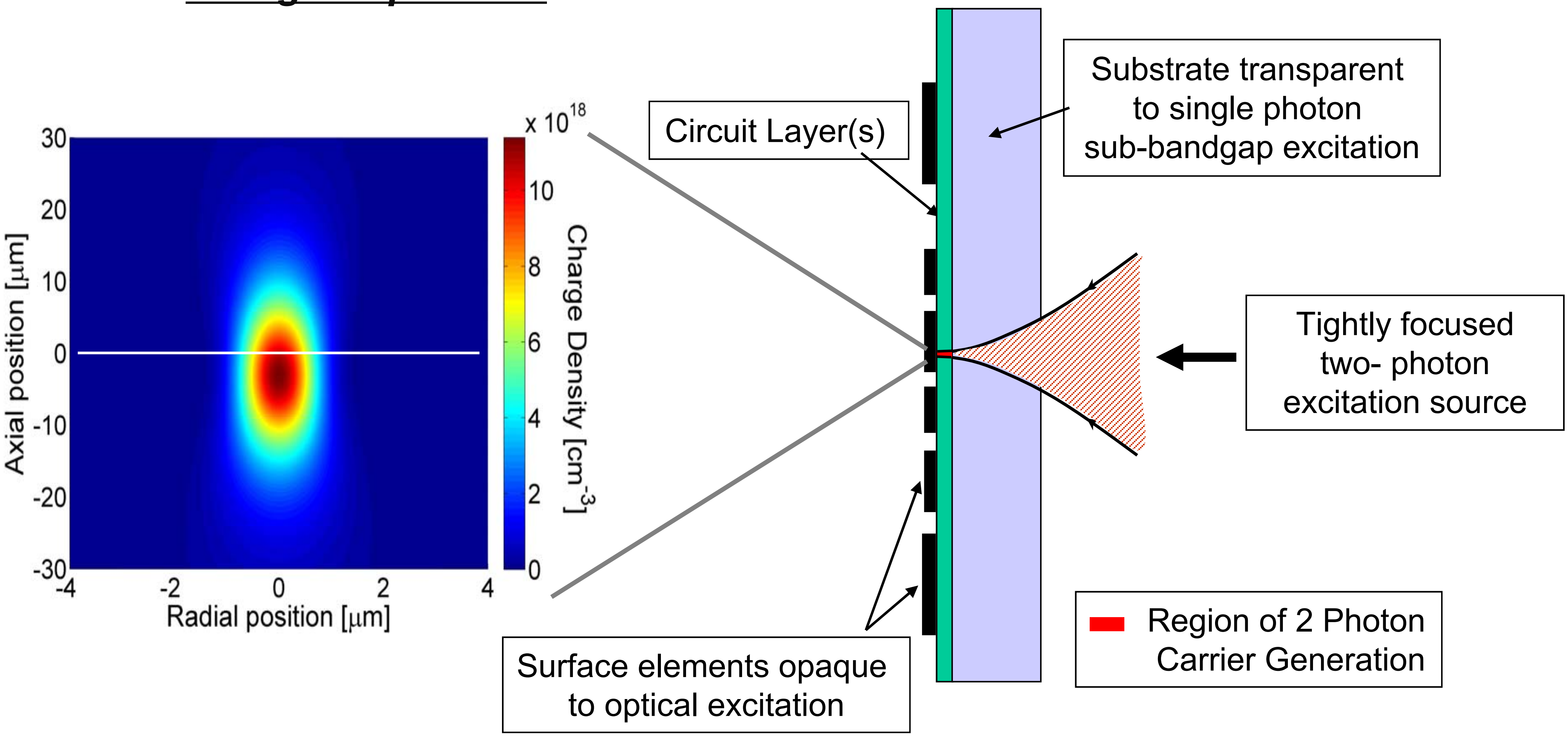
- *Net conclusion*: results described here represent a *convenient 0^{th} order approximation* and are valid only at low pulse irradiances. ***Recent work is addressing these higher-order effects….***

Recent Developments:

Quantitative Characterization of TPA SEE

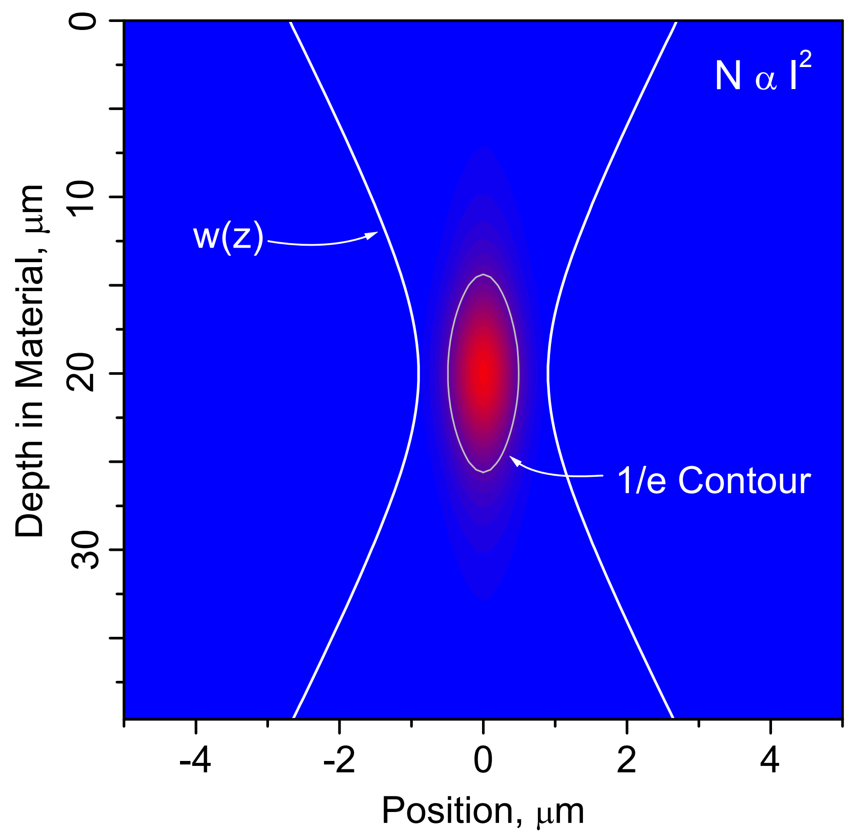
Inside the Silicon: Charge Deposition

Pulse Delivered to the Chip: TPA Dosimetry



What Happens Inside the Silicon?

- Need exists for understanding *quantitatively* the carrier density distribution in TPA SEE experiments
  - *Complicated problem*
- Community has been relying on a *"Zeroth Order"* representation
  - *Only considers carrier generation*
  - *Neglects all all other effects*
- NRL has been initiated a program to address this problem
- The current status of this effort is presented here



McMorrow, et. al, TNS 49, 3002 (2002).

NRL TPA Modeling: *Beyond Zeroth Order*

Goals:

- *Produce a software program that can accurately simulate the TPA-induced carrier deposition profile in silicon for any given set of experimental conditions*
- Simulate/predict impact of various optical nonlinearities on the beam *propagation* through, and *generation of free carriers* in the medium

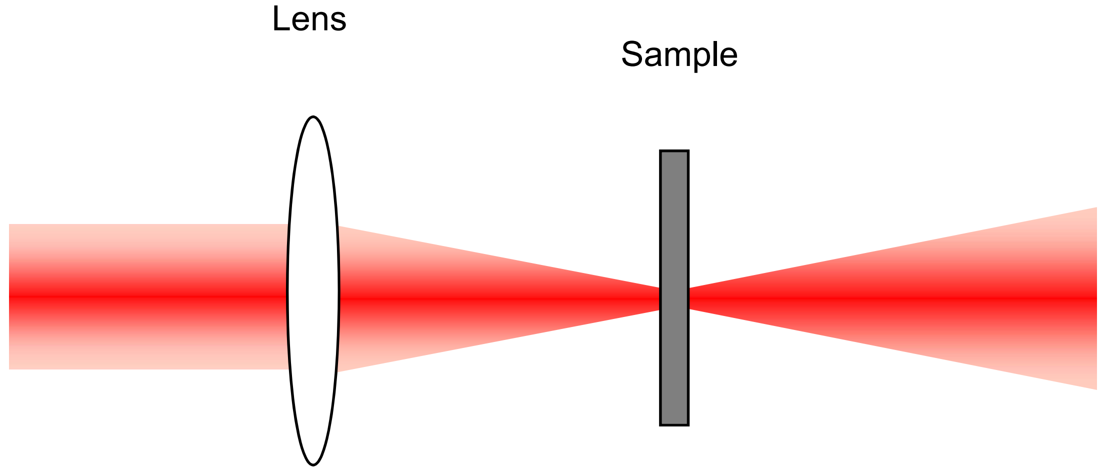
Approach:

- Numerical modeling using existing simulation software (NLO-BPM) adapted for carrier generation and applied to silicon
  [Kovsh, et al., Applied Optics, 38, 1568 (1999)]
- Confirm that capabilities can accommodate experimental conditions
- Validate results through experimental measurement

Nonlinear Beam Propagation in Si

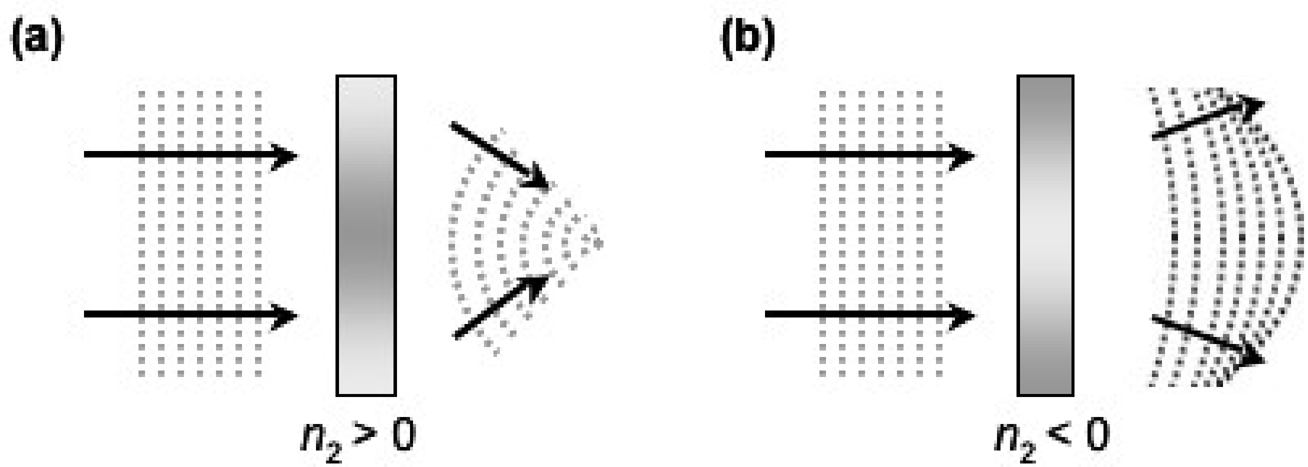
Two-photon absorption (TPA), β

$Im\{\chi_{NL}\}$:



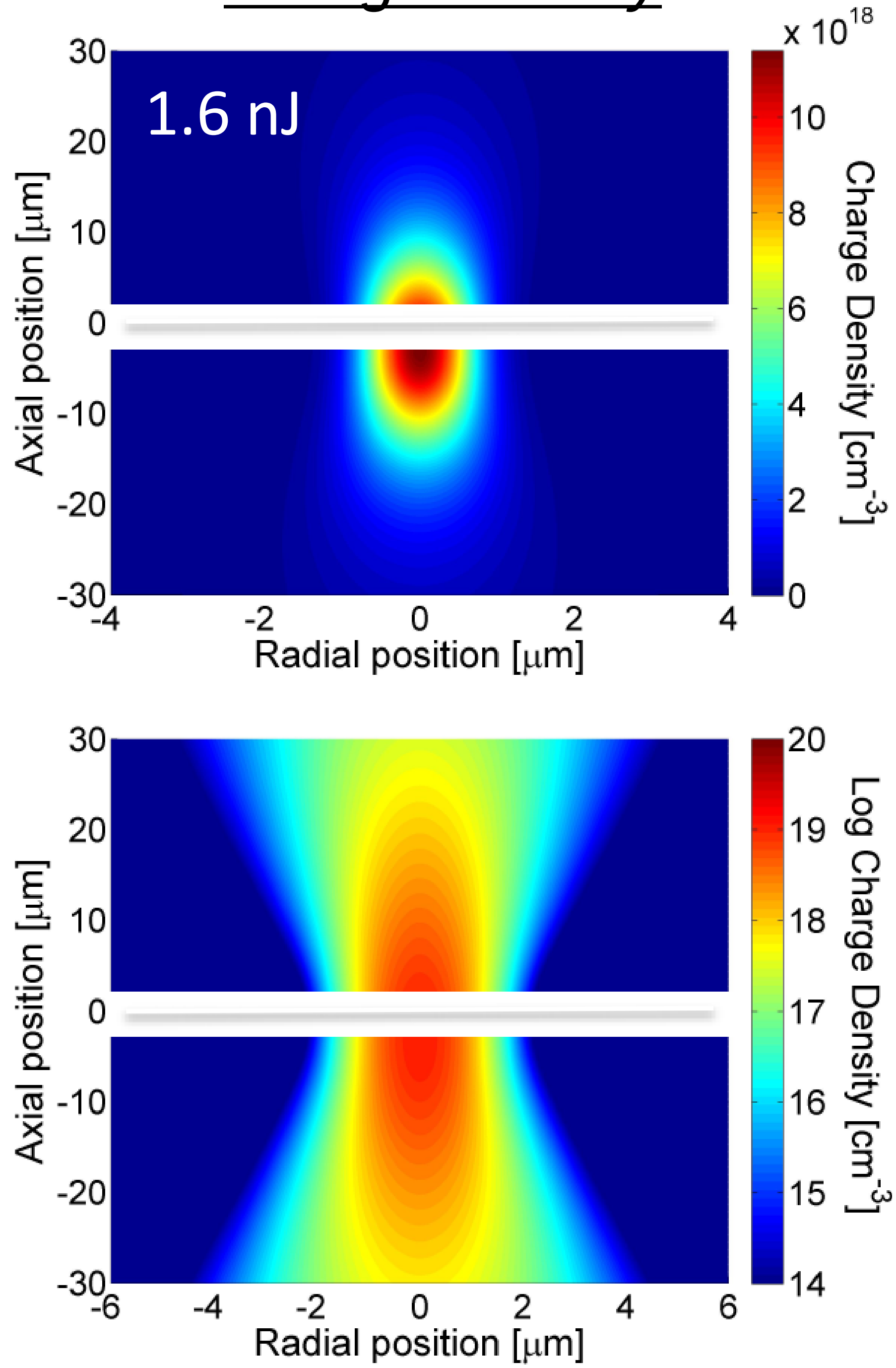
Nonlinear refraction (NLR), n_2

$Re\{\chi_{NL}\}$:



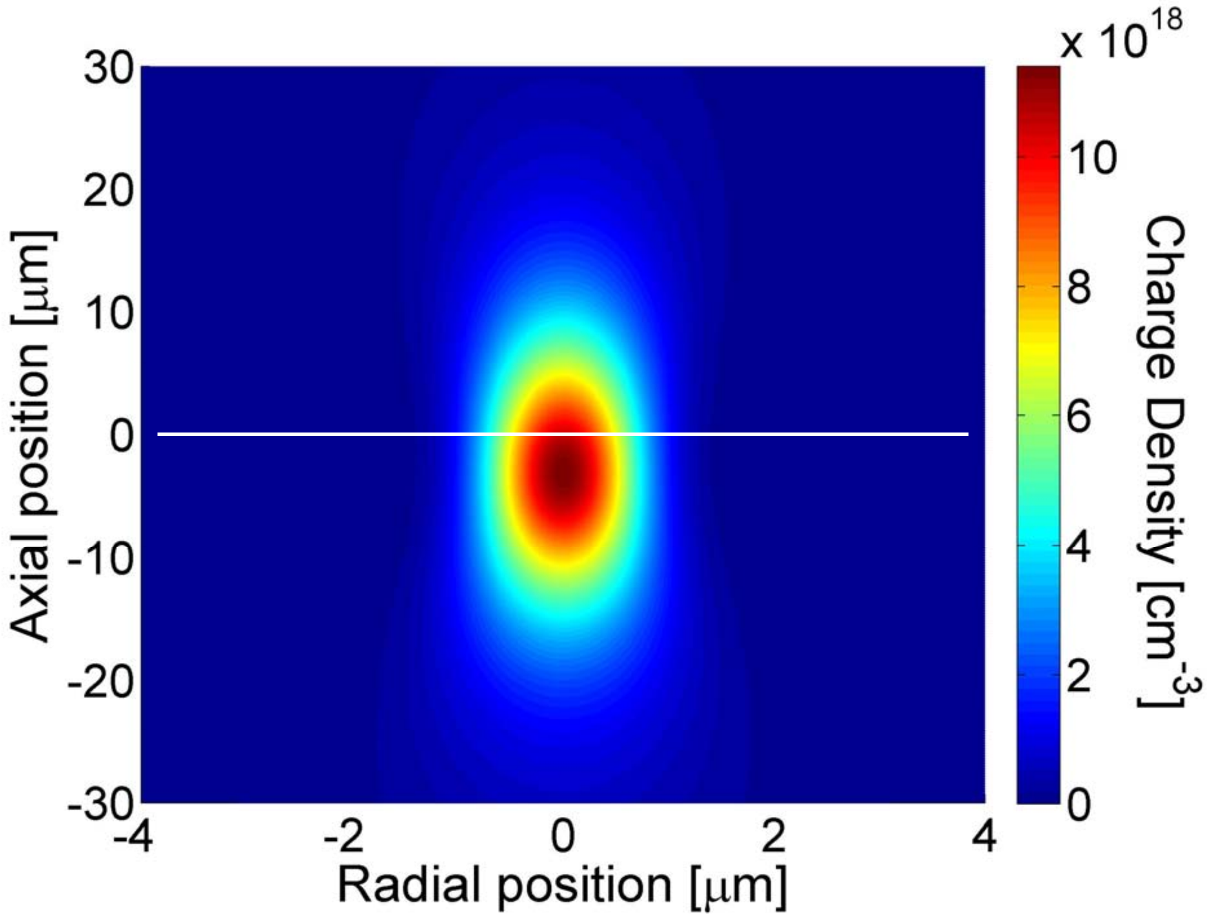
1.6 nJ Gaussian Beam

Charge Density



Hales, et al., IEEE TNS 61, 3504 (2014)

1.6 nJ Gaussian Beam

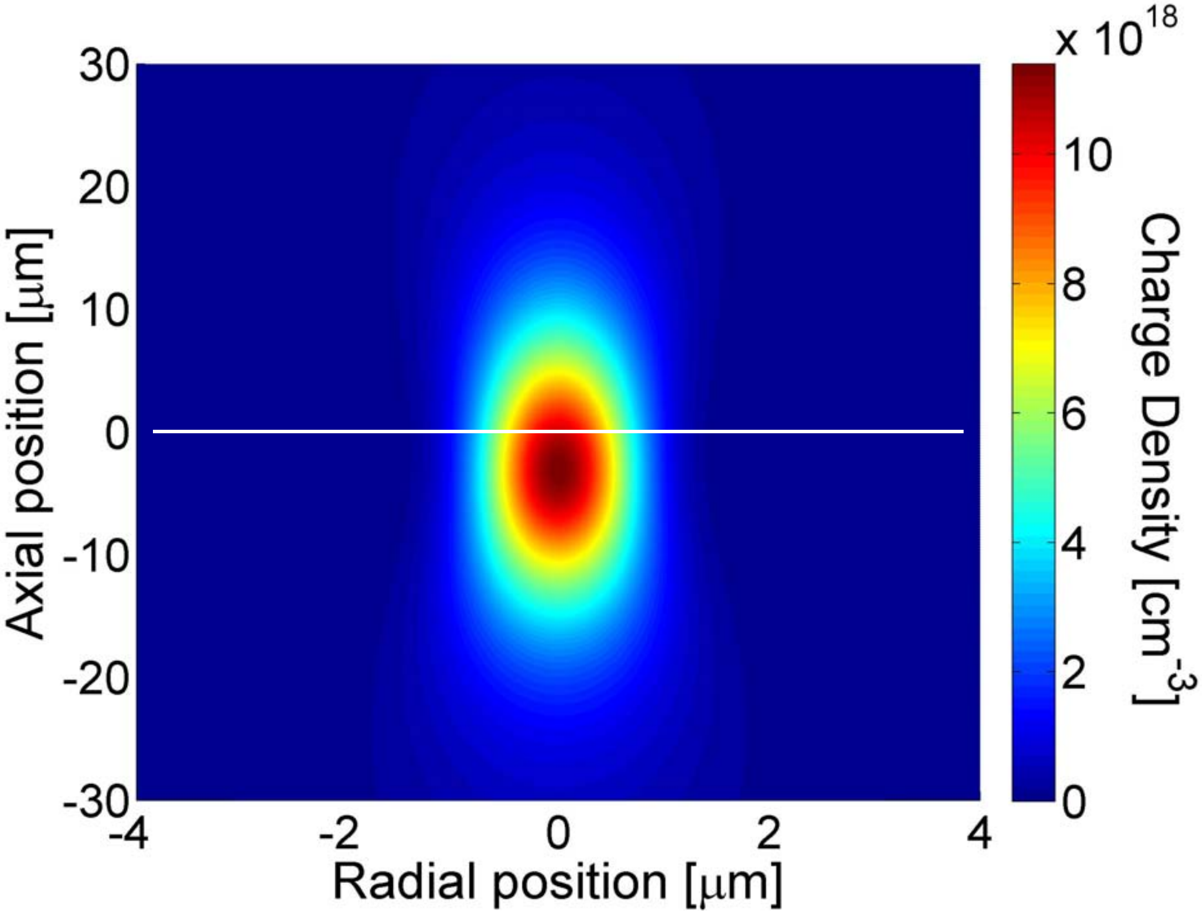


***What is the origin of this effect*:**

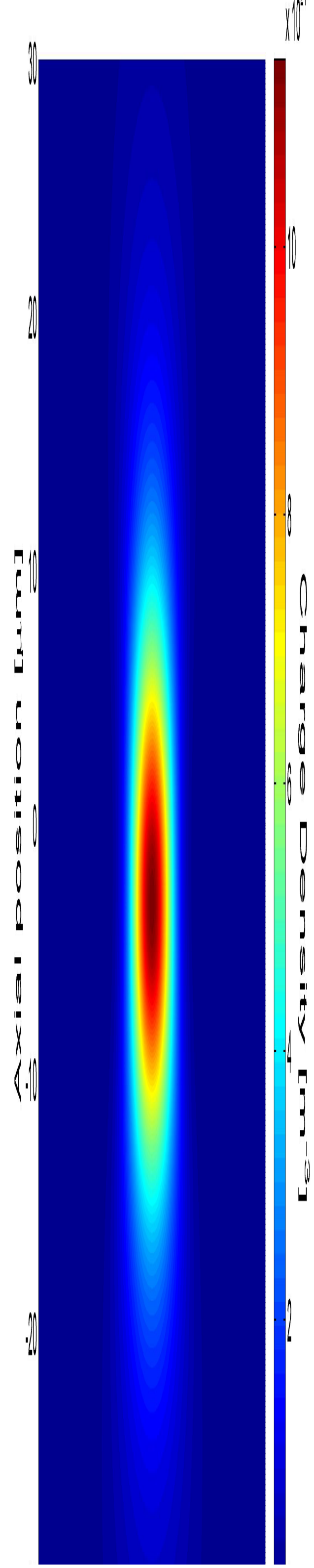
- *Photon loss to TPA*
- *Photon loss to FCA*
- *FCR*

FCA: *Free-Carrier Absorption*
FCR: *Free-Carrier Refraction*

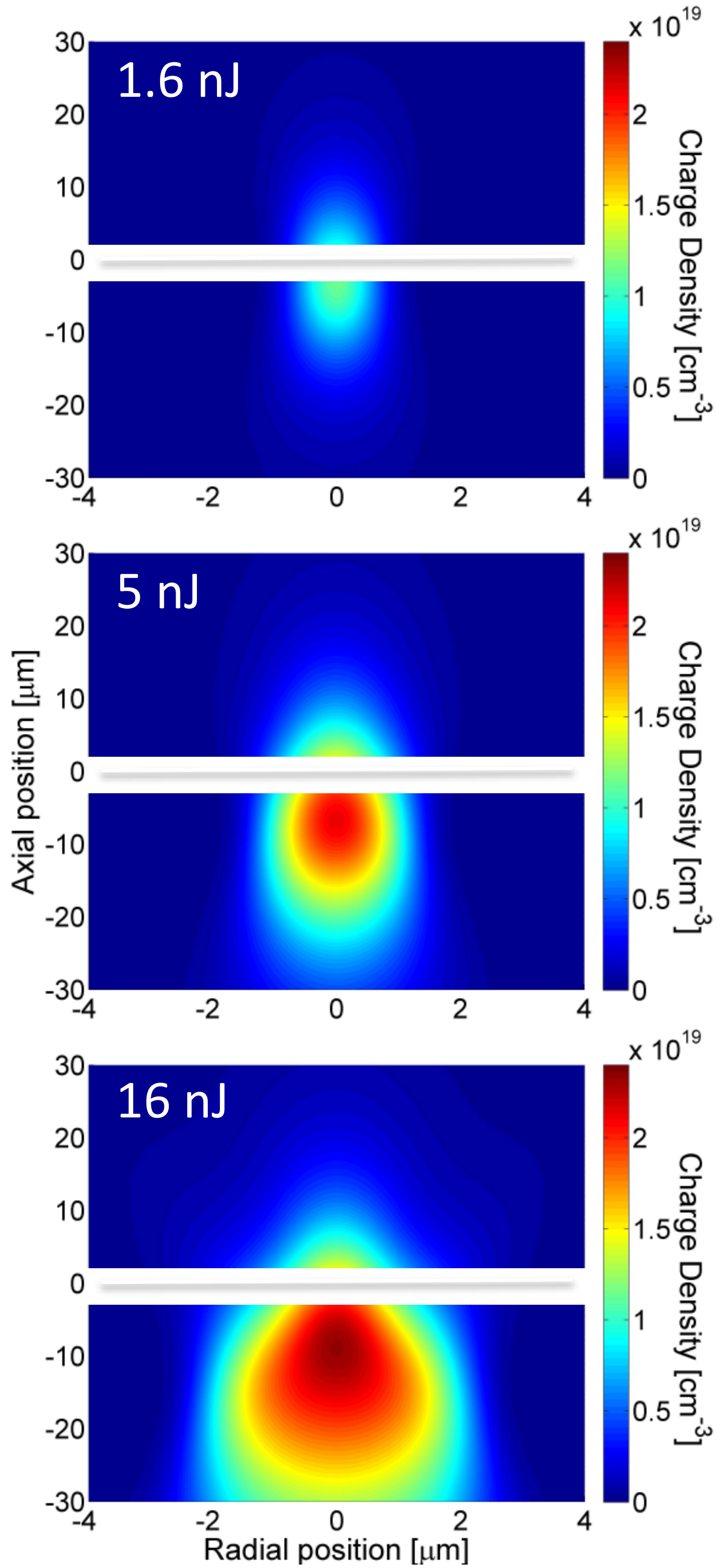
Hales, et al., IEEE TNS 61, 3504 (2014)



x 10^18
Charge Density [cm^-3]
Axial position [μm]
Radial position [μm]
30
20
10
0
-10
-20
-30
-4
-2
0
2
4
10
8
6
4
2
0



Charge Density [m^-3]
Axial position [μm]



1.6 nJ

5 nJ

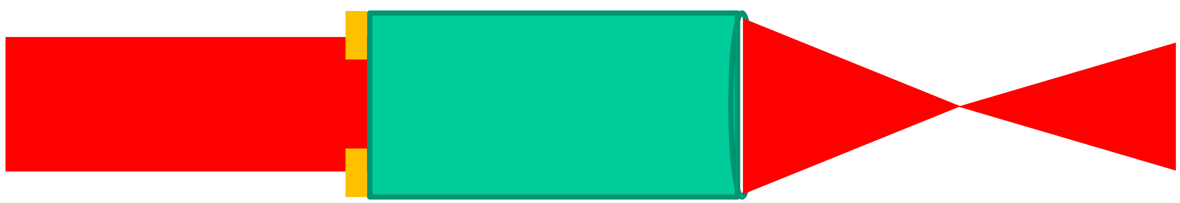
16 nJ

Hales, et al., IEEE TNS 61, 3504 (2014)

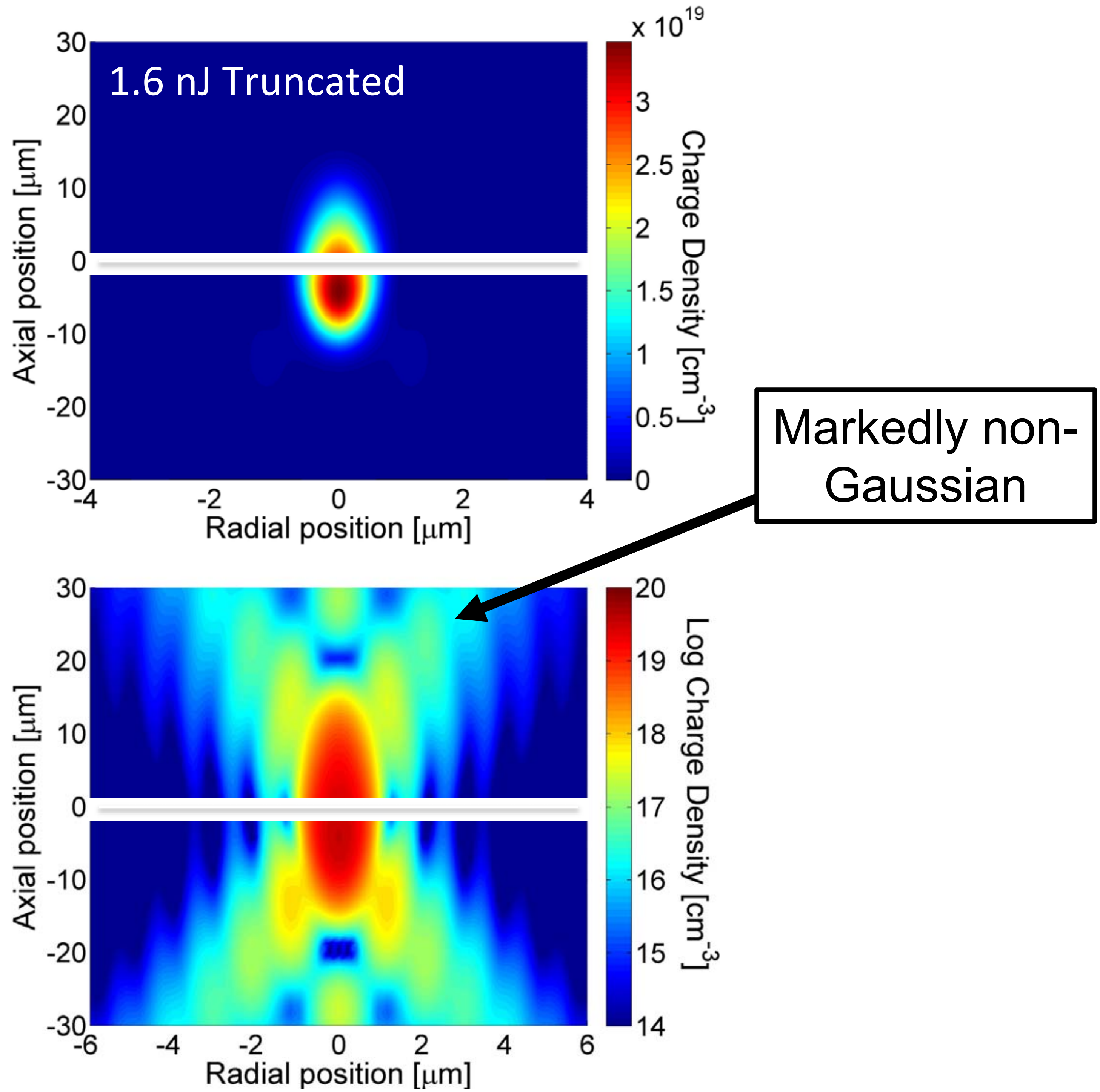
Controlling the Focused Laser Spot Size

Underfilled Objective: Gaussian Beam

Overfilled Objective: Non-Gaussian (Truncated) Beam



1.6 nJ Truncated Beam



TPA Dosimetry:
Quantitative Characterization in TPA SEE

Why do we care?

- The primary advantage of laser-based SEE approaches lies in their *qualitative capabilities*:
  - sensitive node identification
  - RHBD verification
  - basic mechanisms/model validation/calibration
  - part screening (ASET, SEL)
  - fault injection
- However:
  - *Set operating point prior to experiment*
  - *Monitor operating point during experiment*
  - *Require correlation between subsequent experiments*
  - *Next-level understanding of basic mechanisms*

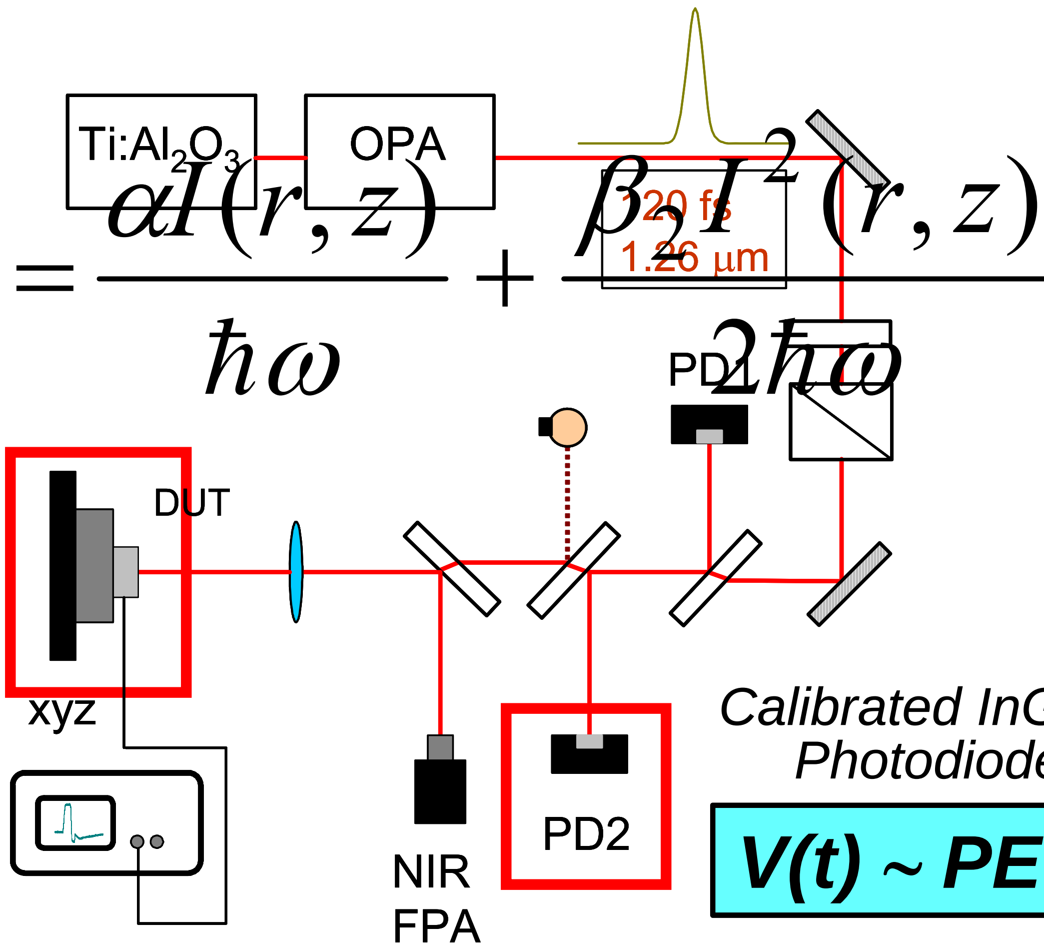
Quantitative Characterization in TPA SEE

Why is it so difficult?

$$\frac{dN(r,z)}{dt} = \frac{\alpha I(r,z)}{\hbar\omega} + \frac{\beta_2 I^2(r,z)}{2\hbar\omega}$$

Experimental Observable:

$$\boldsymbol{Q_{dep} \sim \frac{(PE)^2}{r^4 * \Delta\tau^2}}$$



Calibrated InGaAs Photodiode:

V(t) ~ PE

TPA SEE Dosimetry

Definition for TPA Dosimetry:

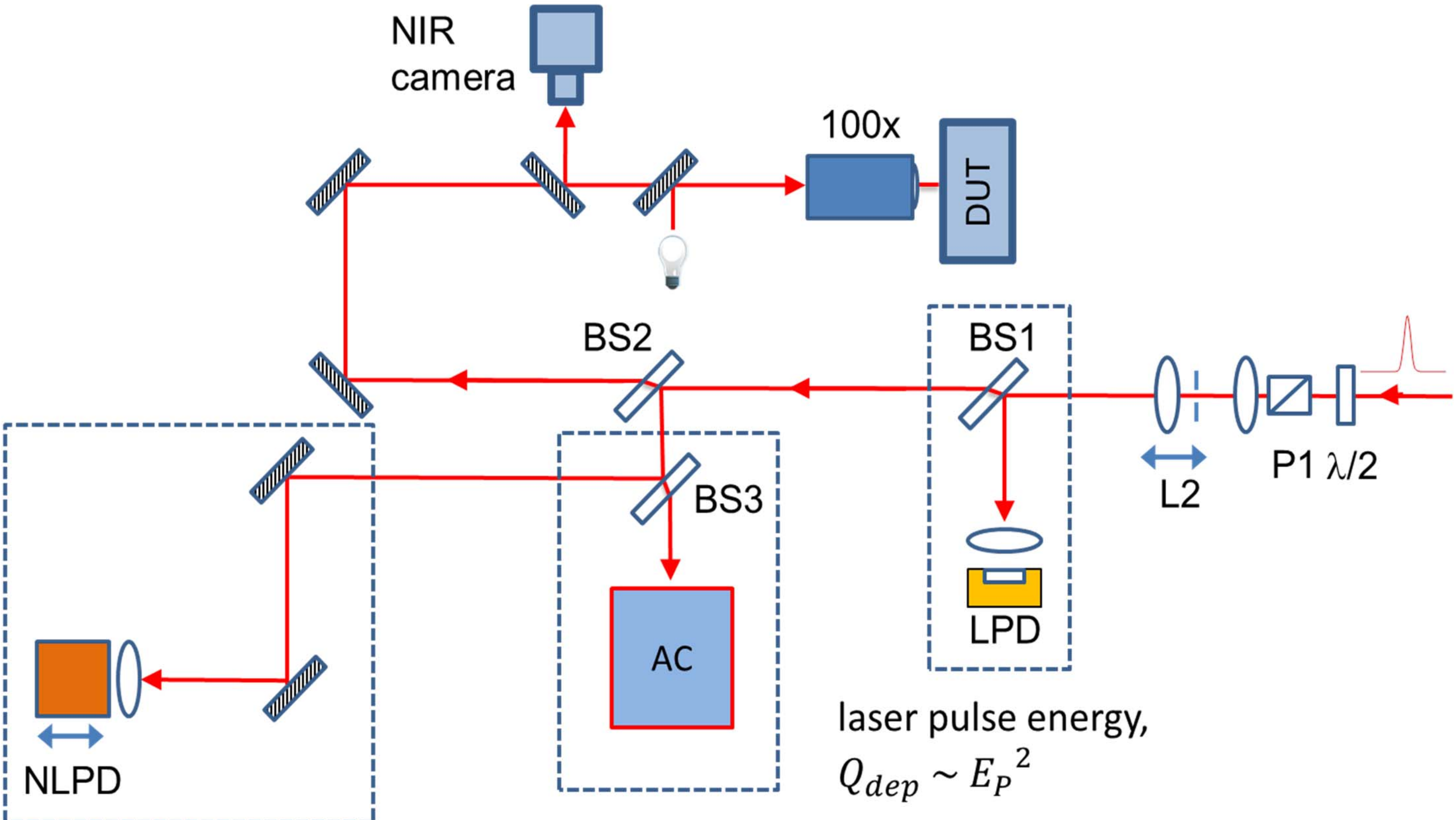
Measurement of the relevant characteristics of the optical pulse delivered to the surface of the DUT

Goals for TPA Dosimetry System:

Convenient, reliable, reproducible measurement of the relevant characteristics of the optical pulse delivered to the surface of the DUT

- Development of online monitors
- Develop ability for control vs. monitoring

Experimental Setup for TPA SEE Dosimetry



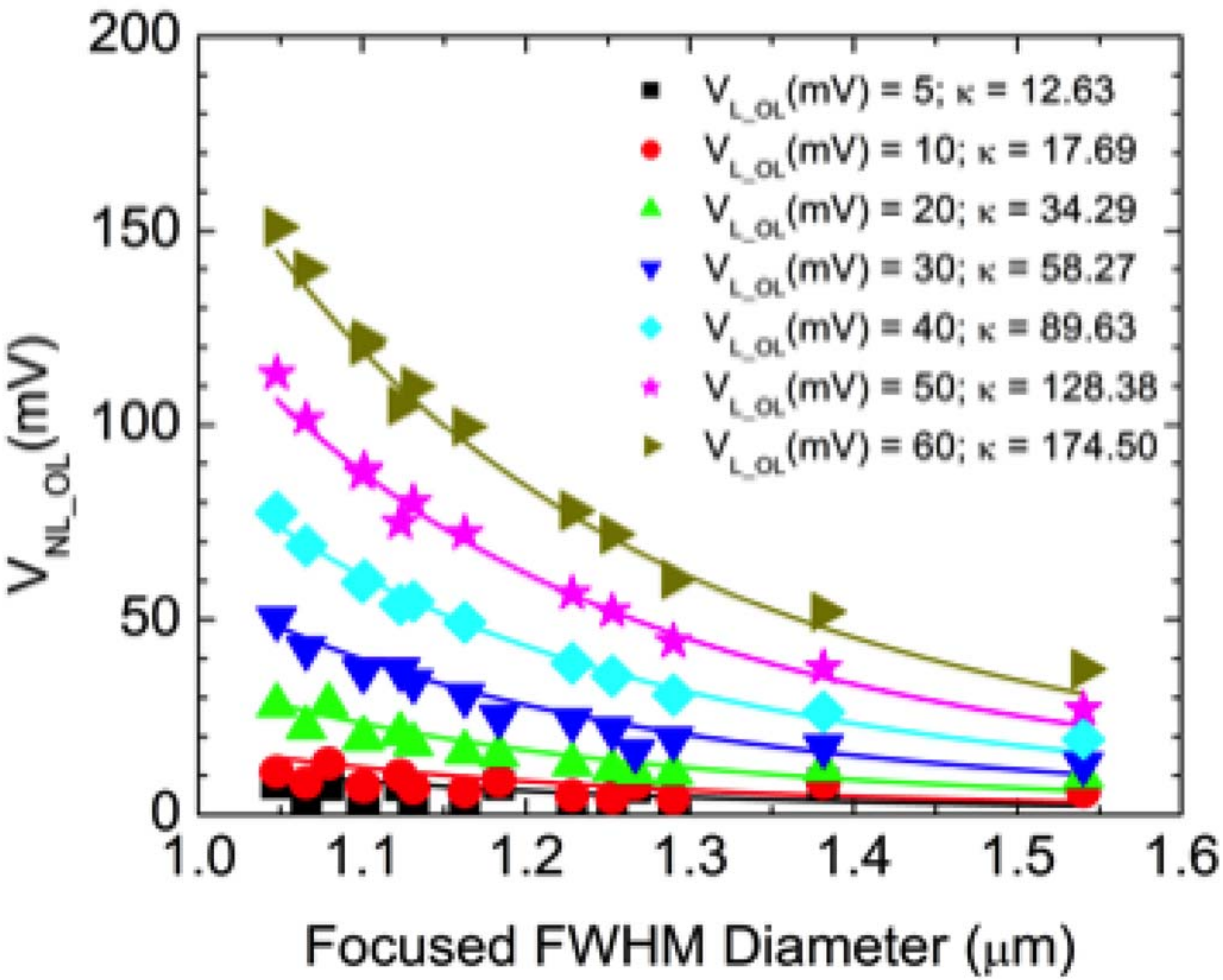
laser pulse energy,
$Q_{dep} \sim E_P{}^2$

laser beam radius,
$Q_{dep} \sim 1/r(z)^4$

laser pulse width,
$Q_{dep} \sim 1/\Delta\tau_p{}^2$

Khachatrian, et al., IEEE TNS 61, 3416 (2014)

TPA Dosimetry: Focused Laser Spot Size



$$V_{NL\_OL} = \kappa / S_{FWHM}{}^{4}$$

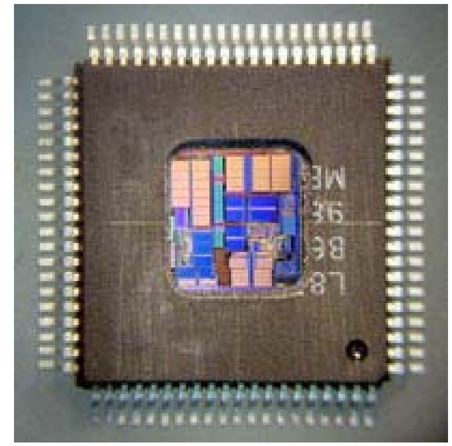
$$S_{FWHM} = \kappa^{1/4} / V_{NL\_OL}{}^{1/4}$$

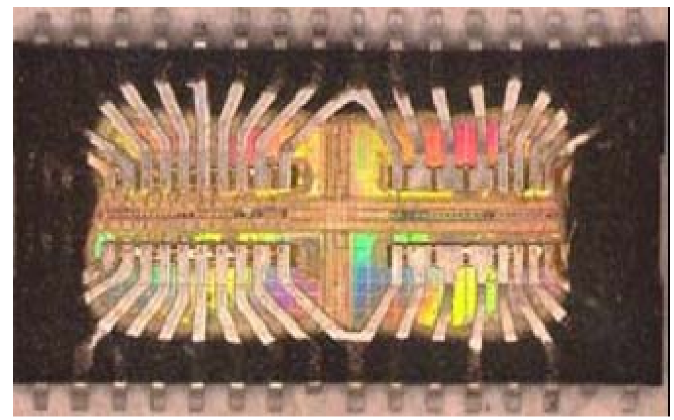
Data exhibit the expected r^4 dependence

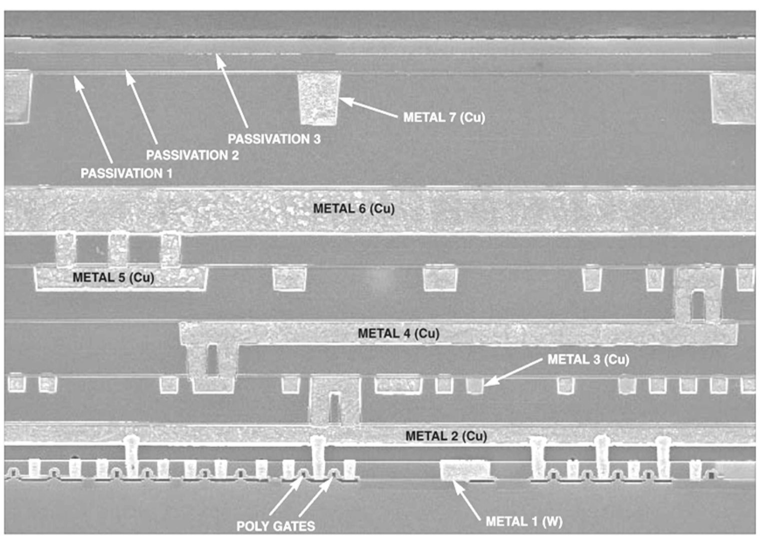
Khachatrian, et al., IEEE TNS 61, 3416 (2014)

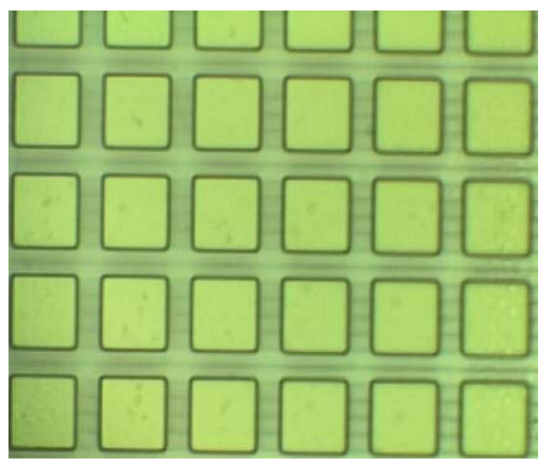
Laser SEE testing, technology and packaging

- **Main constraint of the laser technique:**
  - *Optical access to silicon is mandatory*
- **Packaging**
  - Ceramic or plastic opening
  - Lead frame masking => repackaging
  - Flip-chip
- **Modern process technologies**
  - Many interconnections layers
  - Metal lines totally absorb light
  - Dummy cells: metal filling for process planarization



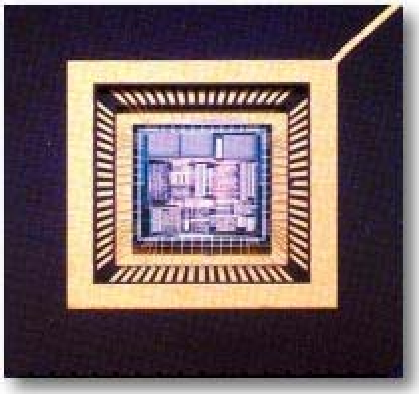


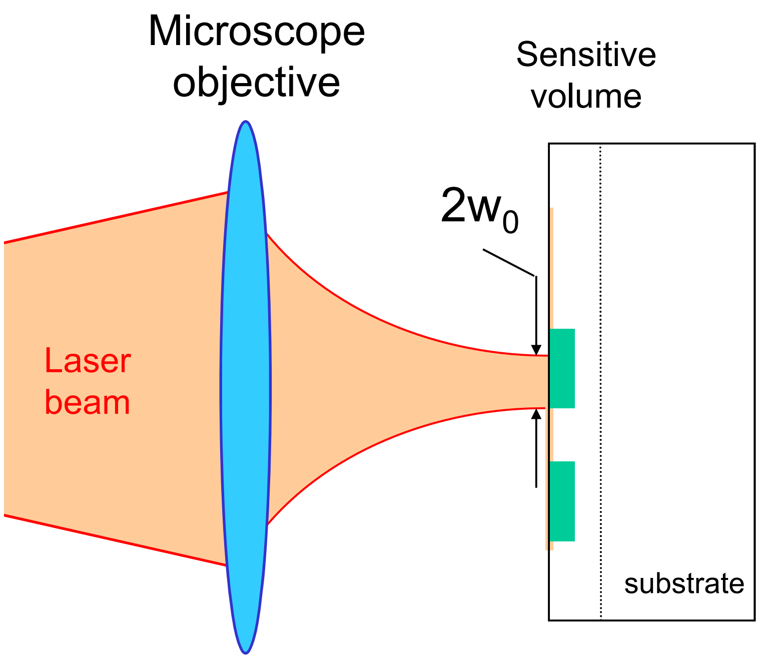




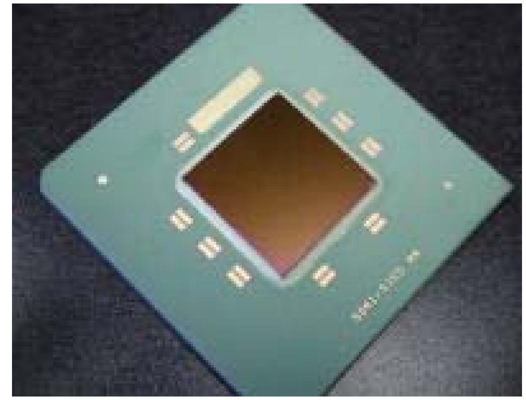
Solution:
backside testing

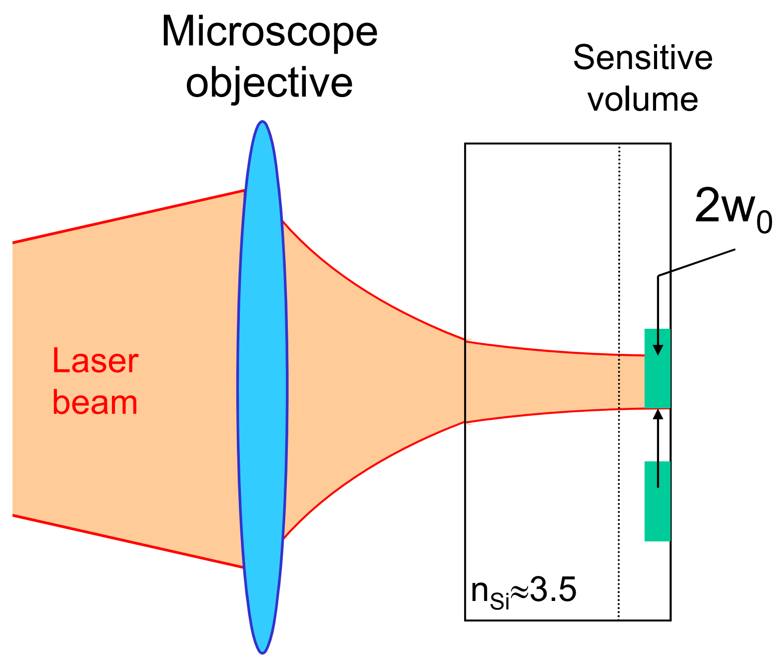
Front side or backside approach





Front side





Backside

Relevant Experimental Parameters: Laser-induced electron-hole generation rate

E

$$G(r,z,t)=\eta\alpha\frac{2TE_0}{E_\gamma \pi^{\frac{3}{2}} w_0^2 \tau}\frac{w_0^2}{w_{Si}(z)^2}e^{-\frac{2r^2}{w_{Si}(z)^2}}e^{-\alpha z}e^{-\frac{t^2}{\tau^2}}$$

λ w τ

Laser Parameter Summary

- **Wavelength**
  - Determines absorption in silicon
  - The longer the deeper (but lower resolution)
- **Pulse duration**
  - The shorter the closer from particles

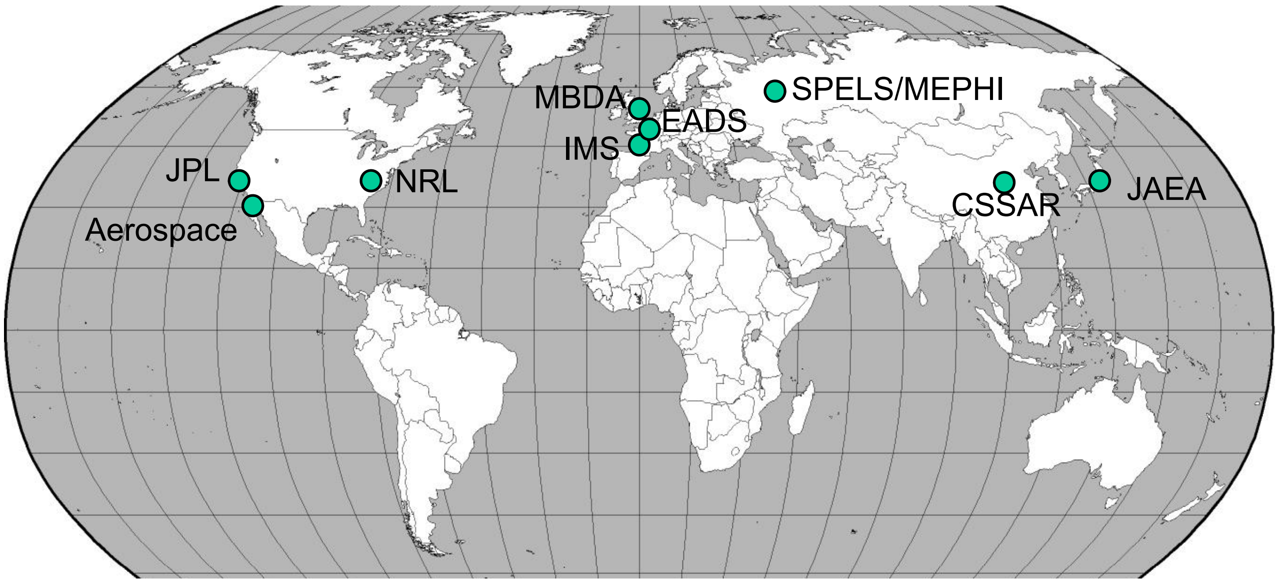
Fixed by laser source technology & cost

- **Spot size**
  - Limited by diffraction
  - Minimum value = maximum fidelity

Often fixed by optical setup, but can be adjusted

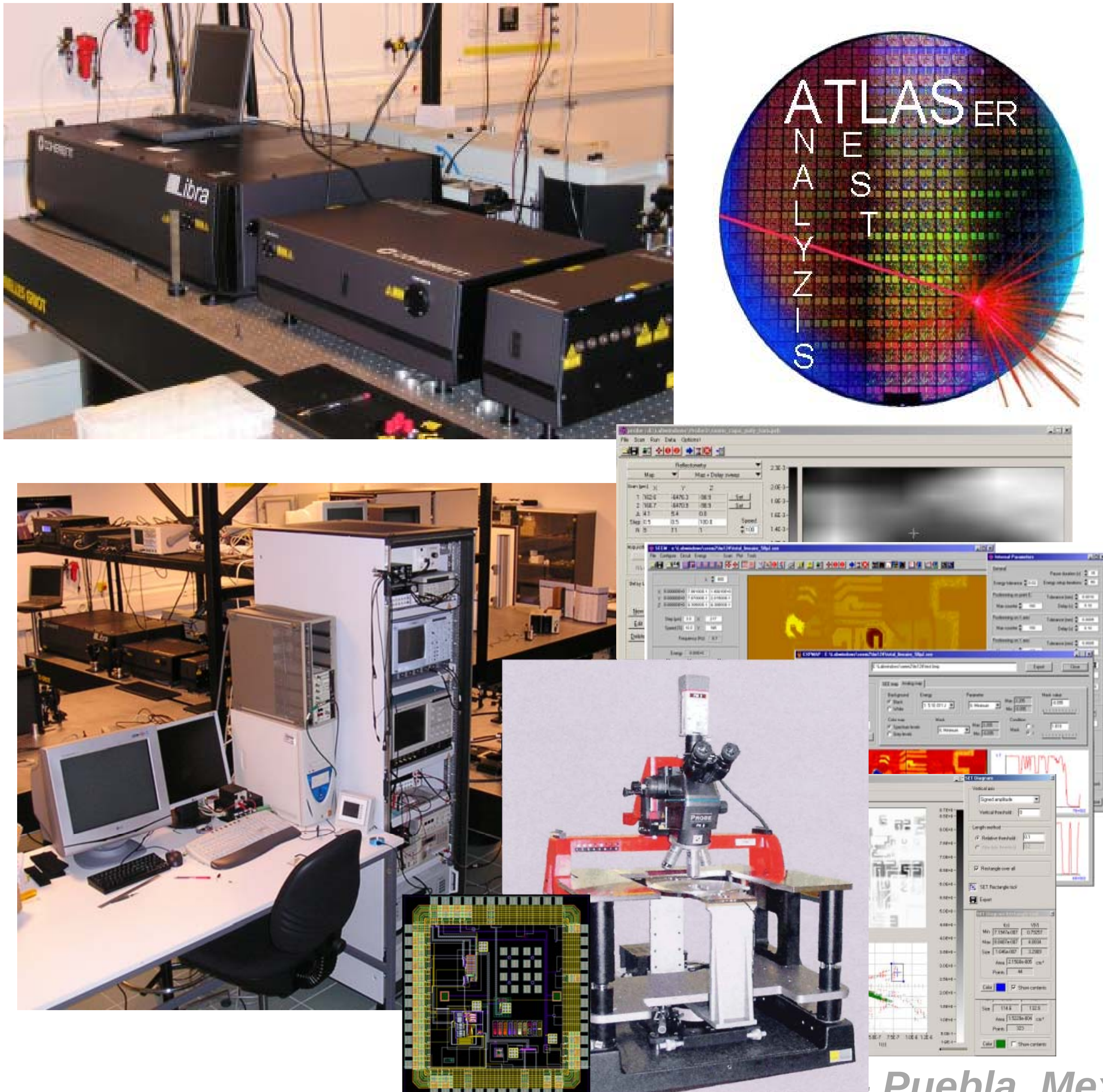
- **Energy**
  - Main experimental variable
  - Difficult link with LET

Laser SEE testing options



- **Several laser facilities around the world**
  - R&D facilities: flexibility, accuracy
  - Industrial facilities: cost, speed, reliability
- **Test services**
  - Beam time + support engineer
- **Commercial systems now available**

ATLAS Laser Facility at IMS



- **NIR-tunable picosecond laser source**
- **Amplified femtosecond parametric laser source**
- **Computer controlled tunability**

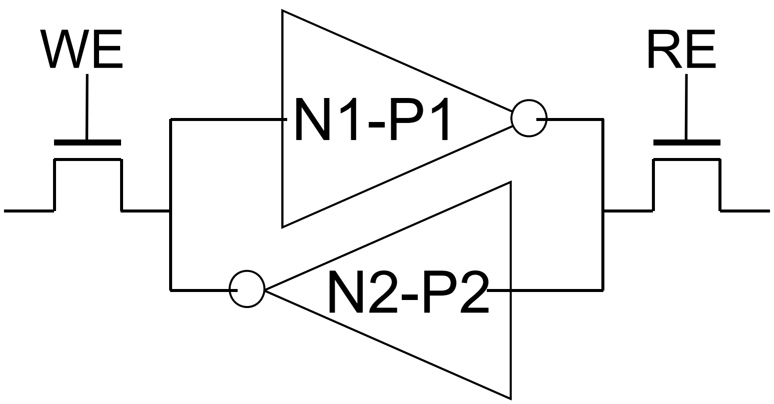
  : 400 - 2500 nm
- **Energy :** up to 1 mJ
- **Picosecond synchronization of laser pulse with test vector**
- **5 laser-injected microscopes**
- **Backside testing**
- **Microprobing station with backside laser scanning microscope**
- **New laser techniques for failure analysis**
- **Dedicated test chips**

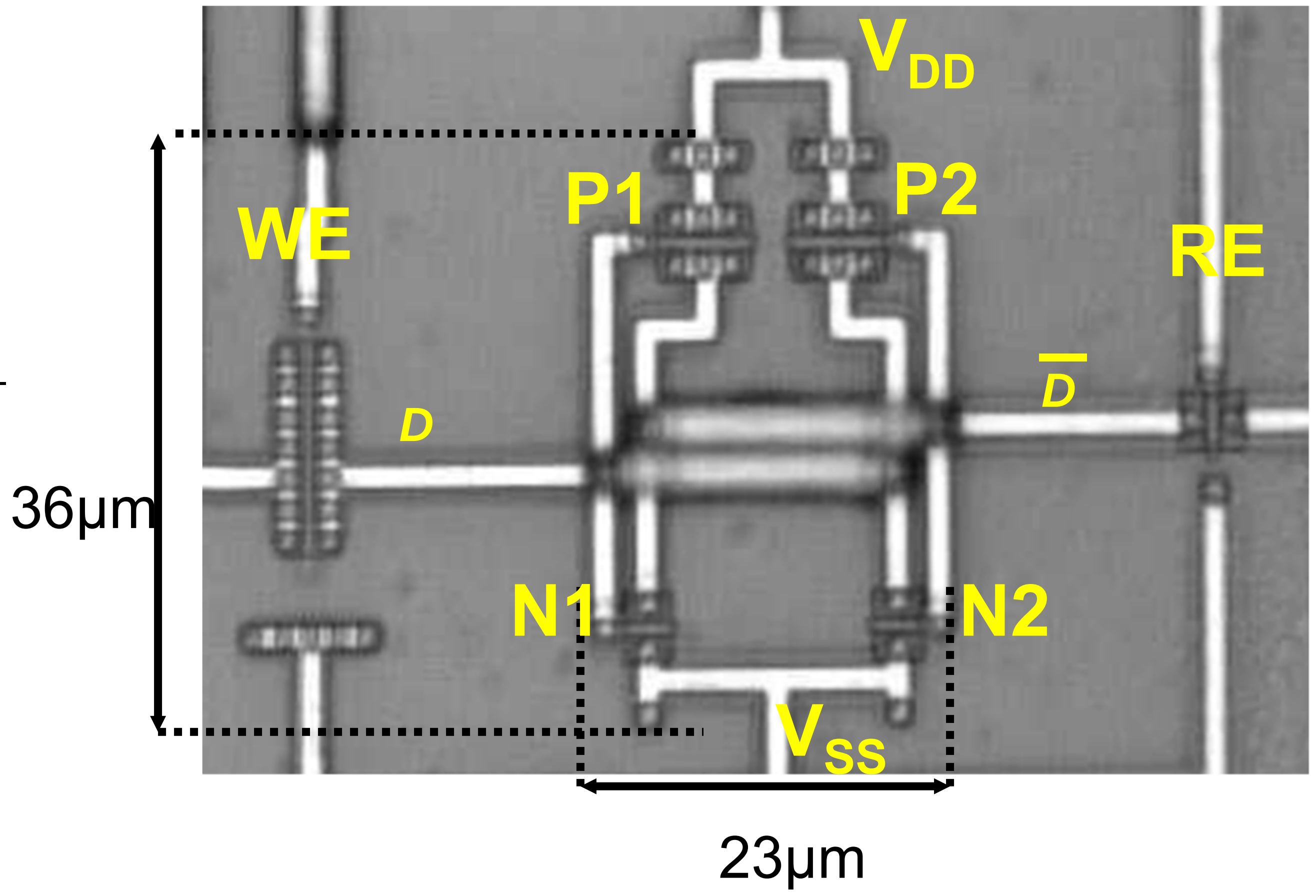
CASE STUDY 1

Single-Event Upset Mapping in
an SRAM Cell

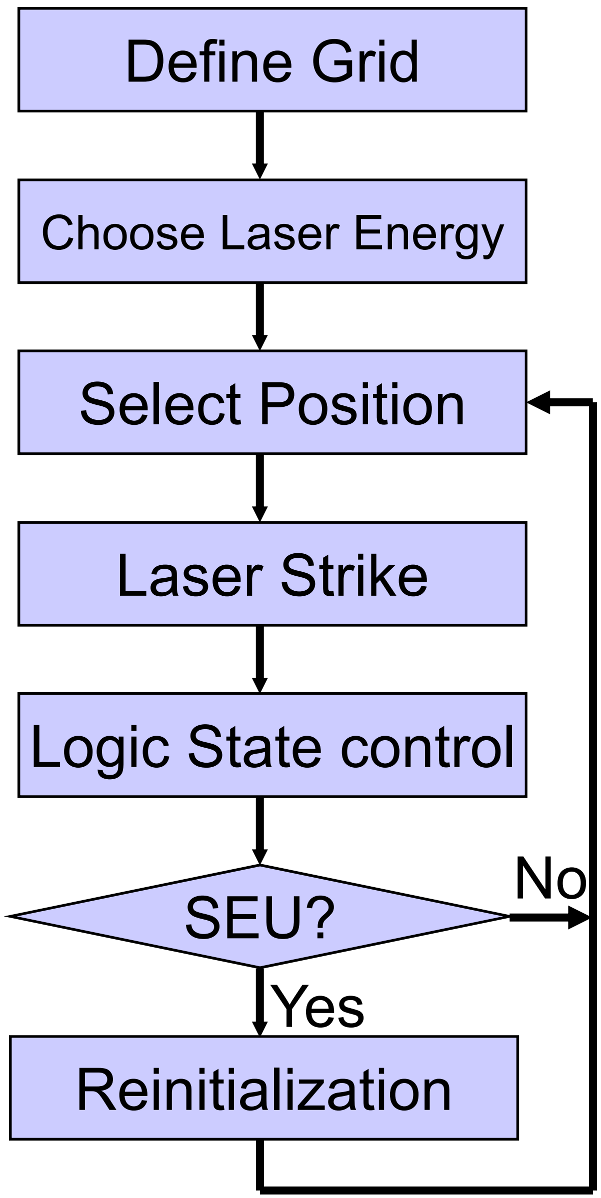
Test Vehicle : 6T SRAM cell

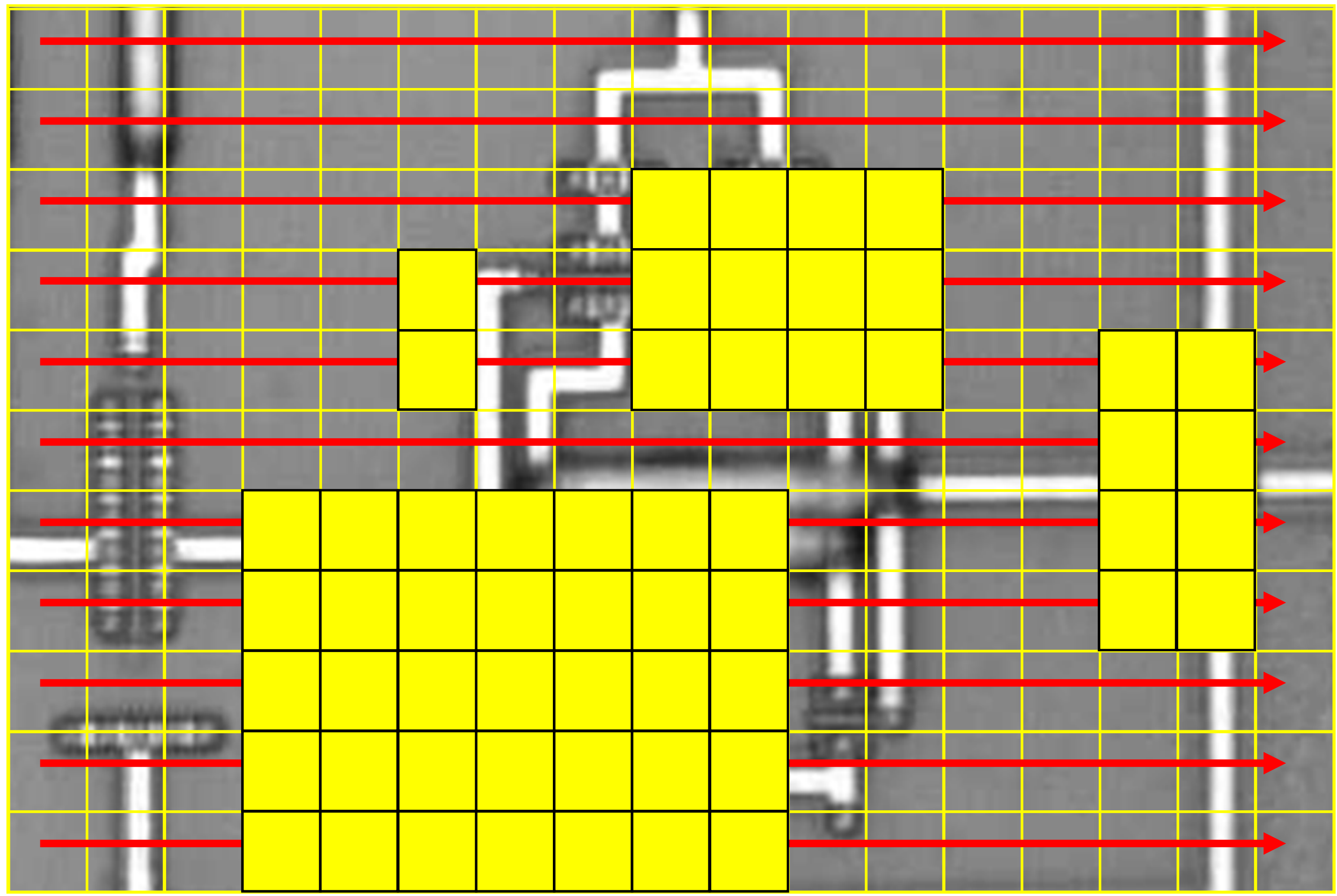
- 0.8 µm AMS BiCMOS technology
- low density of metal tracks (SPA technique and frontside testing)





Scanning automation : basic principle



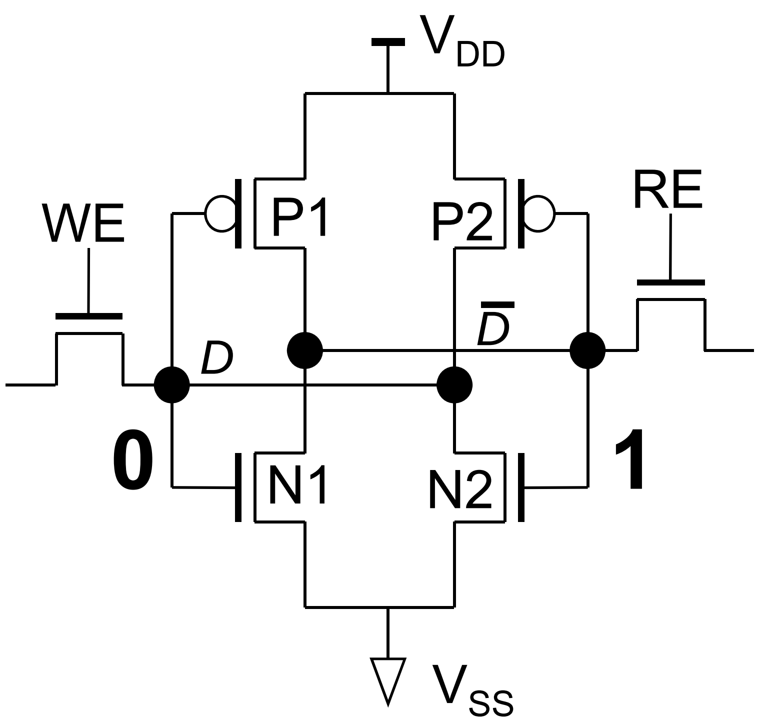


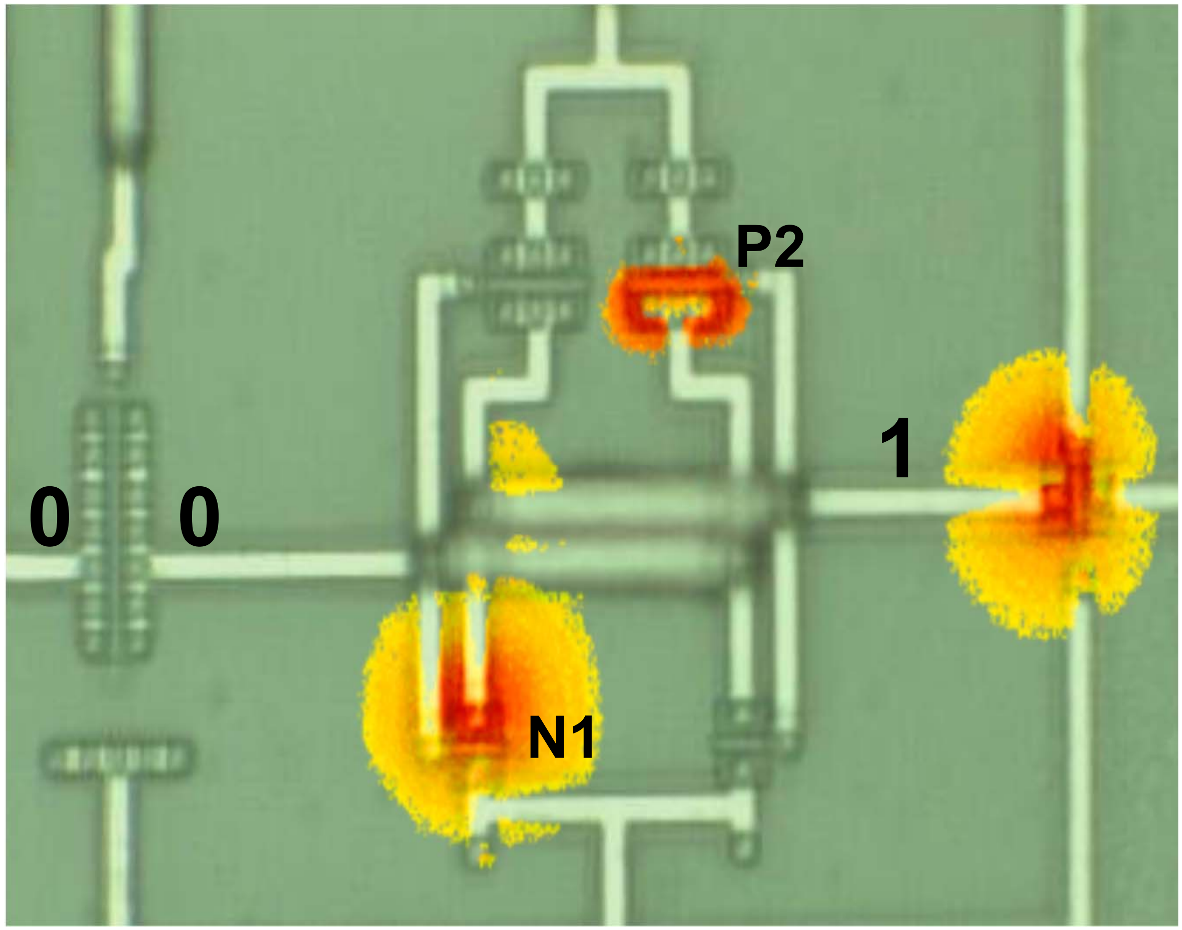
1st level of Laser Energy

2nd level of Laser Energy

3rd level of Laser Energy

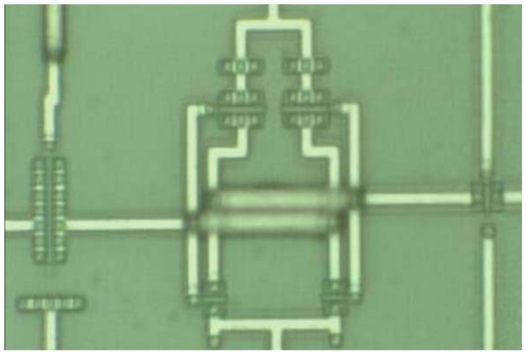
SEU Mapping : Sensitivity of the NMOS drain

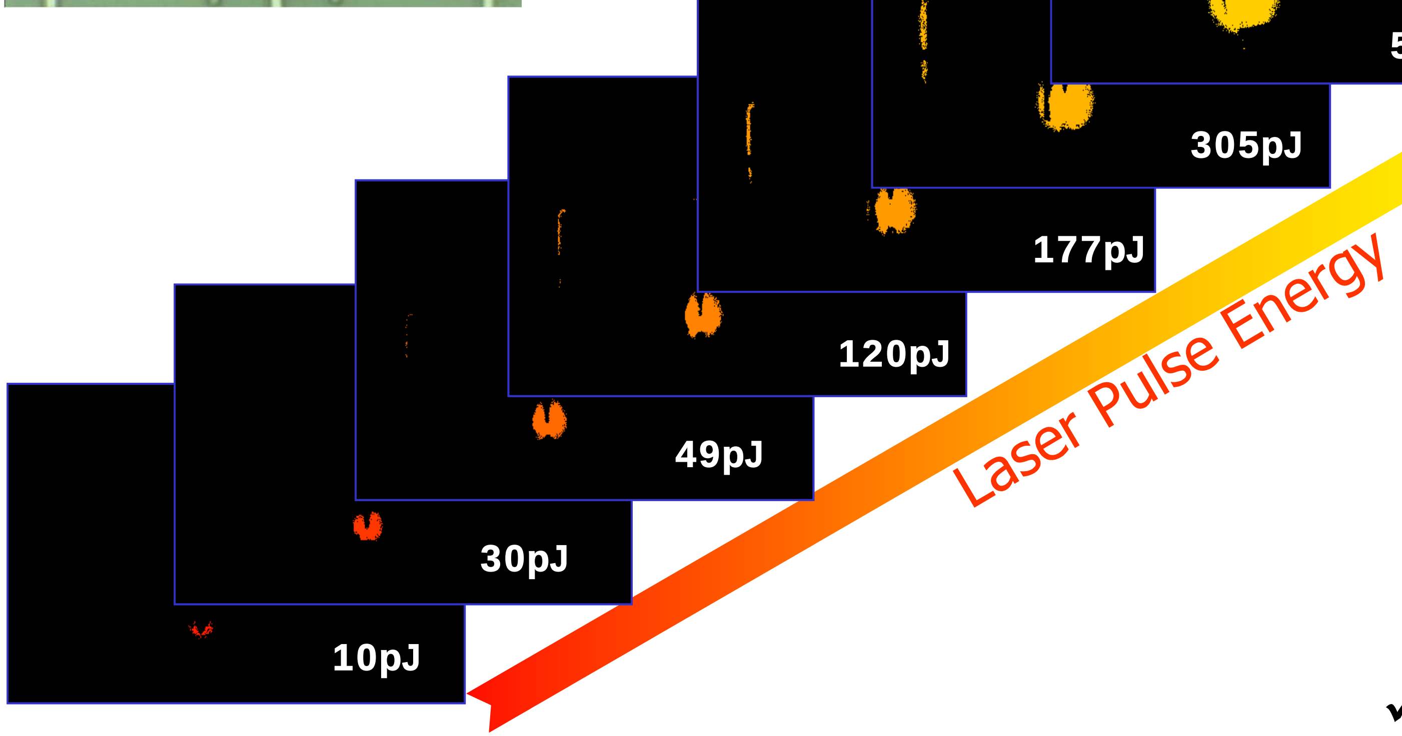




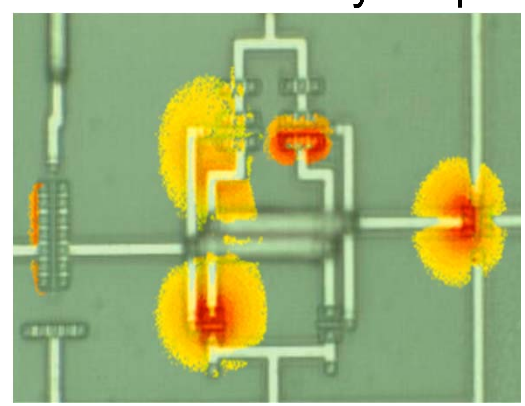
SEU mapping

6T SRAM Test Vehicle



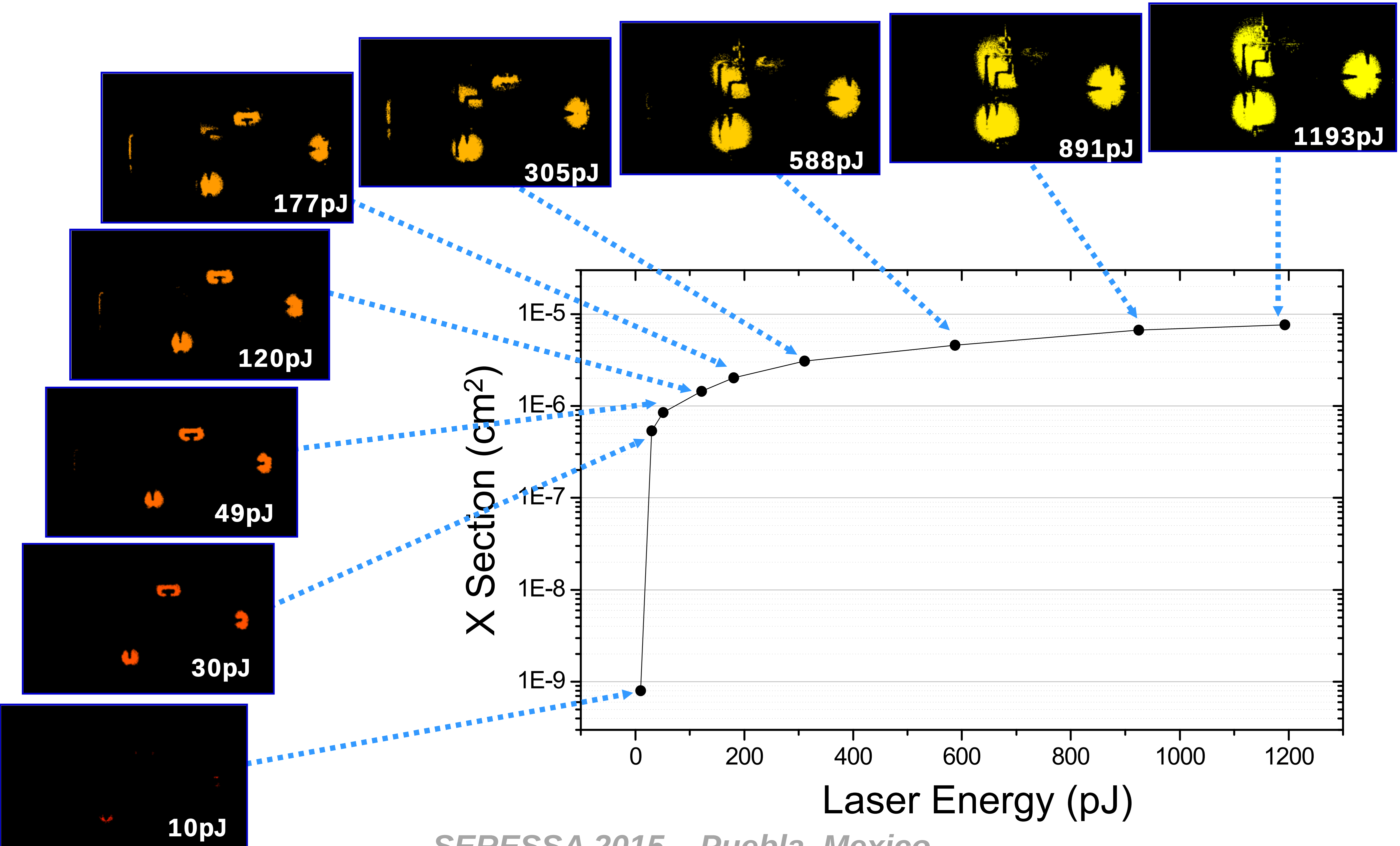


SEU sensitivity map



- ✓SEU mechanisms
- ✓Design optimization

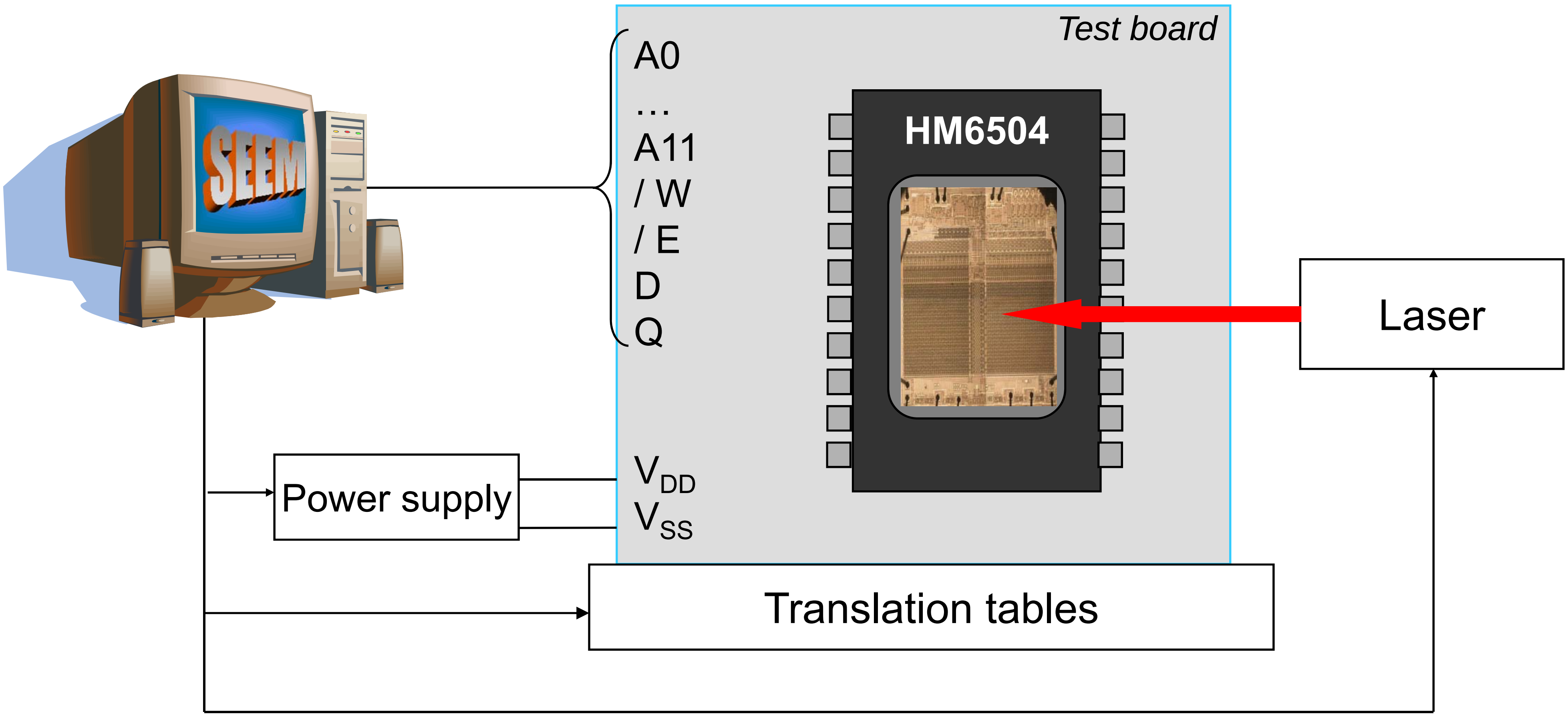
From SEU mappings to X Section analysis



CASE STUDY 2

Single-Event Upset Mapping in
of a commercial SRAM

Case study 1: HM6504 SRAM



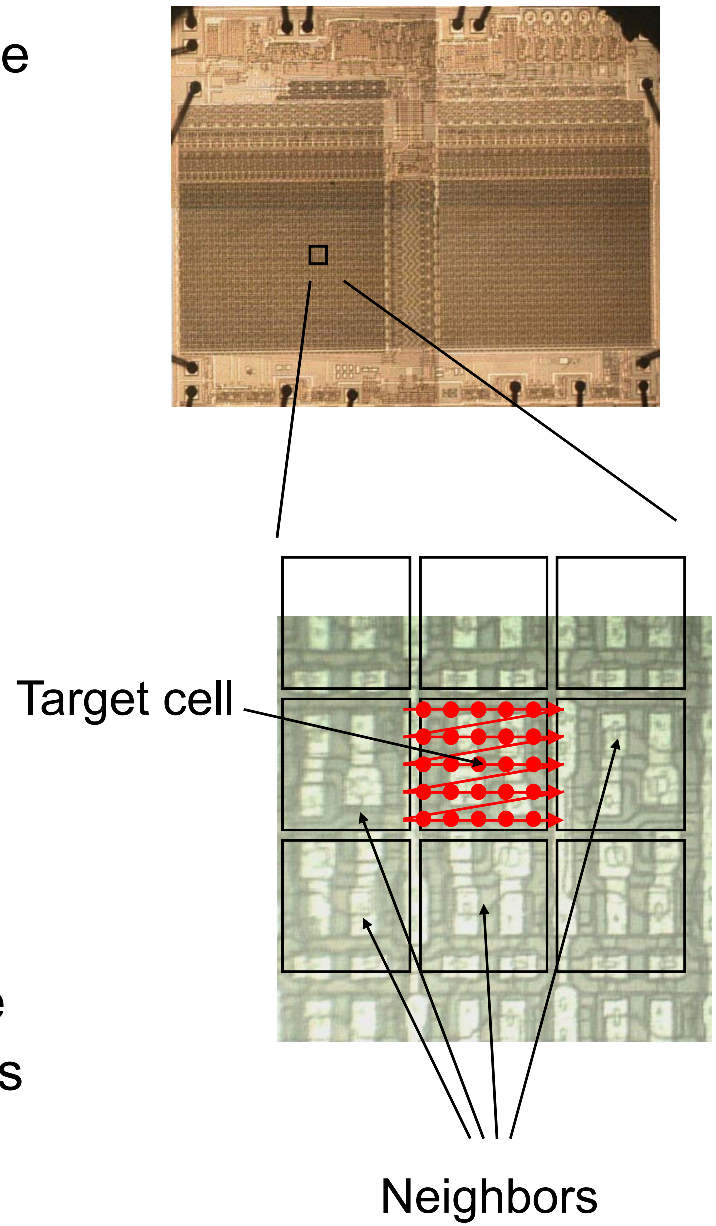
- V_{DD}=5V
- I_{DDmax}=50mA

- Wavelength : 800nm
- Pulse length : 1ps
- Spot 1/e ∅ : 1.1µm

- Scanning step : 1µm

SEU mapping of a single SRAM cell

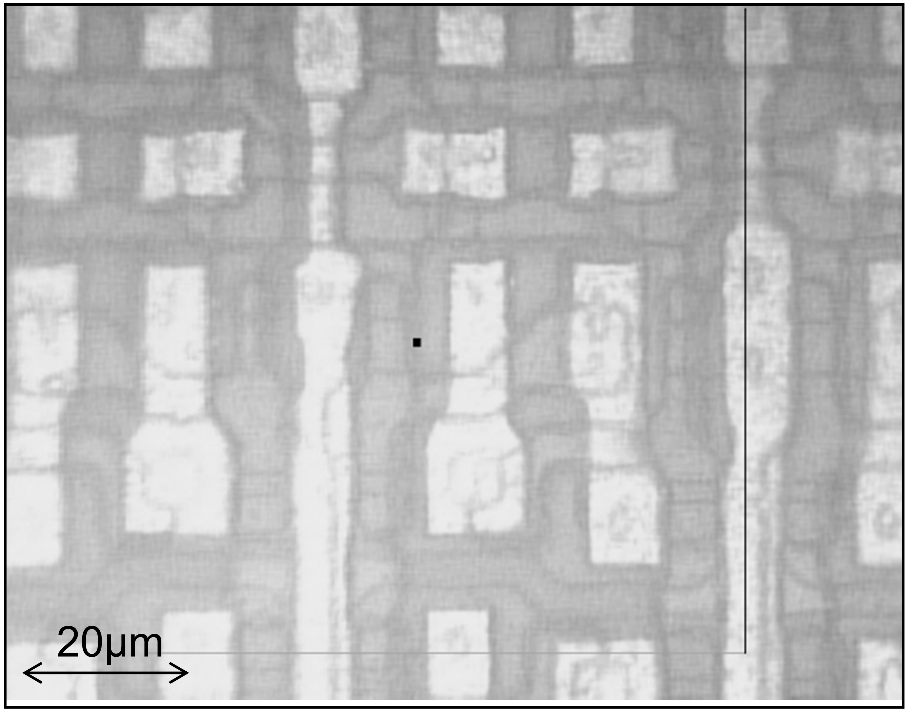
- A single cell is visually selected in the middle of the array : the « target cell »
- Its logical address is read from the tester by inducing an SEU with the laser
- The adresses of the surrounding cells (the « neighbors ») are also noted
- During the scan, after each laser strike :
  - only upsets in the target cell are used to build the mapping
  - neighbors state is monitored to ensure that the electrical environment of the target cell remains the same



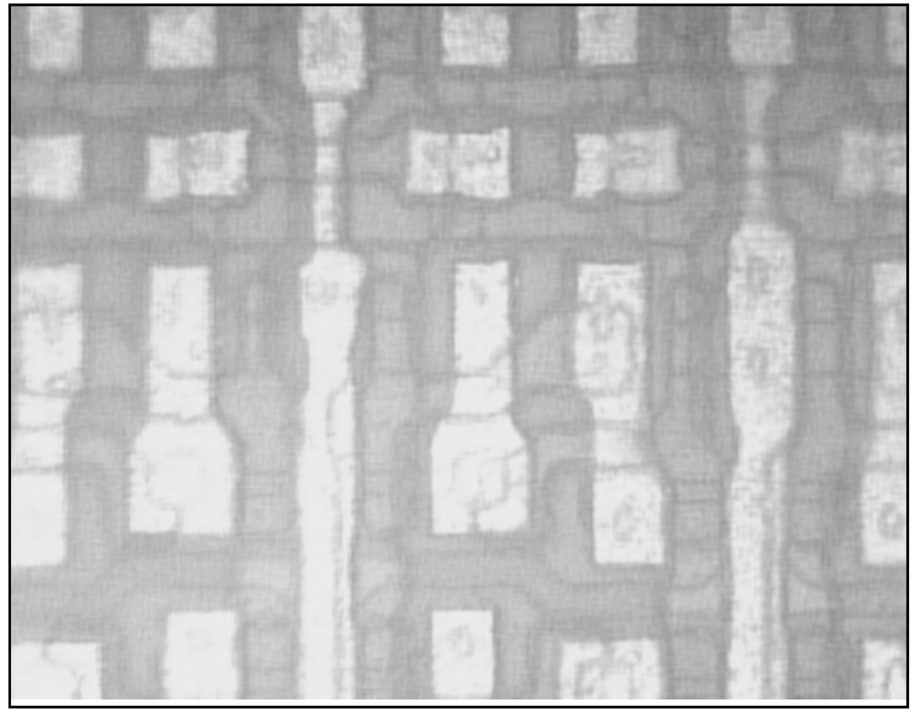
SEU mapping

4 pJ

All to 0



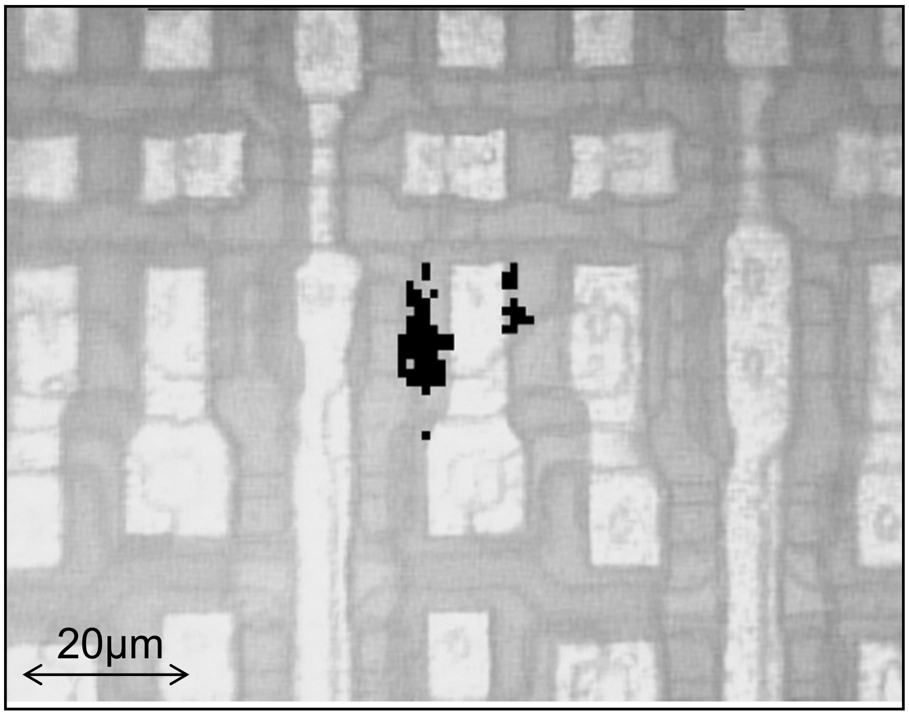
All to 1



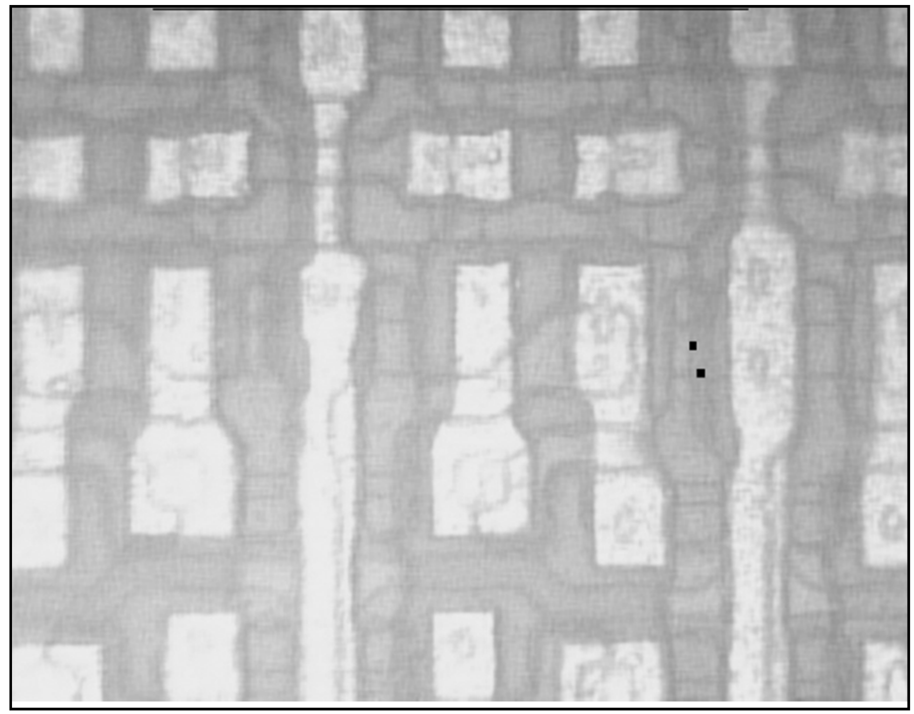
SEU mapping

7.2 pJ

All to 0



All to 1

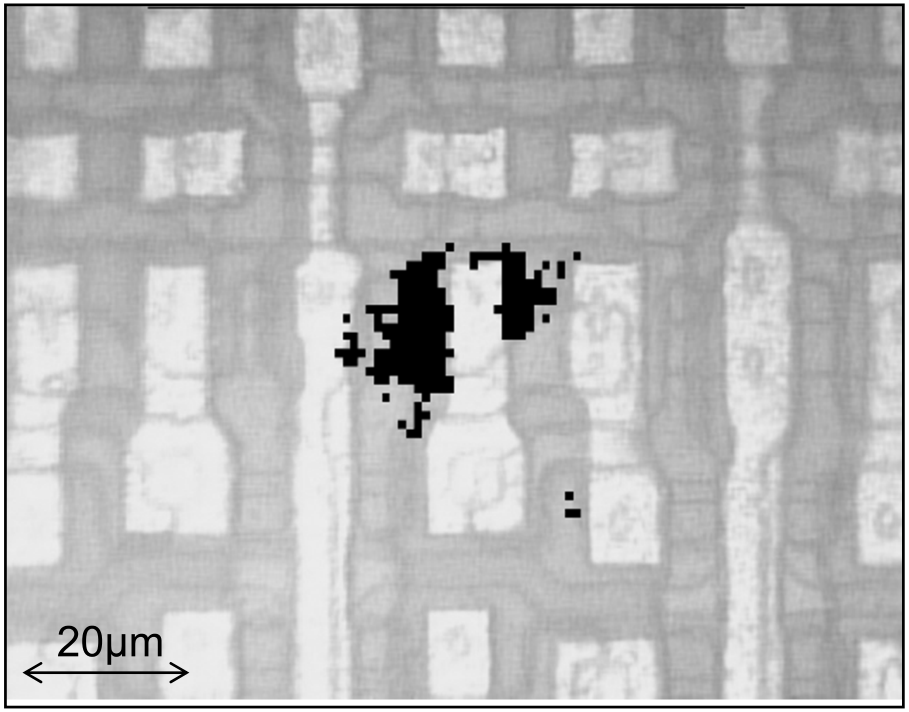


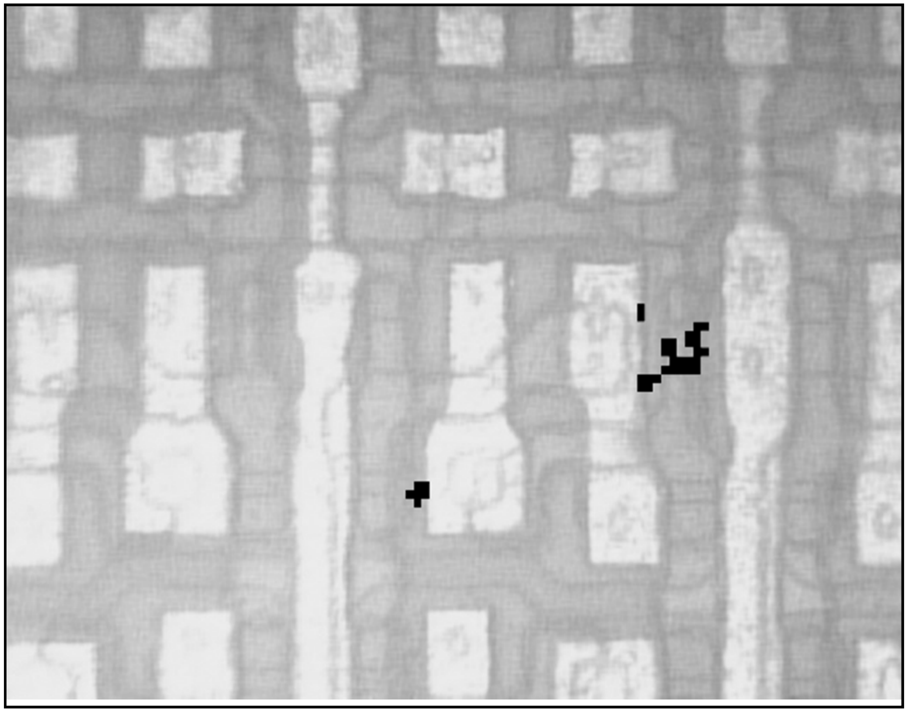
SEU mapping

10.4 pJ

All to 0

All to 1

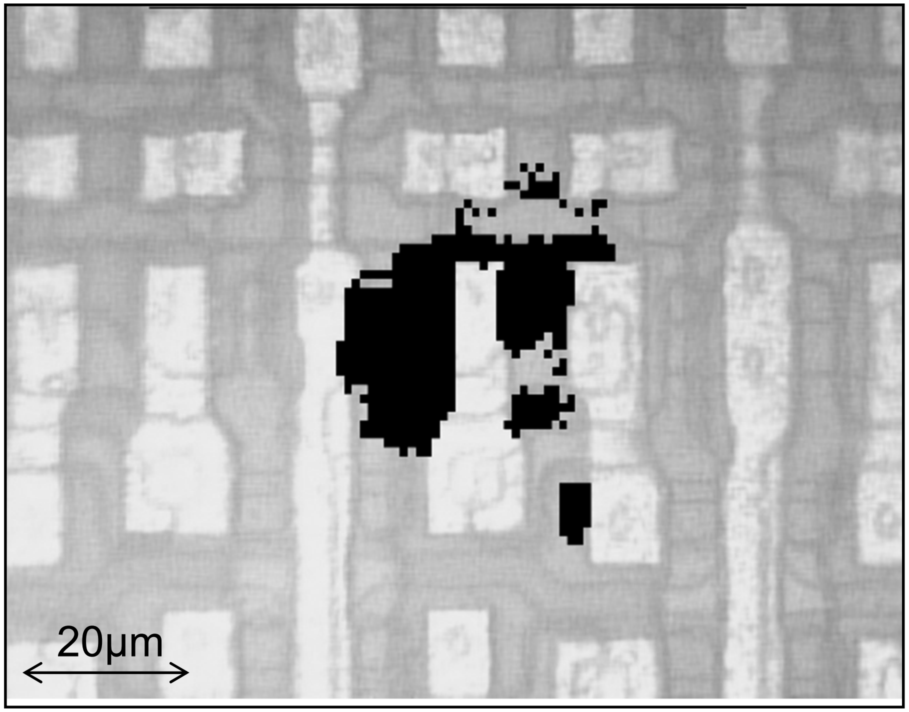




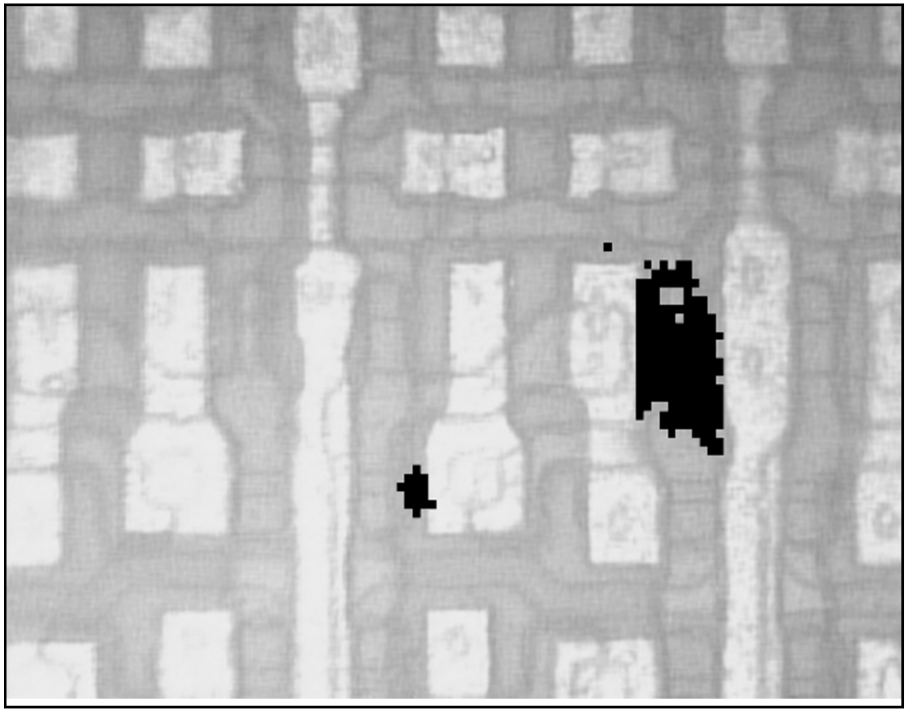
SEU mapping

20 pJ

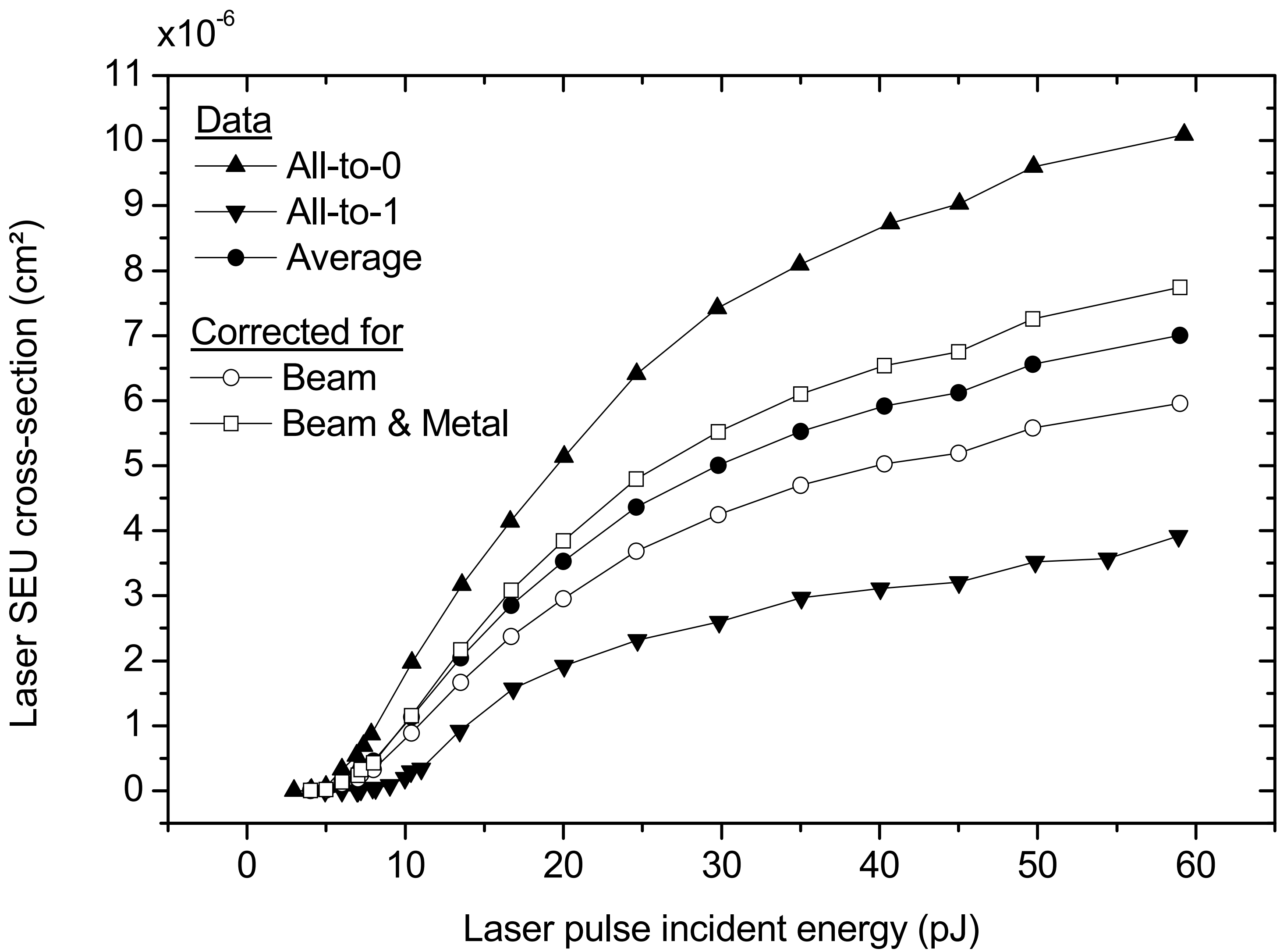
1 to 0



0 to 1



SEU Laser cross-section

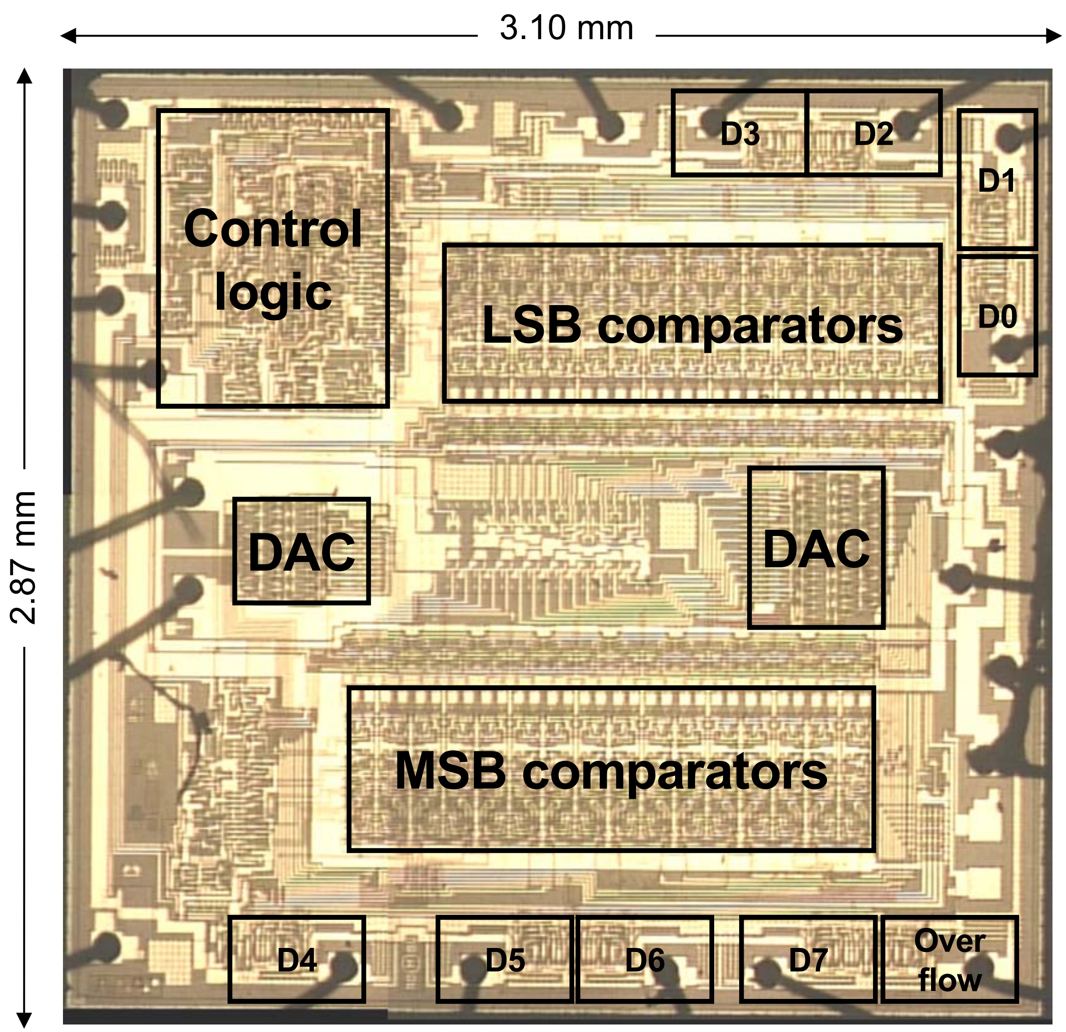


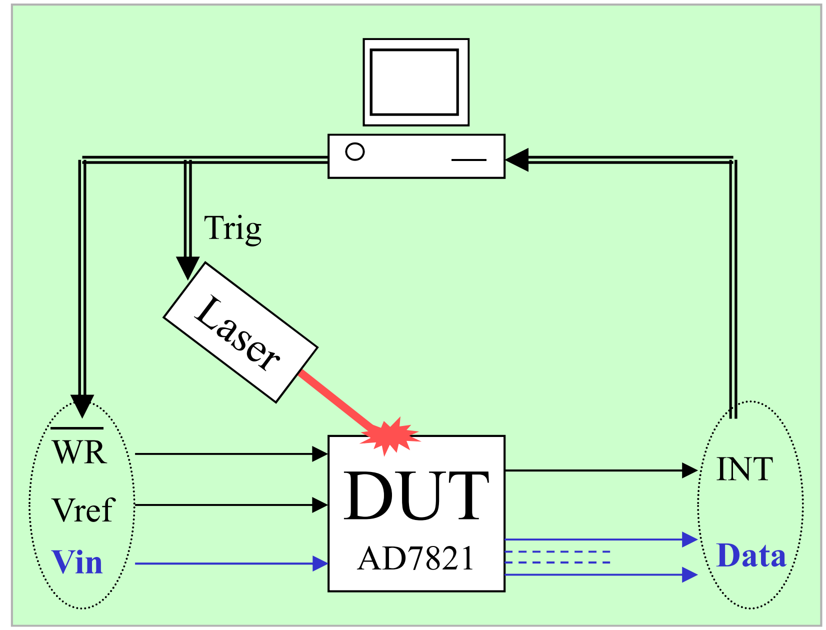
CASE STUDY 3

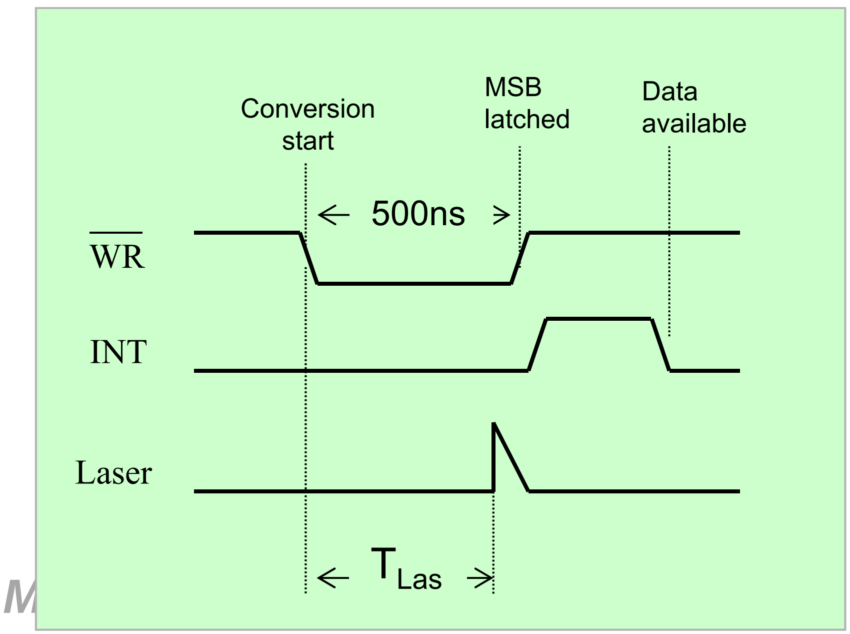
Dynamic Testing of ADCs

Transient fault injection in an ADC

- ✓Mixed signal ICs = complex errors
- ✓AD 7821, 8 bits, 100kS/s, 1/2 flash ADC



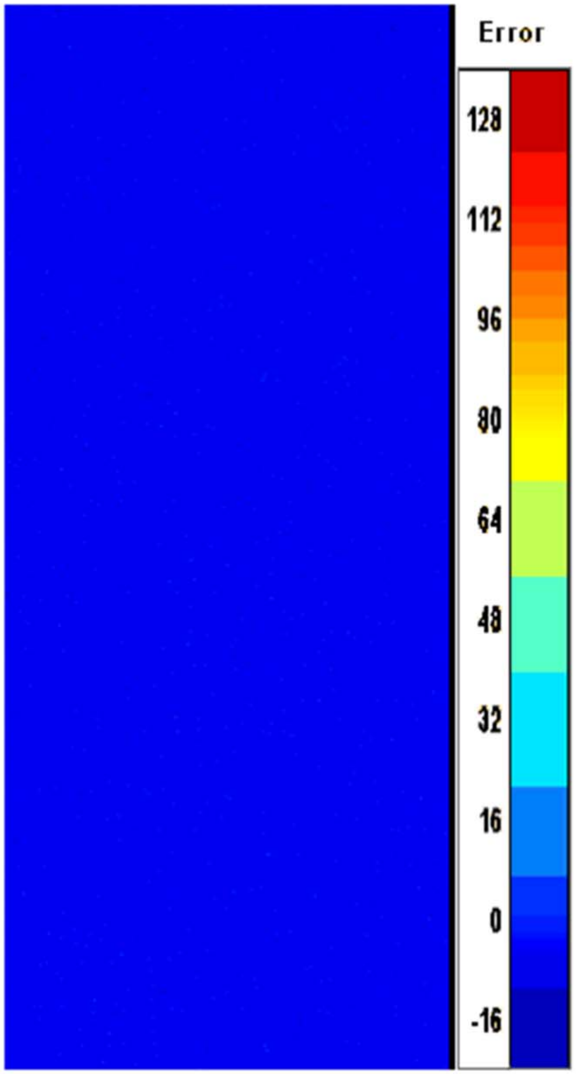


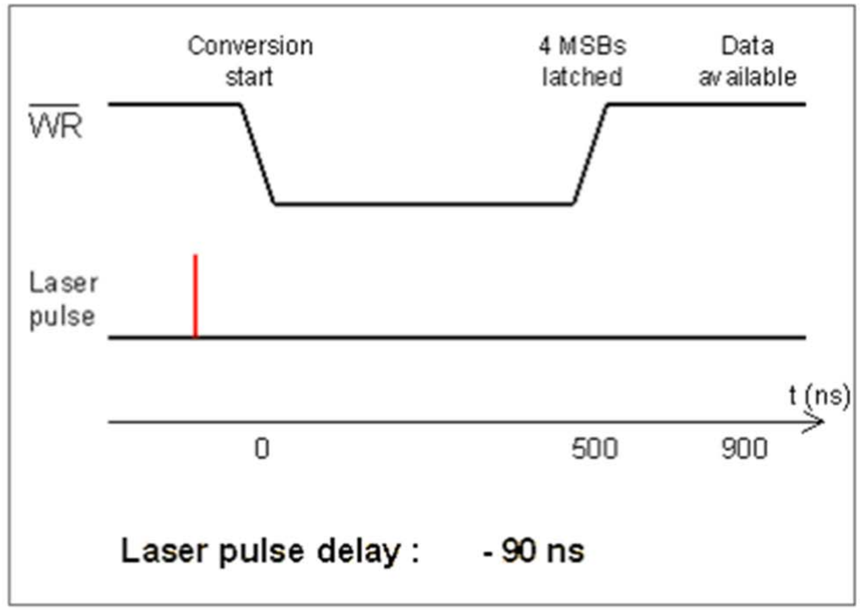


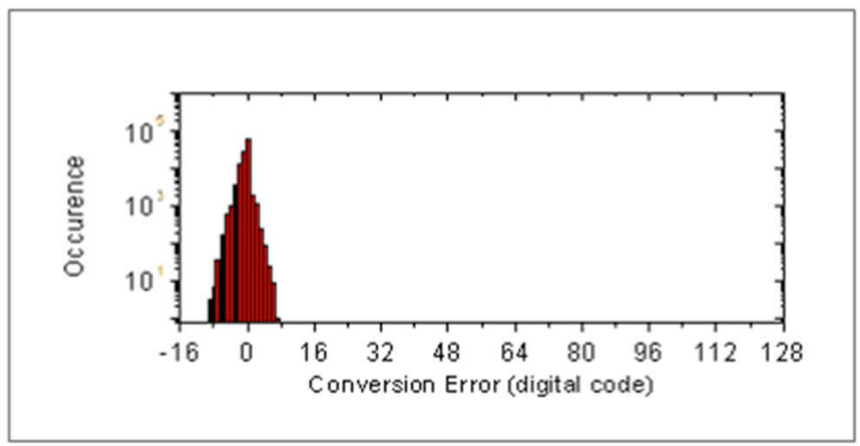
Experimental results with ADC (2)

Dynamic sensitivity of comparators

2 MSB comparators





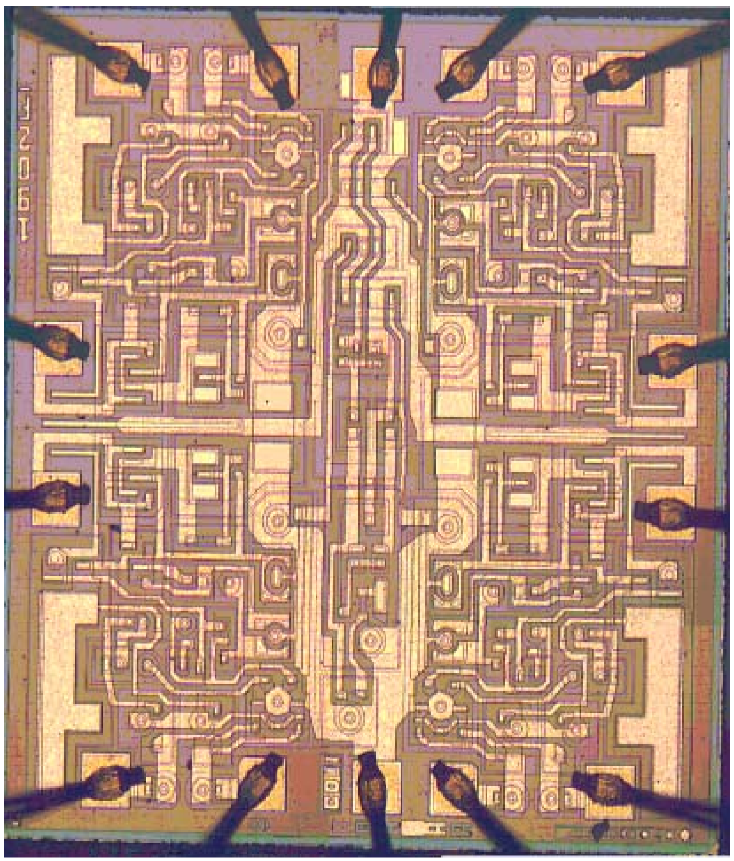


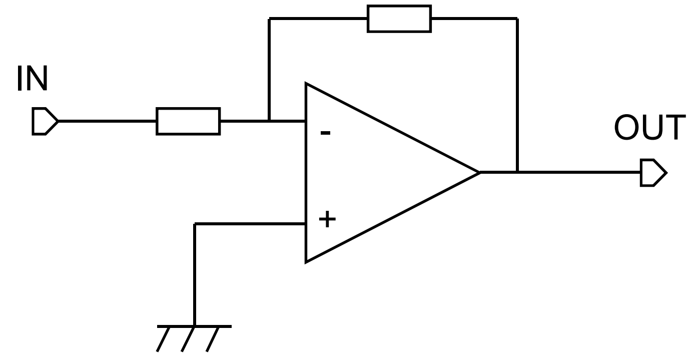
CASE STUDY 4

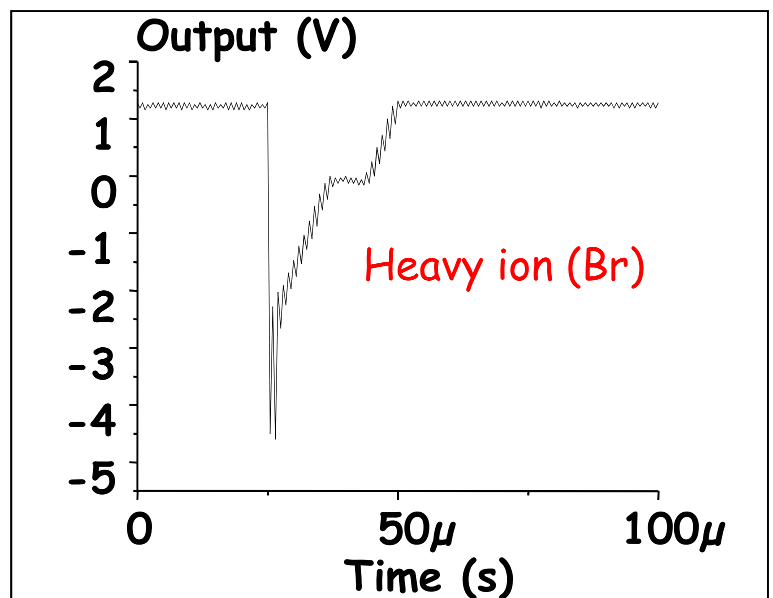
Analog Single-Event Transients in an Operational Amplifier

Case study 4: LM124

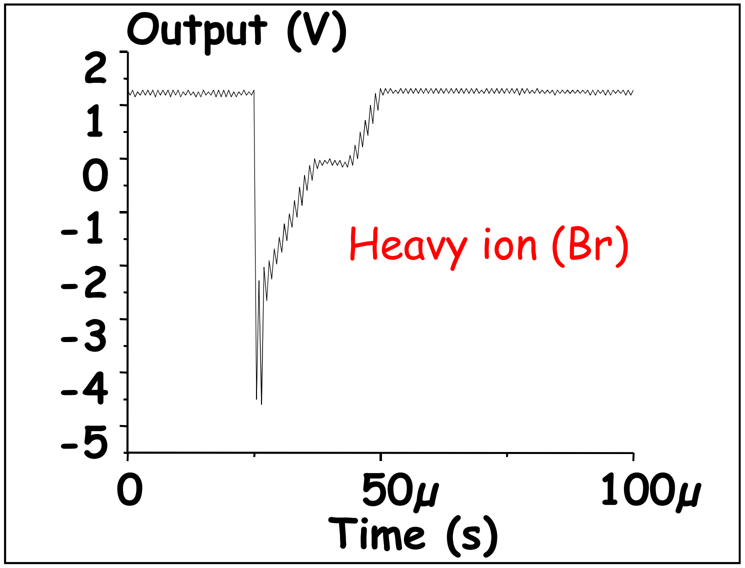
- **LM124 : quad operationnal amplifier**
- **Analog SET observed during particle accelerator testing**
- **Transients duration in the µs domain**

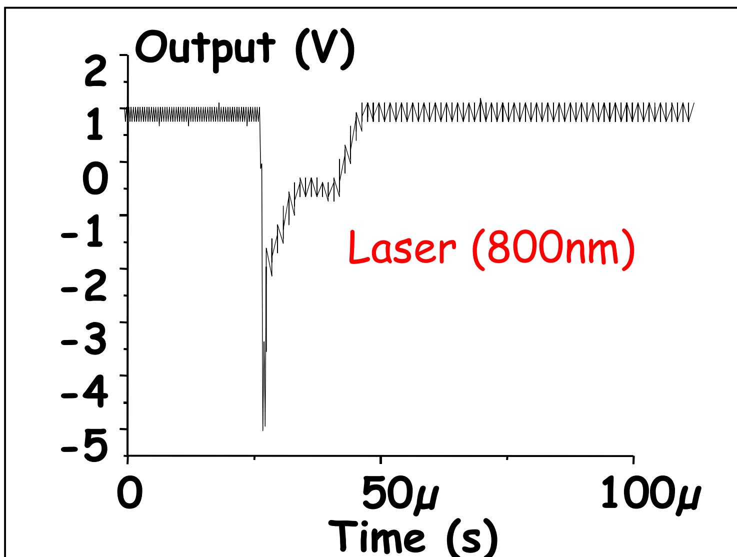






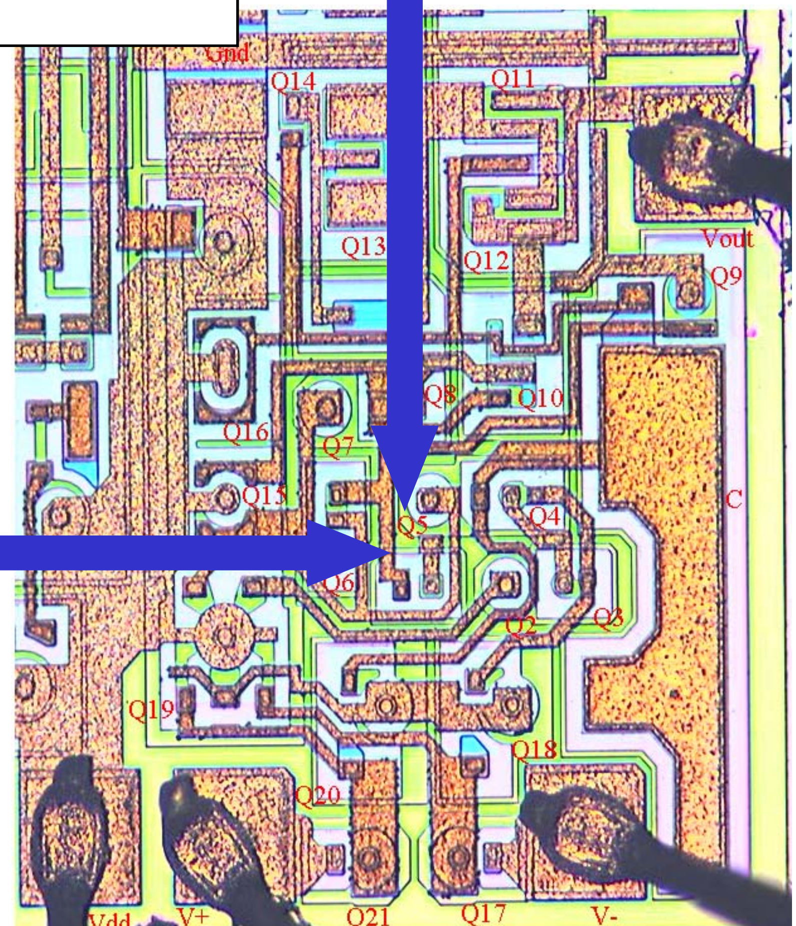
ASET reproduction with laser



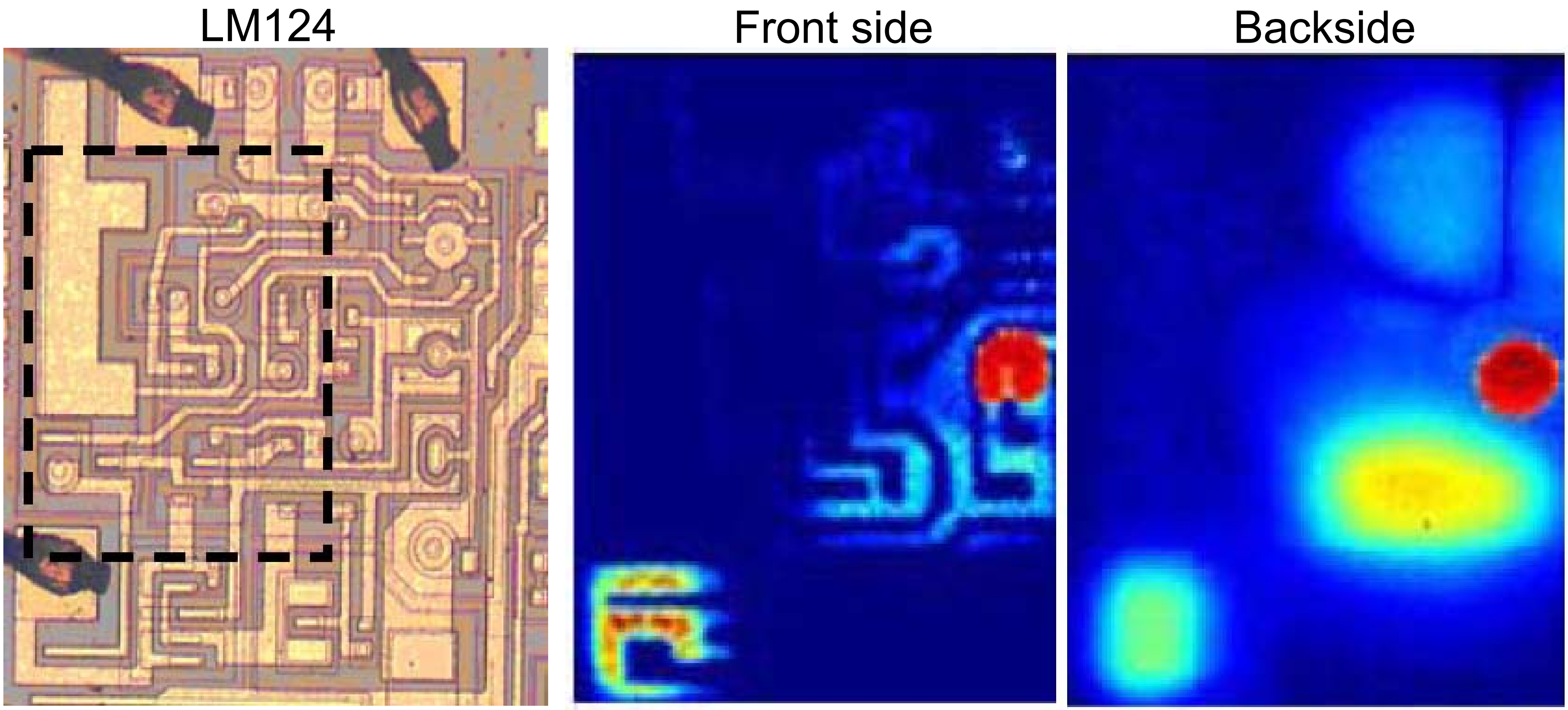


Electrical model of the device

SPICE analysis



ASET amplitude mapping



- Mappings of the amplitude of the transient measured
- Sensitive areas clearly identified
- Possibility of measuring the laser cross section from backside

CASE STUDY 5a

Laser-Induced Latchup Screening in CMOS Devices

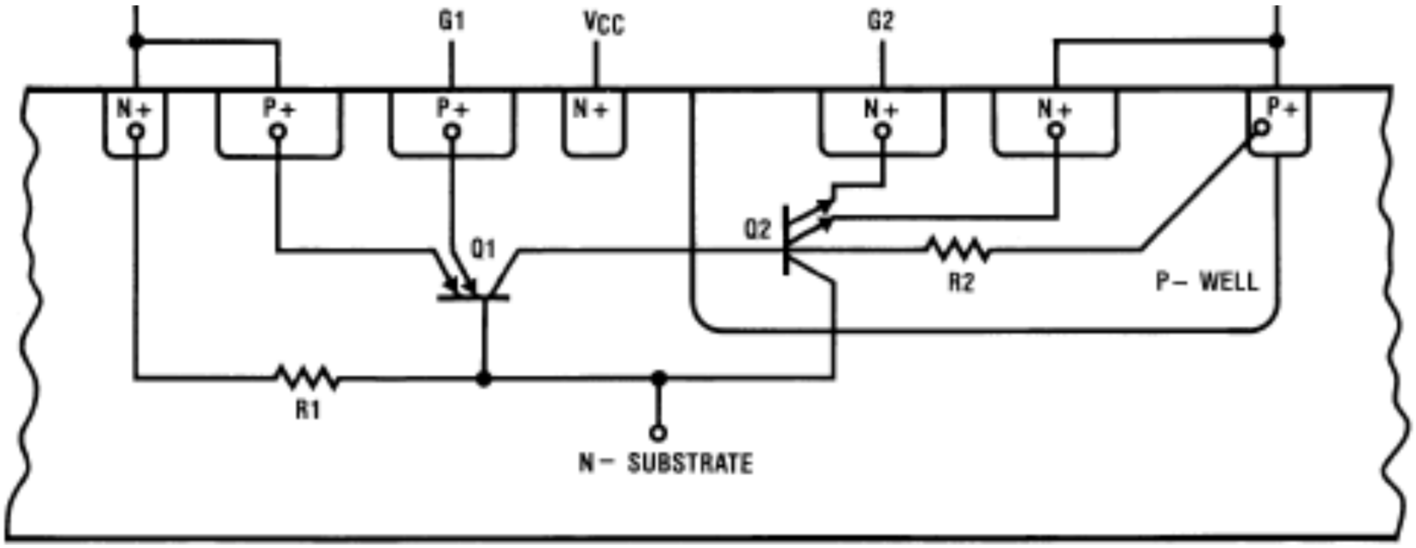
Laser-Induced Latchup Screening and Mitigation in CMOS Devices

- COTS Parts
  - Screening and Characterization
- Space-Qualified Parts
  - Identify SEL sensitive areas
  - Redesign to eliminate problem

Why is Latchup an Issue?

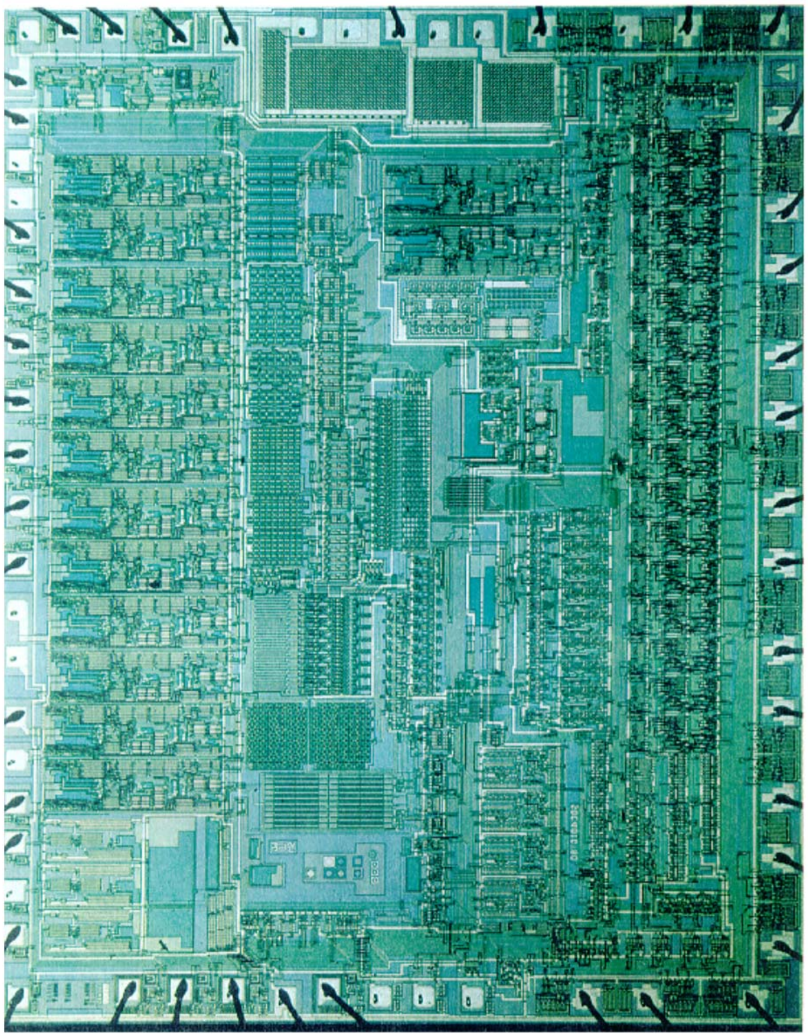
- A single latchup event *can compromise an entire mission*

Latch-Up in CMOS Devices



- Parasitic vertical (n-p-n) and lateral (p-n-p) bipolar transistors are a characteristic of CMOS technology
- If charge is injected into the base of one of the transistors, that transistor turns on; the increased current flow causes an injection of charge into the base of the other transistor, turning it on as well
- The result is that there is a feedback so that both transistors are turned on, leading to a low-resistance path between V_{dd} and Gnd, which is the origin of the latchup current.
- Current continues to flow until the voltage is dropped sufficiently so that the transistors turn off.

Latch-Up Screening of COTS Parts for Space Missions

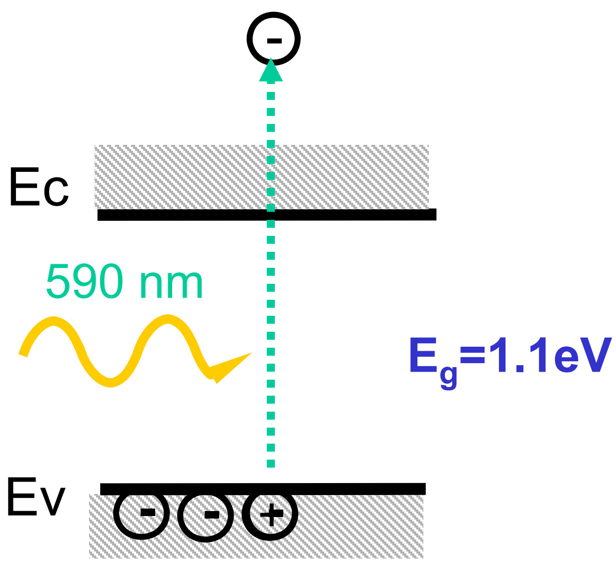


DDC RDC19220

- The pulsed laser permits the rapid and accurate location of SEU and SEL sensitive regions of COTS parts with sub-micron precision
- This example: two Resolver-to-Digital Converters were screened for latchup for a NASA space mission

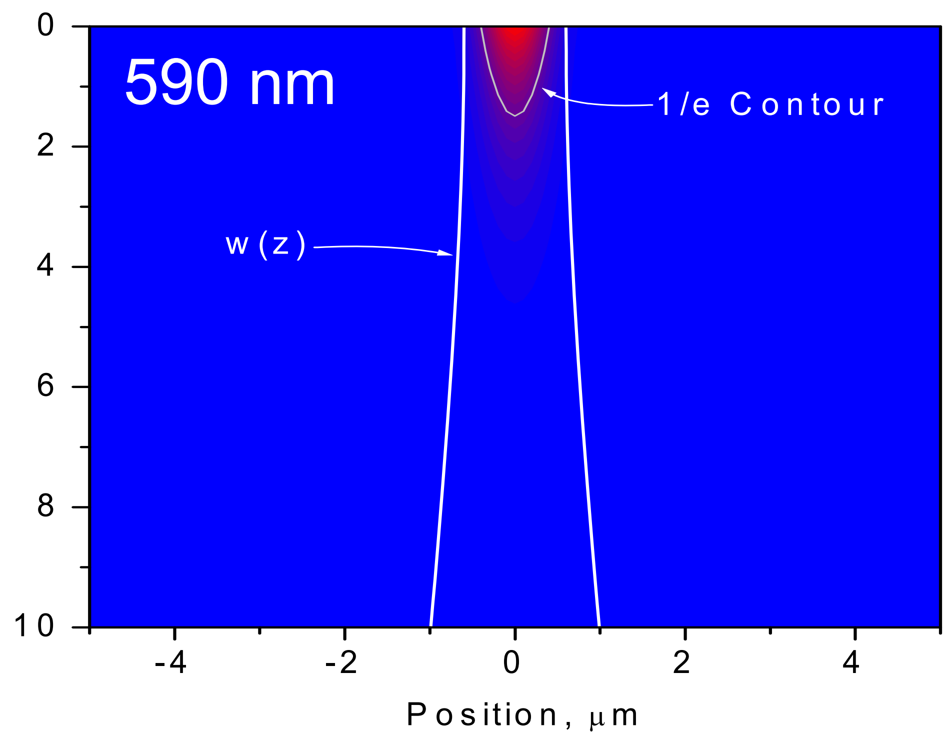
Latch-Up Screening of COTS Parts
Single-Photon Absorption

1-Photon

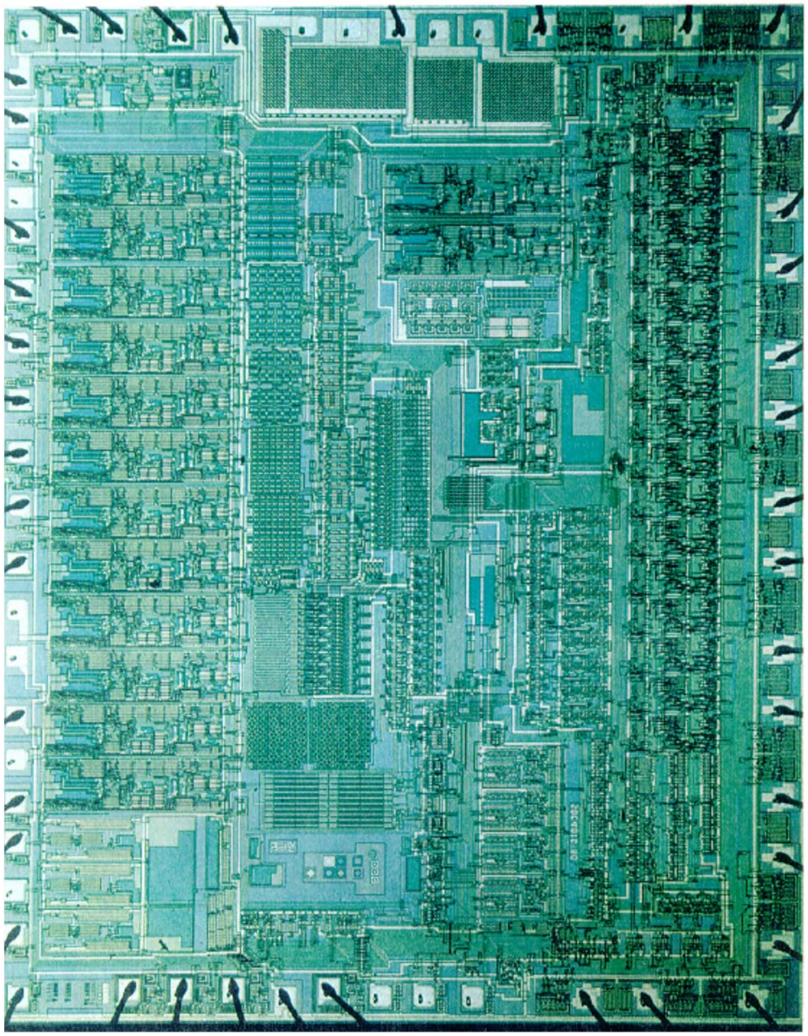


$$I(r,z) = I_o e^{-\alpha z}$$

- ***Single photon absorbed***
- ***Creates a single e-h pair***

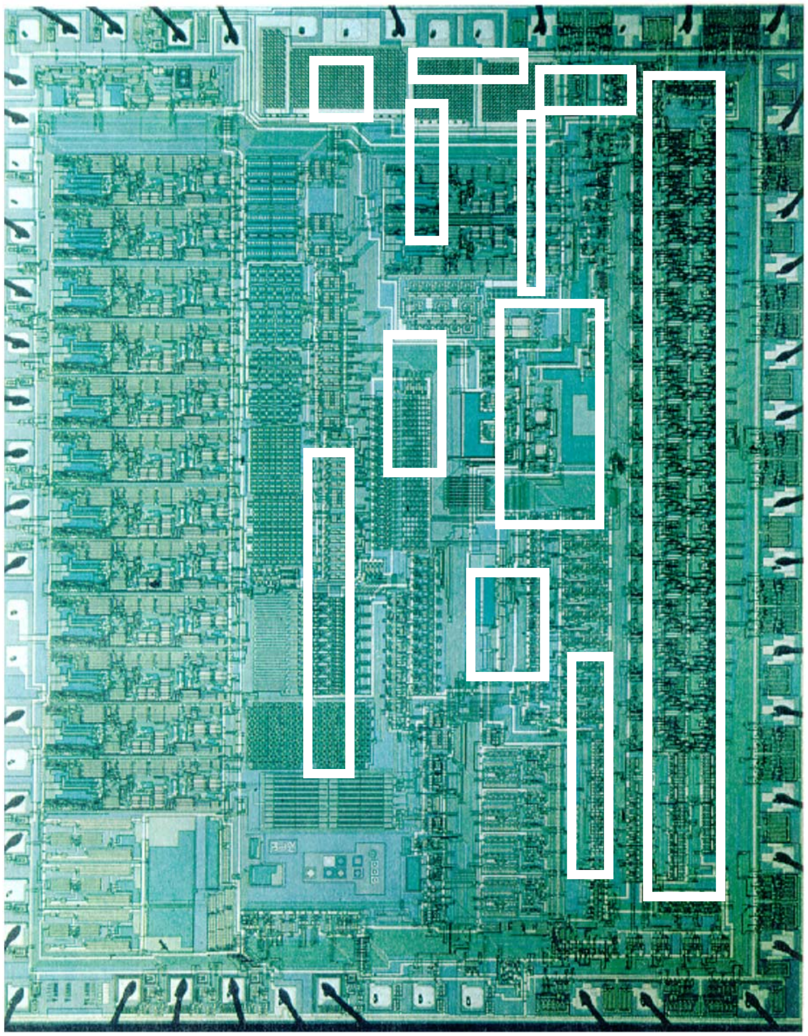


Latch-Up Screening of COTS Parts for Space Missions



DDC RDC19220

Latch-Up Screening of COTS Parts for Space Missions



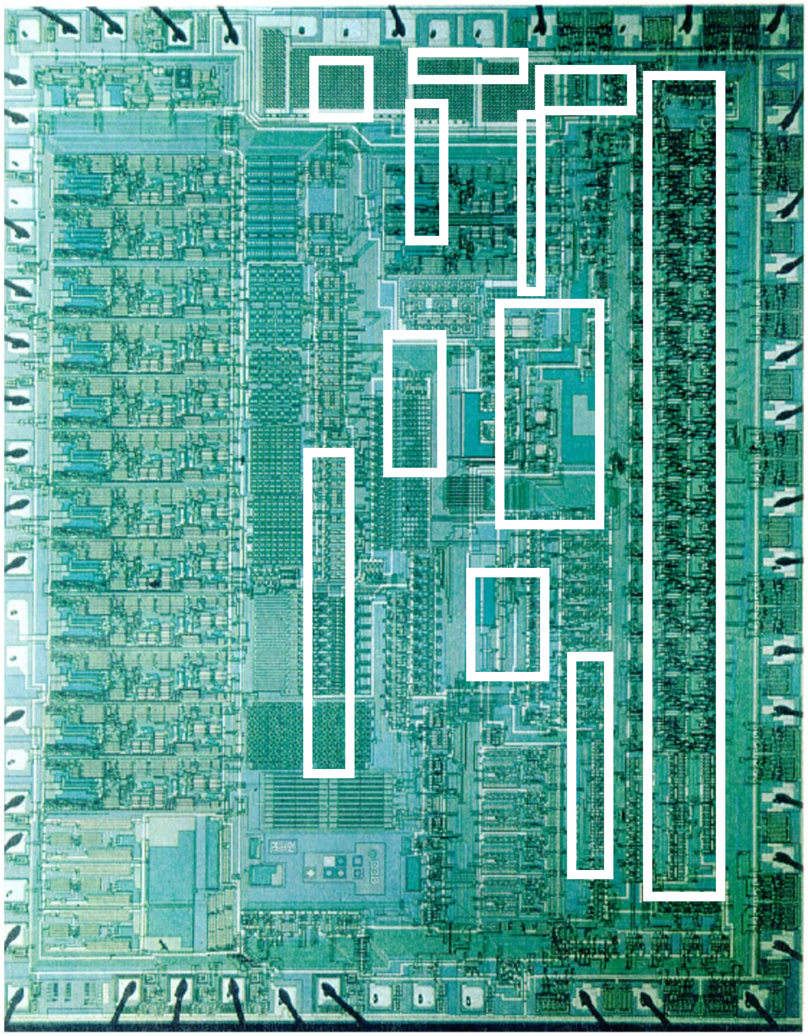
SEL sensitive areas in COTS RDC

(DDC RDC19220)

- The latch-up sensitive areas for one of the parts is shown here
- Based solely on these laser results, this part was eliminated from consideration for this and future NASA missions

*Buchner, et al., TNS, **46**, 1445 (1999).*

Latch-Up Screening of COTS Parts for Space Missions



SEL sensitive areas in COTS RDC

(DDC RDC19220)

- The latch-up sensitive areas for one of the parts is here
- Based solely on these laser results, this part was eliminated from consideration for this and future NASA missions
- The other part, it turned out, was latch-up free and, eventually, was deemed acceptable for the mission in question

*Buchner, et al., TNS, **46**, 1445 (1999).*

CASE STUDY 5b

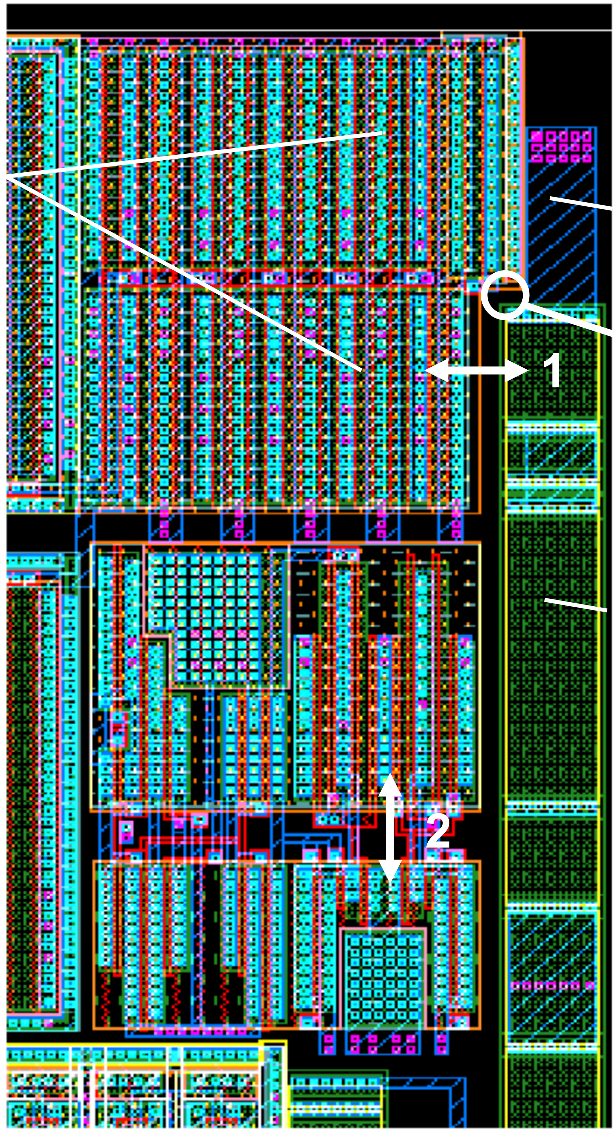
Laser-Induced Latchup Screening and Mitigation in CMOS Devices

National Semiconductor DS90C031 LVDS Original Design

- LVDS Quad differential line driver designed into recent (2006) GPS upgrade program
- Unanticipated latchup sensitivity observed in HI testing (*NASA*)
- Unacceptable for mission requirements; threatened to delay launch date (big $$$)
- Pulsed laser SEL evaluation (*NRL*) revealed sensitivity localized to a small region → redesign possible
- Redesigned (*Boeing*) → refabricated (*NS*) → retested (*NASA*)
- *No Latchup observed in redesigned part*
- Launch on schedule
  - We were HEROS!

National Semiconductor DS90C031 LVDS

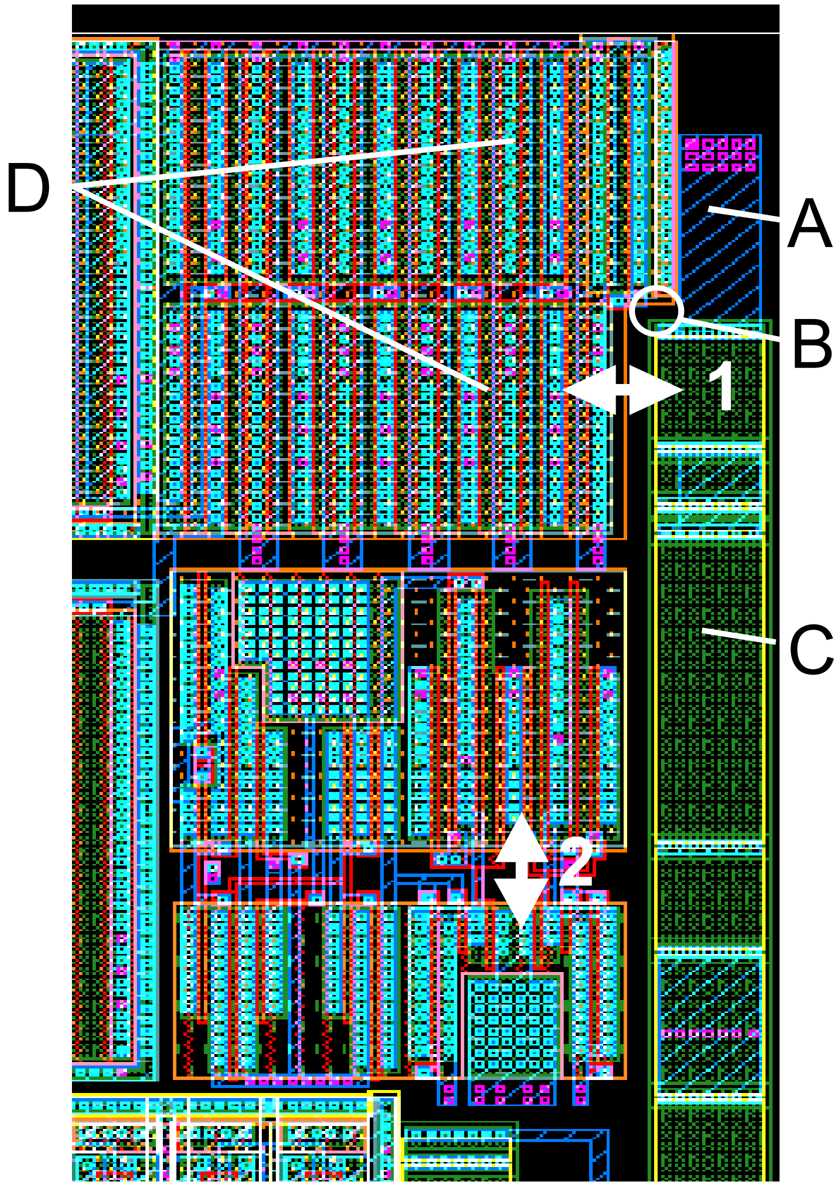
Original Design

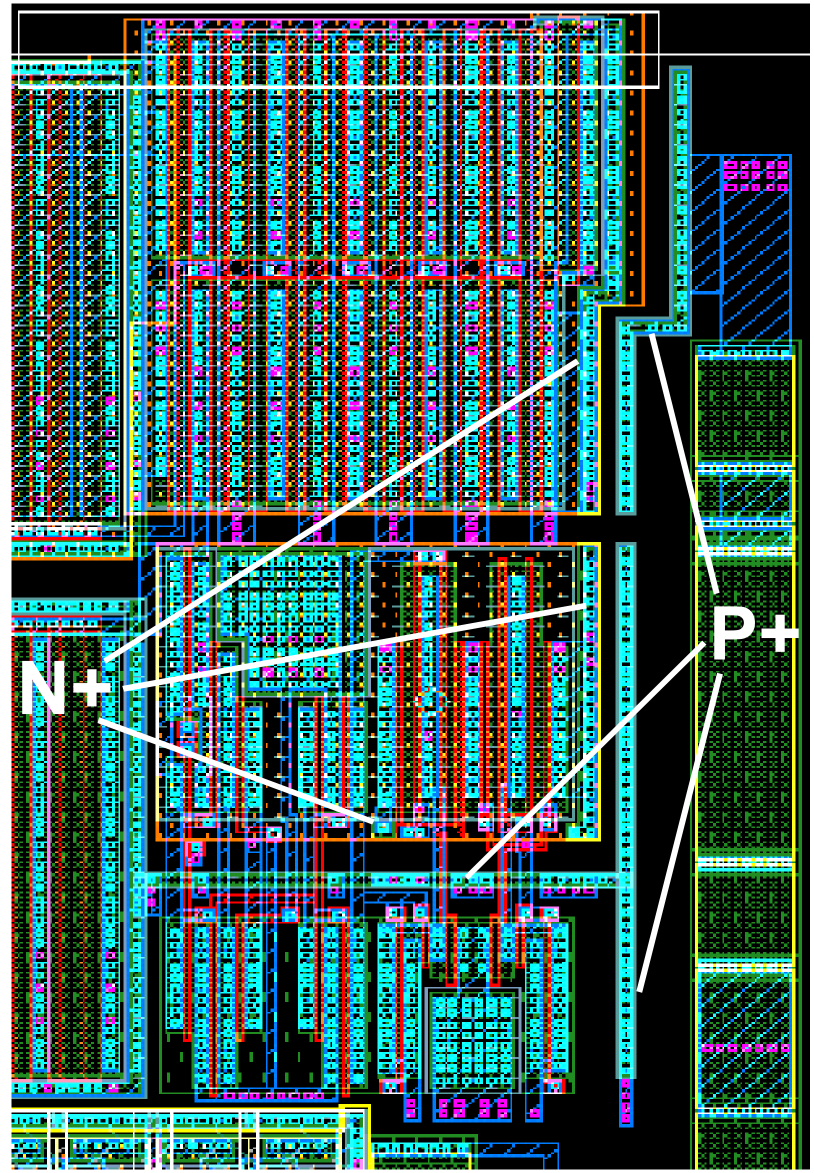


*McMorrow, et al., IEEE TNS **53**, 1819 (2006).*

National Semiconductor DS90C031 LVDS

Comparison of Two Designs





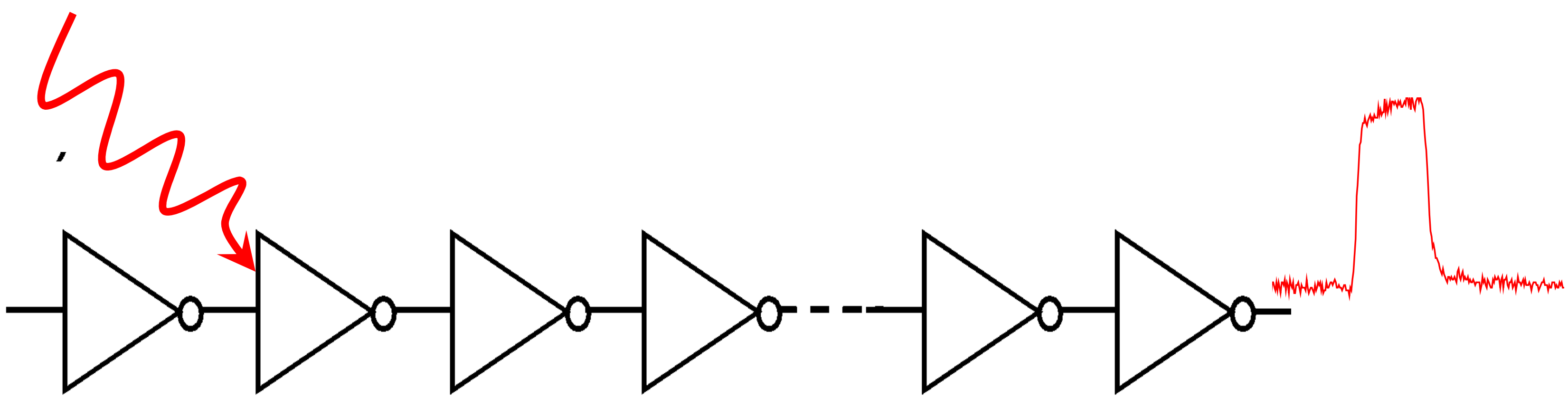
*McMorrow, et al., IEEE TNS **53**, 1819 (2006).*

CASE STUDY 6

SET Propagation in Logic Circuits

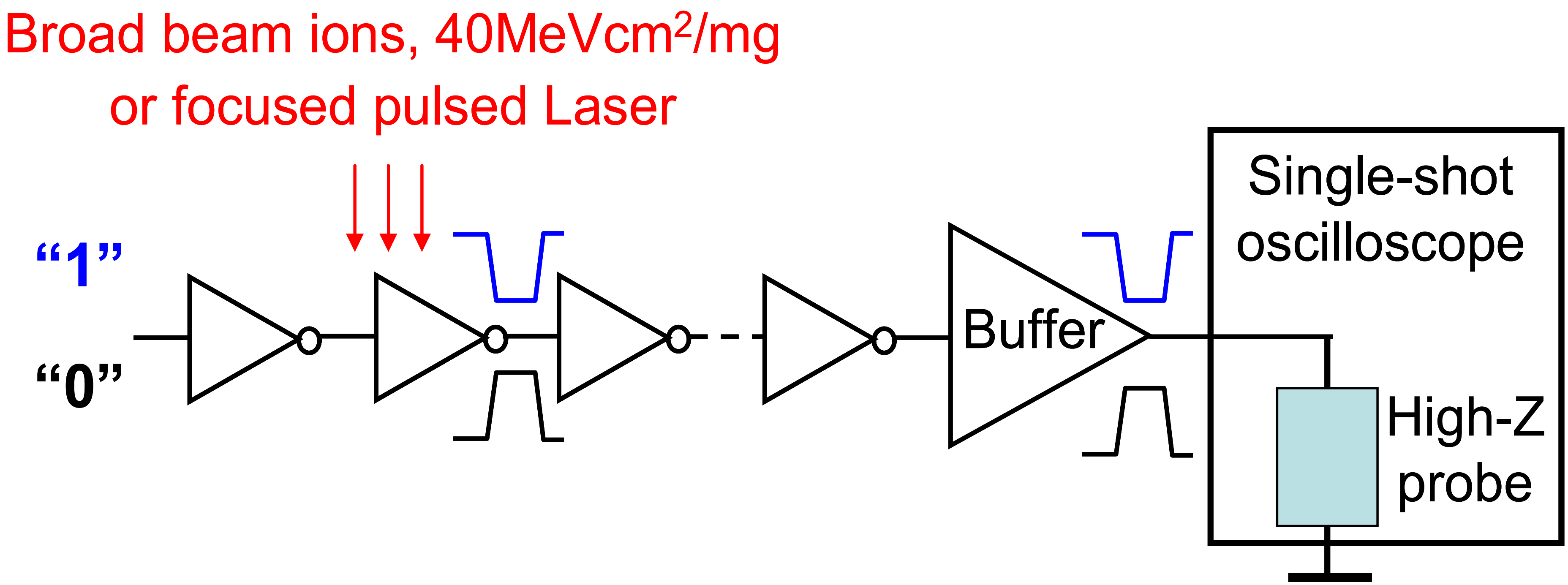
SET Propagation in Logic Circuits

- As of 2006, previous work had shown:
  - SET measurements on **LARGE CHAIN STRUCTURES** under heavy ions can have **WIDE DISTRIBUTIONS** of pulse widths (> 1 ns), in bulk or SOI [Benedetto, Mavis, Eaton, Gadlage, Yanagawa].



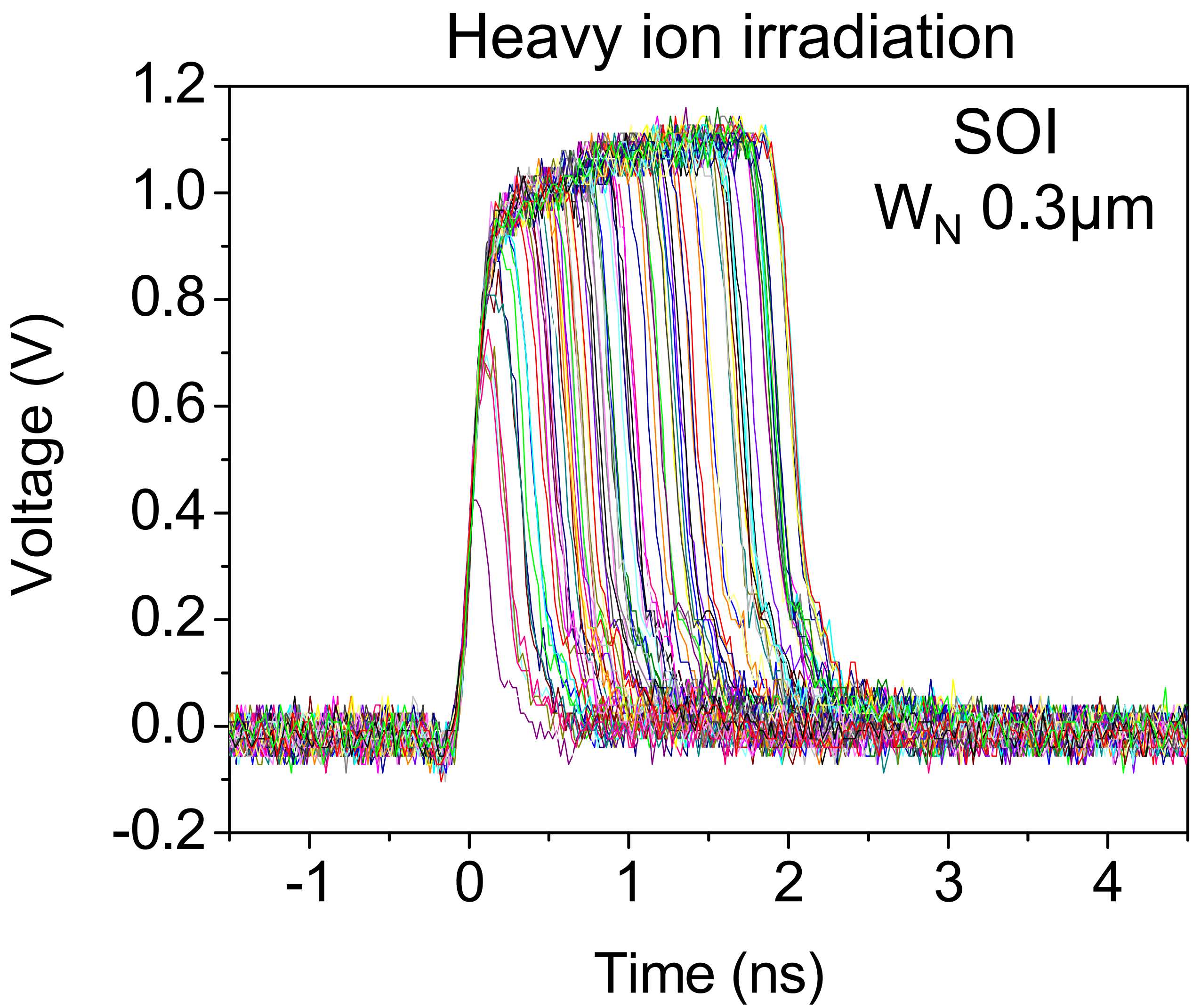
Typically 200-800 Inverters

Direct Measurement of SET Pulses in Chains of Inverters



130 nm partially depleted SOI chains, 800 inverters, four designs

SET Pulse Width Distribution: SOI Inverter Chains



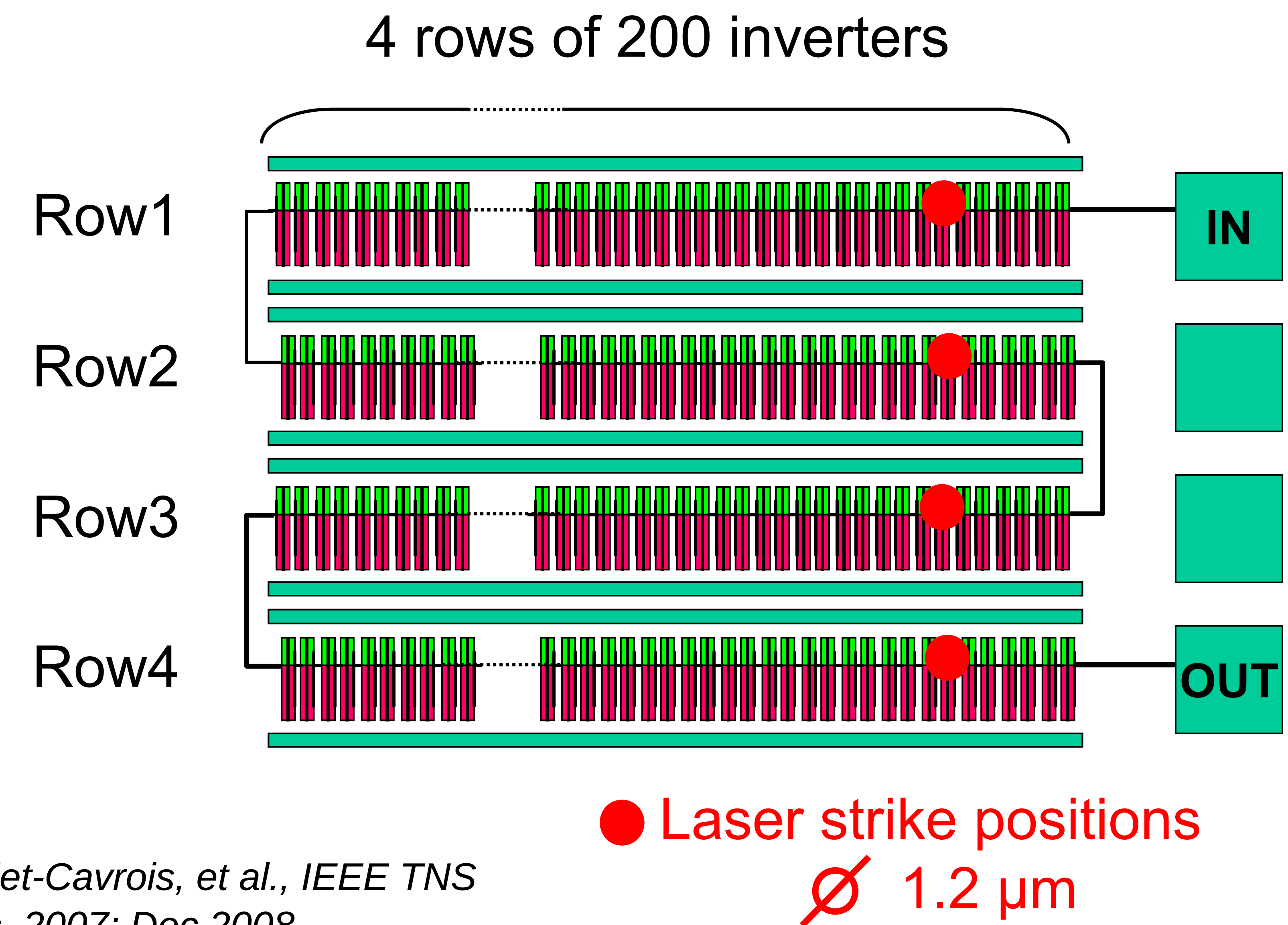
A high-bandwidth single-shot oscilloscope permits direct measurement of voltage transients

Typical runs count at least 200 transients to get enough statistics

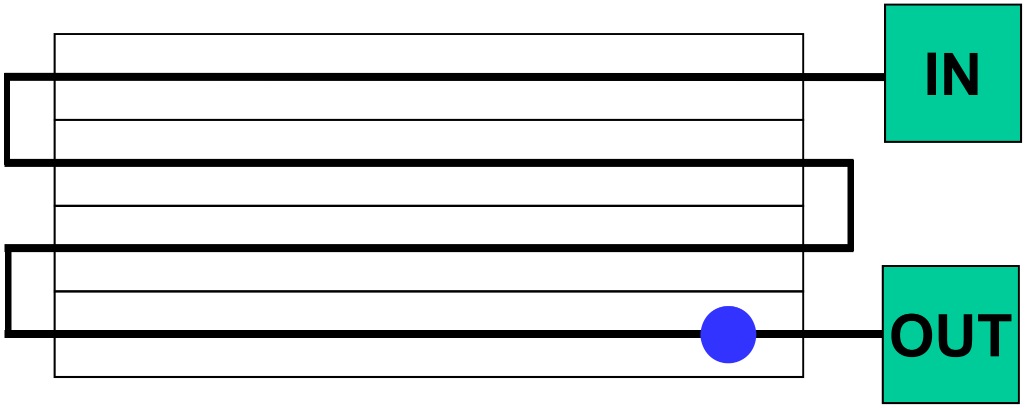
Consistent with previous HI measurements

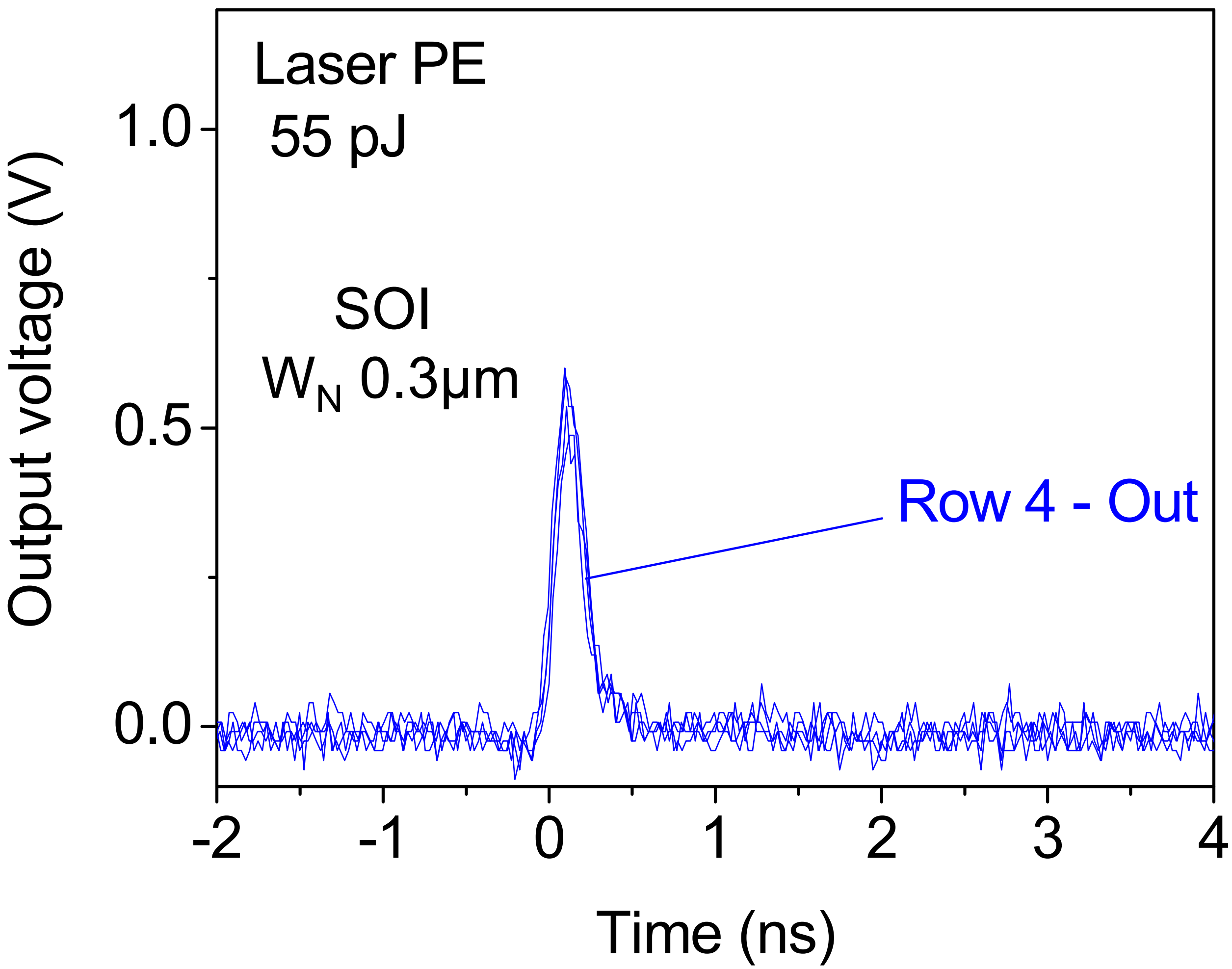
Ferlet-Cavrois, et al., IEEE TNS Dec. 2007; Dec 2008

Focused Pulsed Laser Measurements: Dependence on Strike Positioin



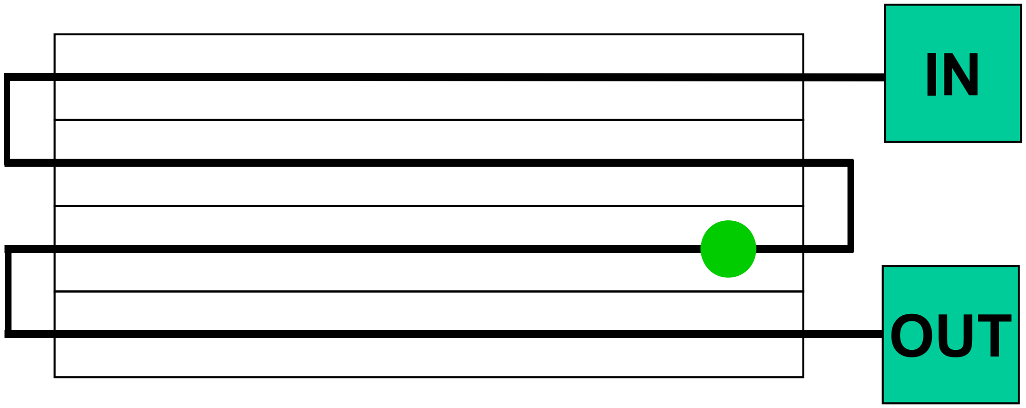
Ferlet-Cavrois, et al., IEEE TNS Dec. 2007; Dec 2008

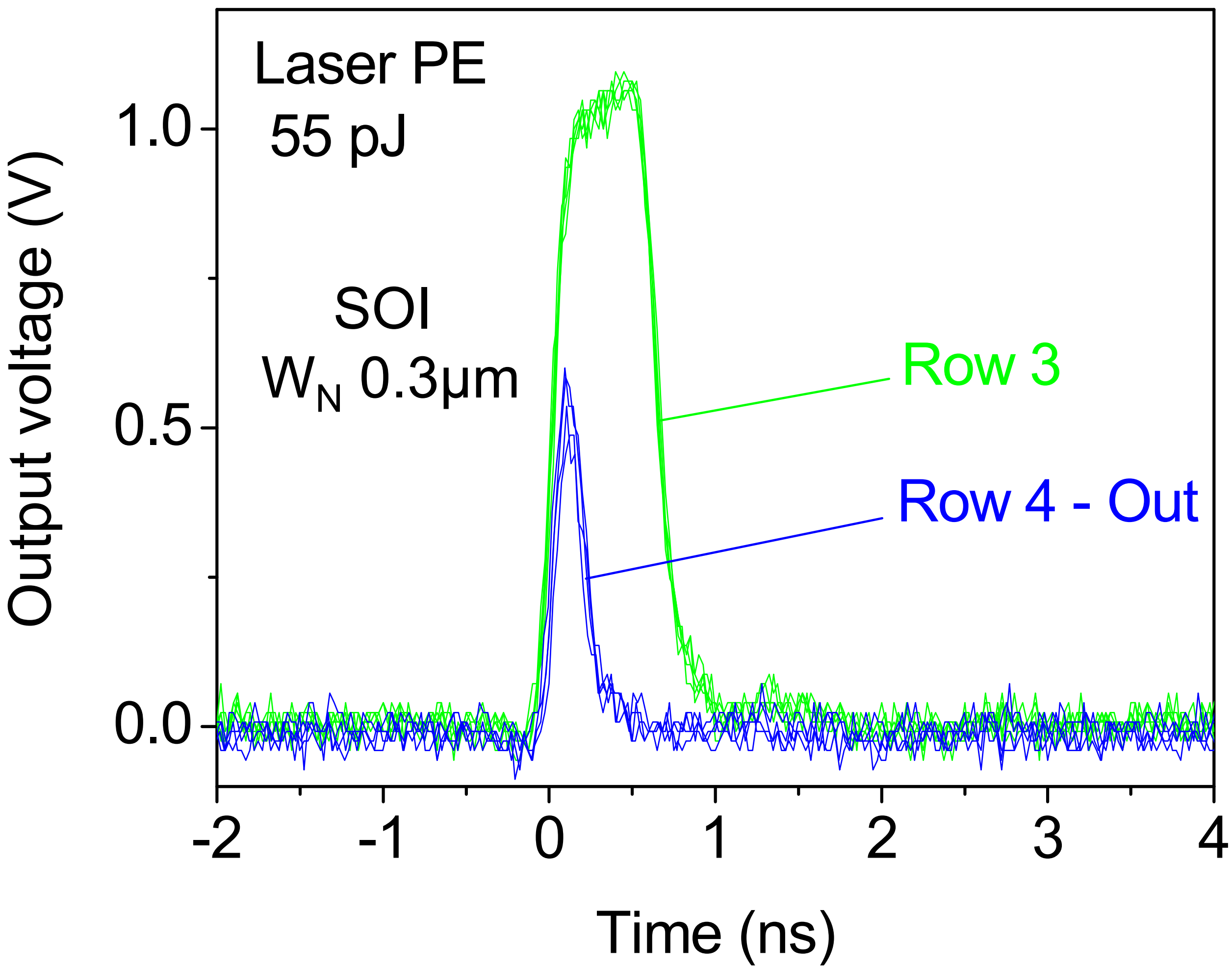




SET width is shorter than 200 ps for laser strikes close to the chain output

Ferlet-Cavrois, et al., IEEE TNS Dec. 2007; Dec 2008

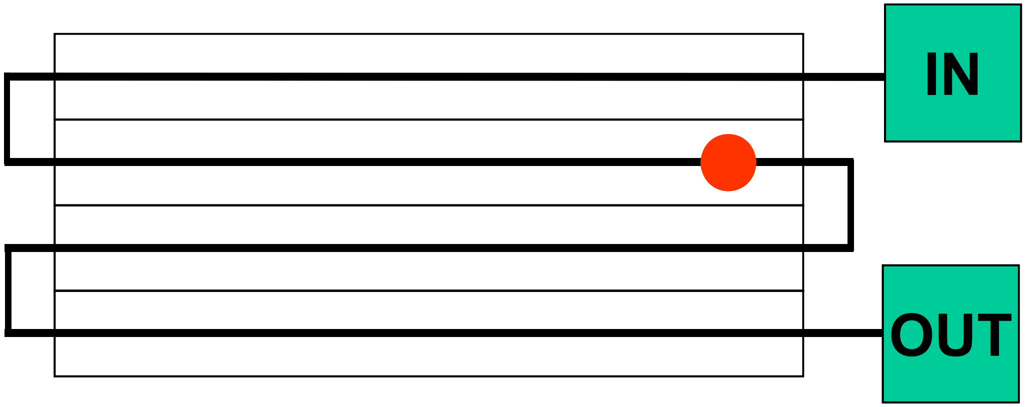


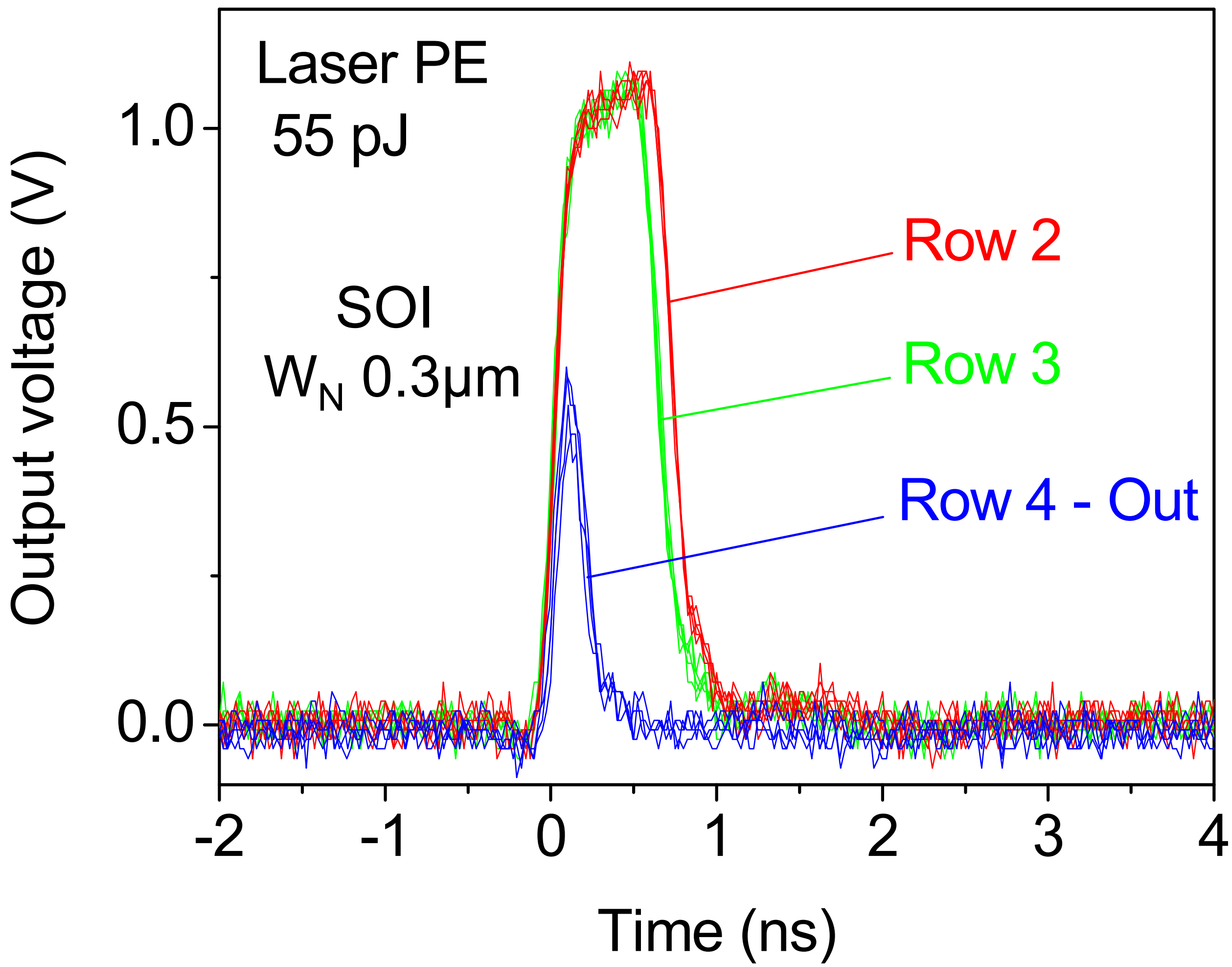


SET width is shorter than 200 ps for laser strikes close to the chain output

Transient widths increase for laser strikes far from the chain output

Ferlet-Cavrois, et al., IEEE TNS Dec. 2007; Dec 2008

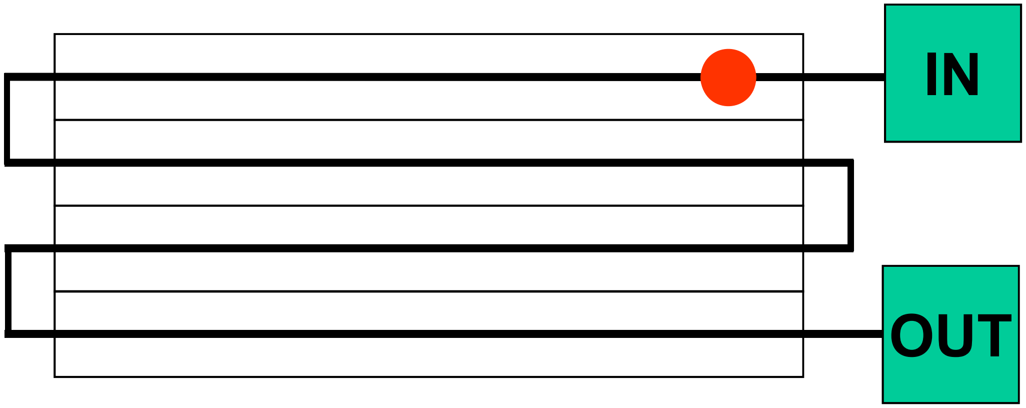


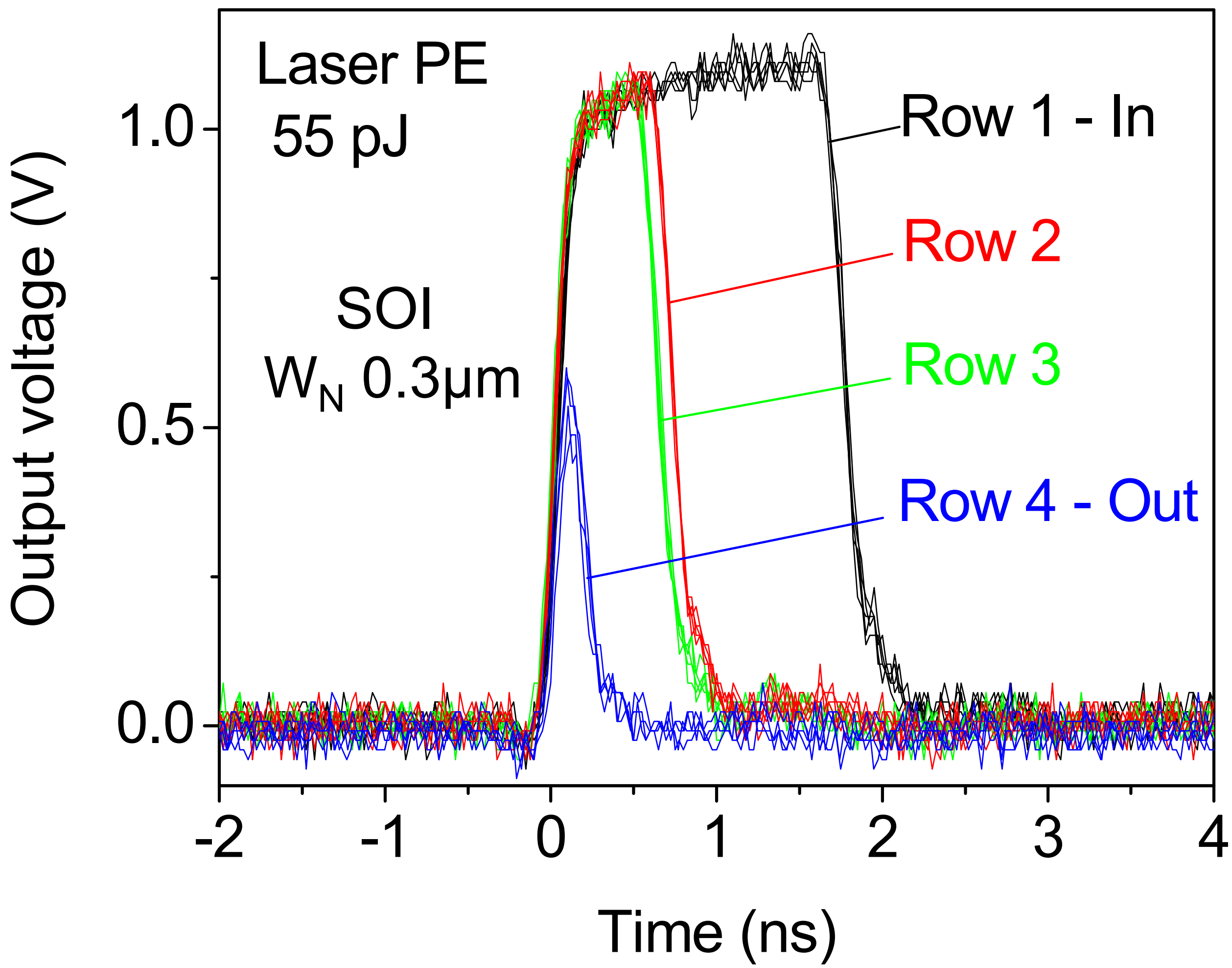


SET width is shorter than 200 ps for laser strikes close to the chain output

Transient widths increase for laser strikes far from the chain output

Ferlet-Cavrois, et al., IEEE TNS Dec. 2007; Dec 2008



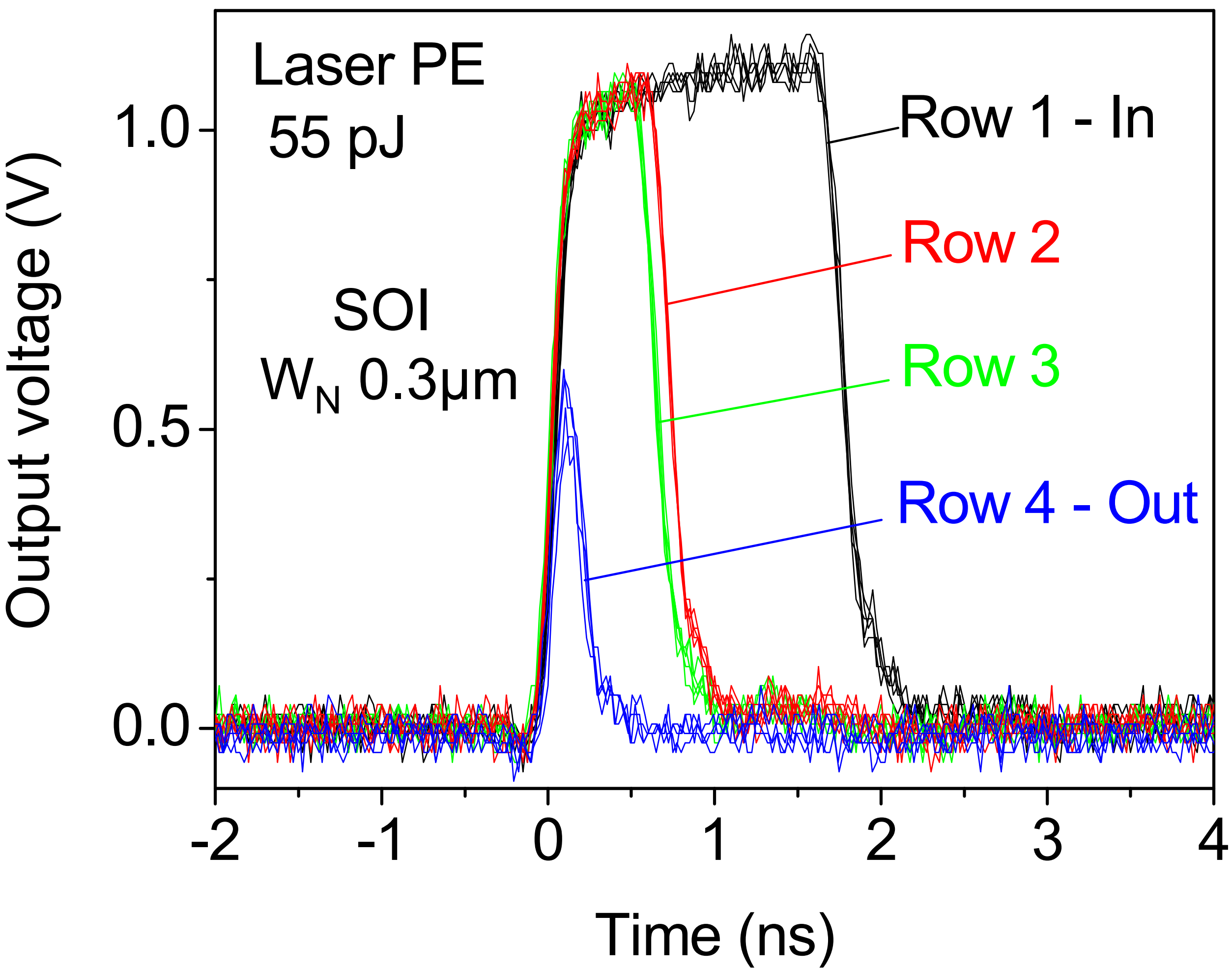


SET width is shorter than 200 ps for laser strikes close to the chain output

Transient width gets very large close to the chain input (1.8 ns)

Ferlet-Cavrois, et al., IEEE TNS Dec. 2007; Dec 2008

Propagation in SOI Inverter Chain has a Progressive Broadening Effect



Propagation-Induced Pulse Broadening

Appx. ***2 ps/inverter***

These results:

- identified the ionization-induced propagation-induced pulse broadening phenomena
- helped explain and understand earlier measurements

Ferlet-Cavrois, et al., IEEE TNS Dec. 2007; Dec 2008

SET Propagation: Summary and Conclusions

- Implications:
  - Test methodologies
  - Interpretation and significance of existing data
  - SET mitigation approaches

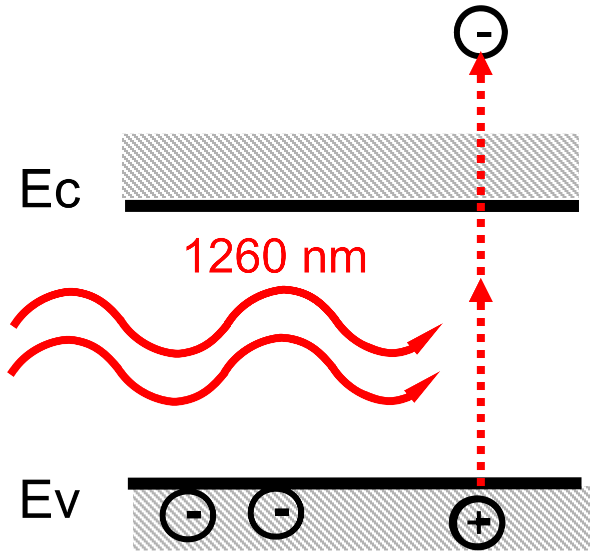
Ferlet-Cavrois, et al., IEEE TNS Dec. 2007; Dec 2008

CASE STUDY 7

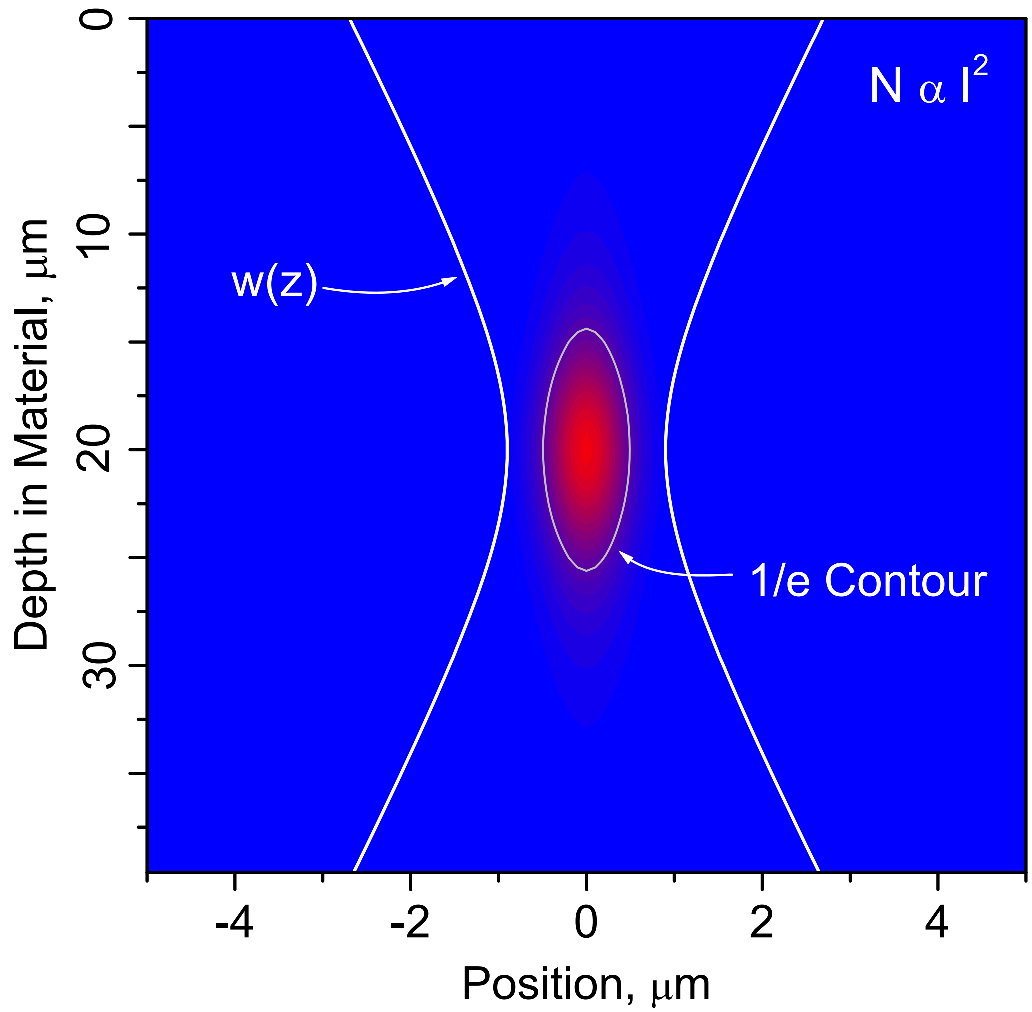
Two-Photon-Induced Single-Event Effects:

3-D Mapping of SET

Femtosecond Sub-Bandgap Laser SEE

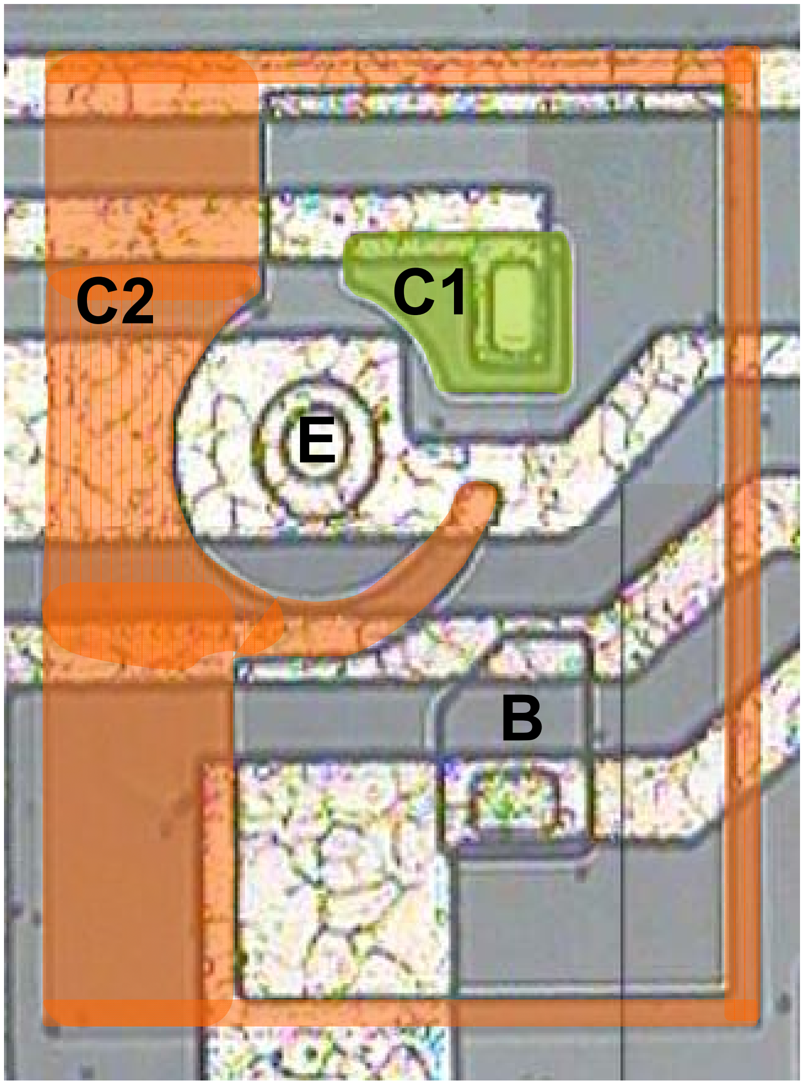


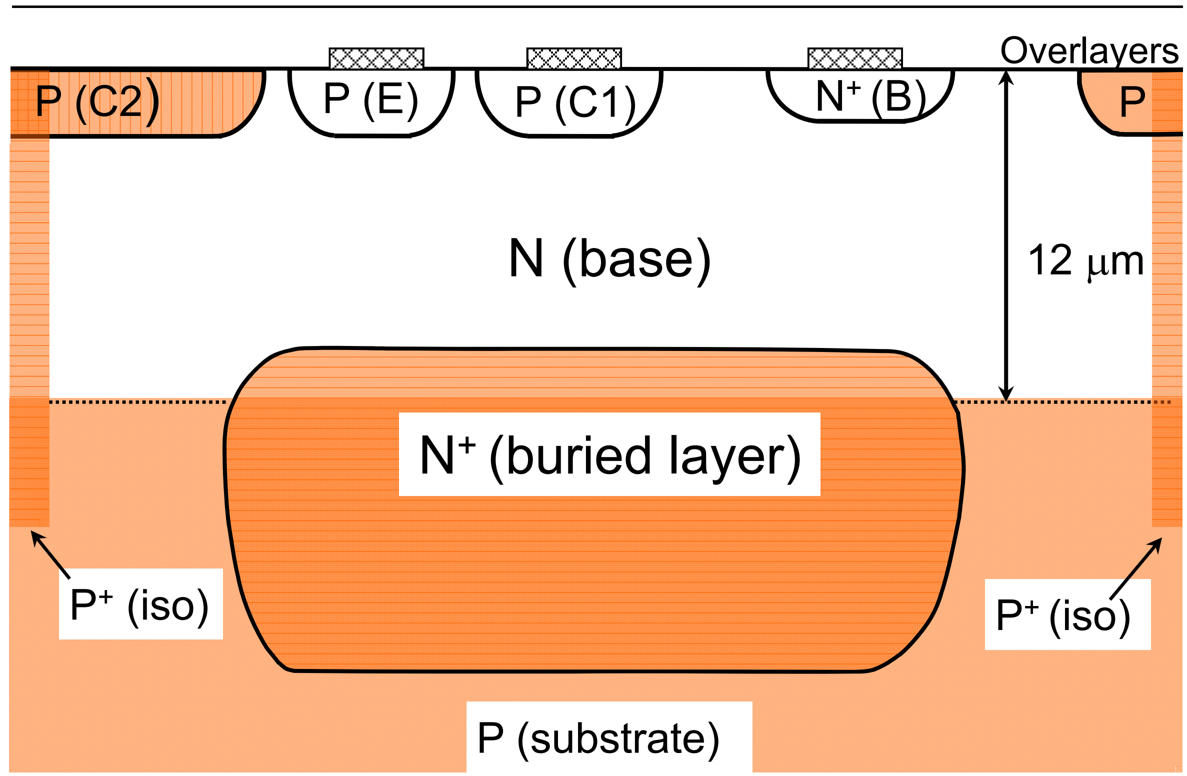
- *Two photons absorbed*
- *By the material (silicon)*
- *Simultaneously*
- *Creates a single e-h pair*



Three-Dimensional Mapping of SEE Sensitivity

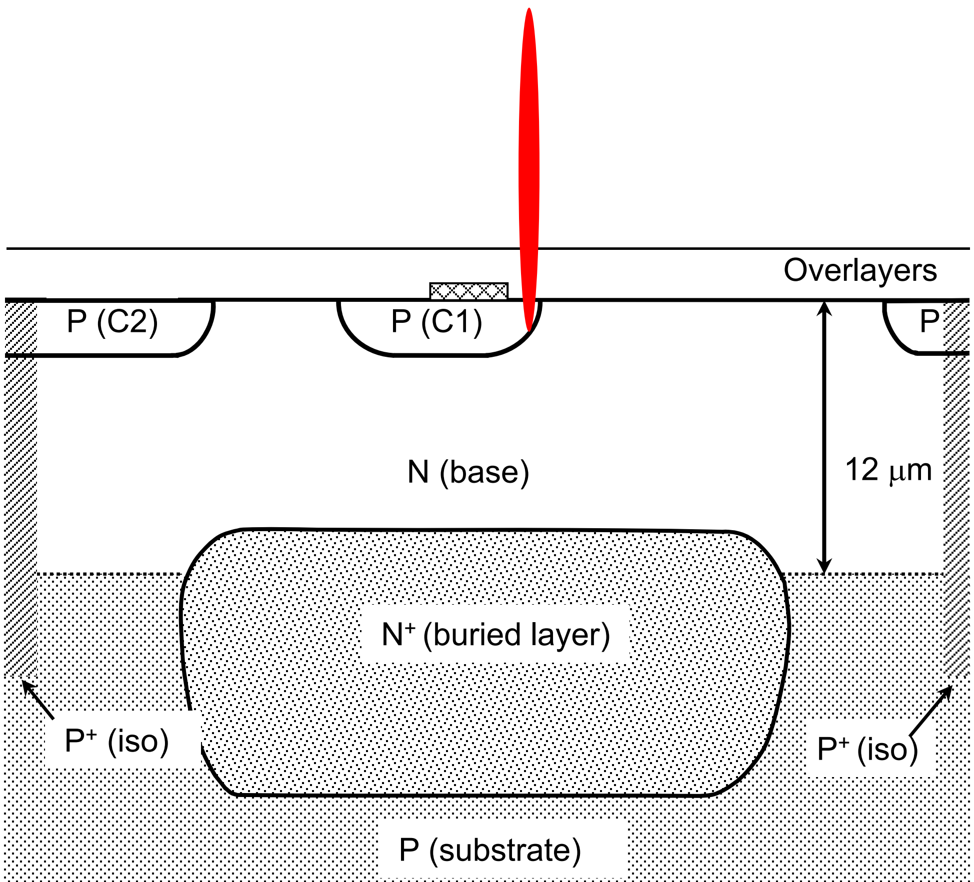
(LM124 Q20: General Characteristics)

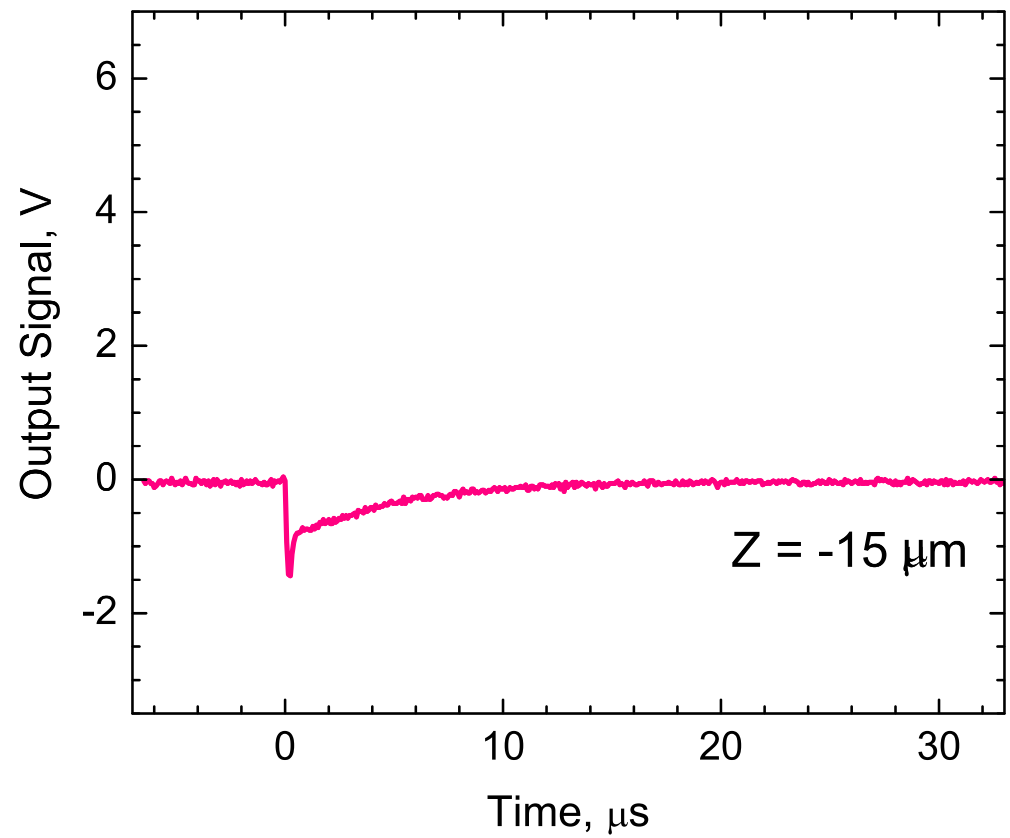




"Z" Dependence: LM124 Q20 TPA: C1-epi Junction

(Inverting Configuration; gain of 20)

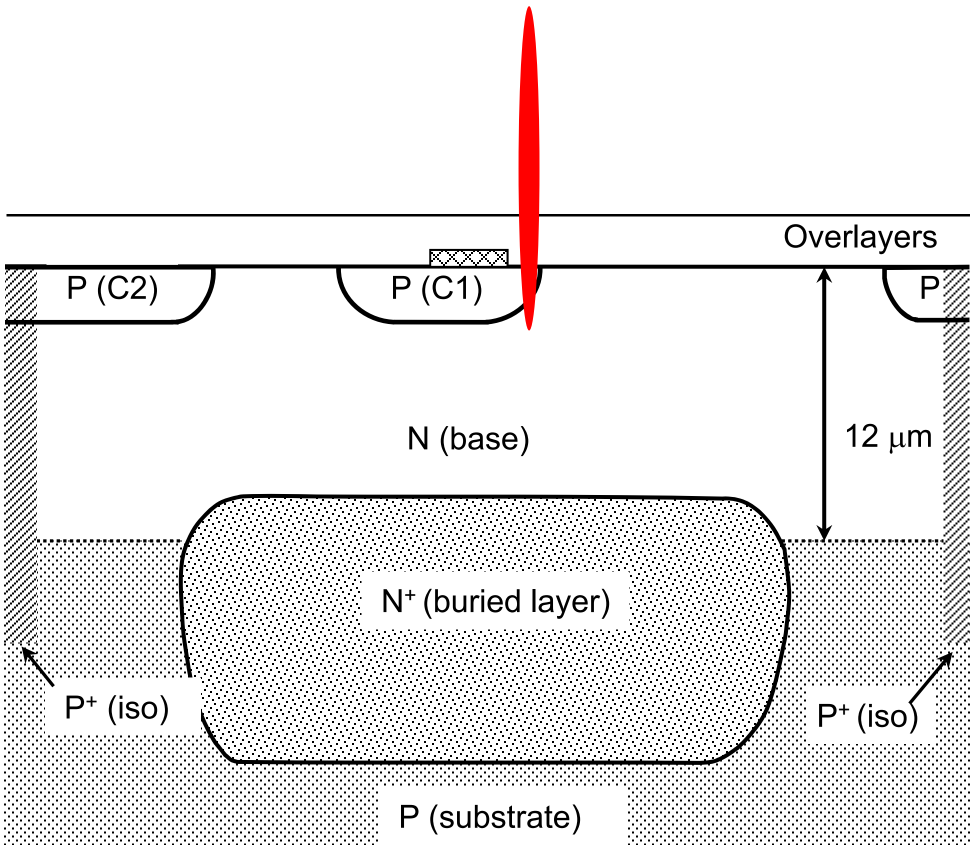


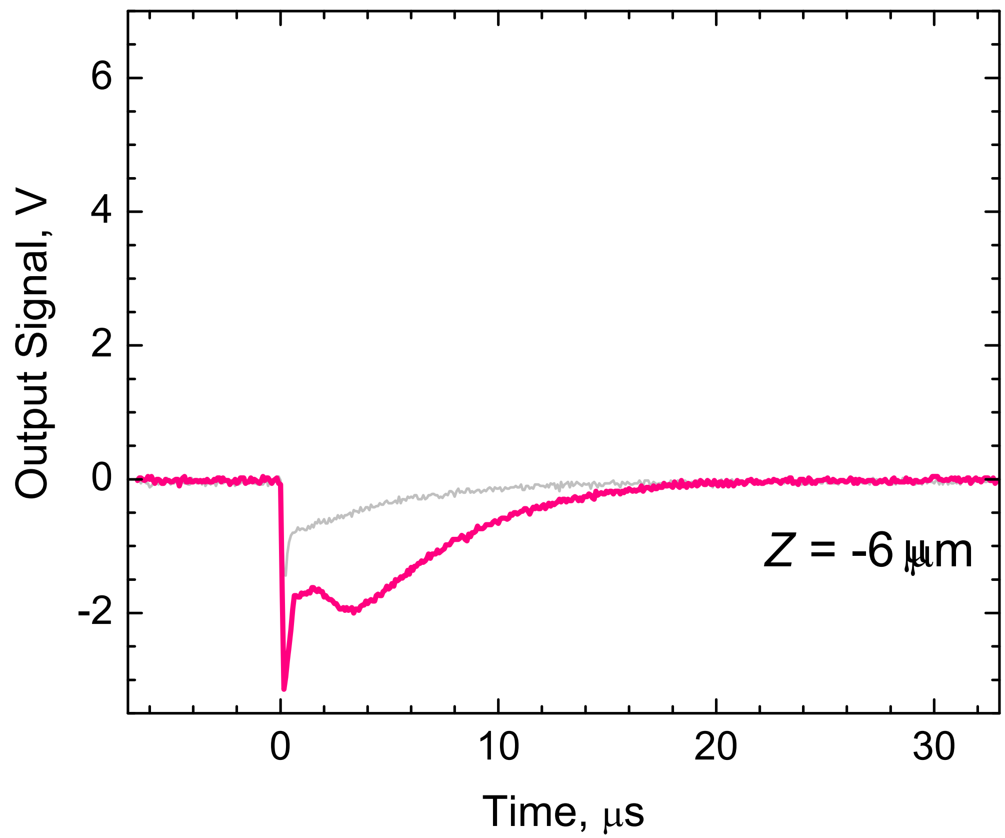


McMorrow, et al., IEEE TNS, __50__, 2199 (2003).

"Z" Dependence: LM124 Q20 TPA: C1-epi Junction

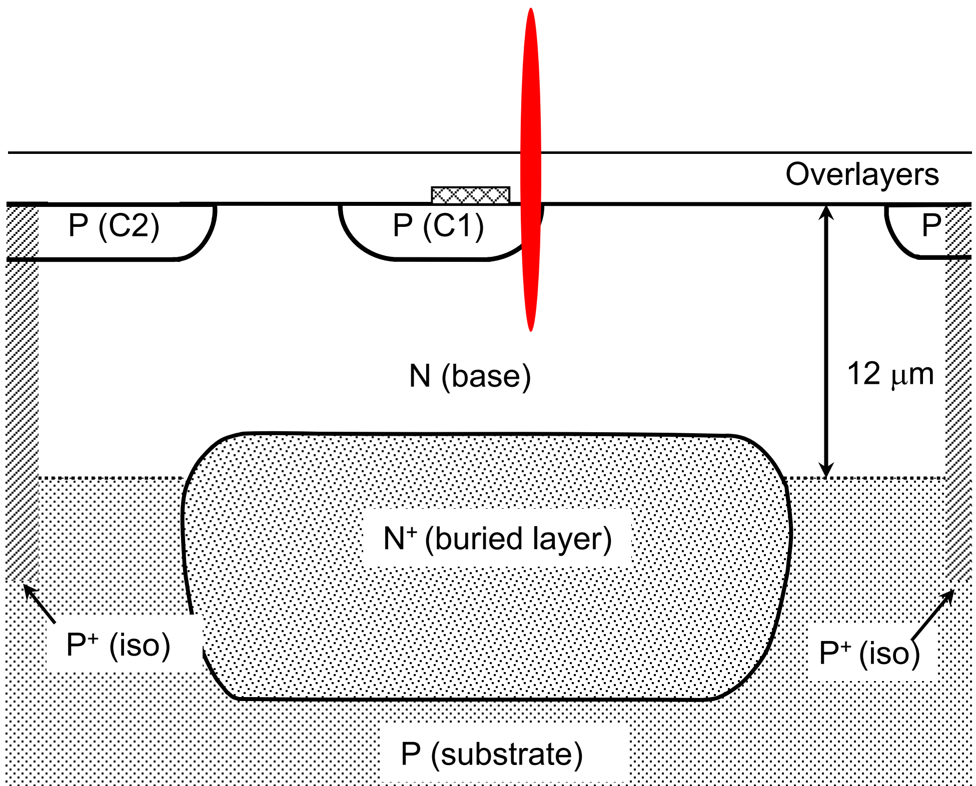
(Inverting Configuration; gain of 20)

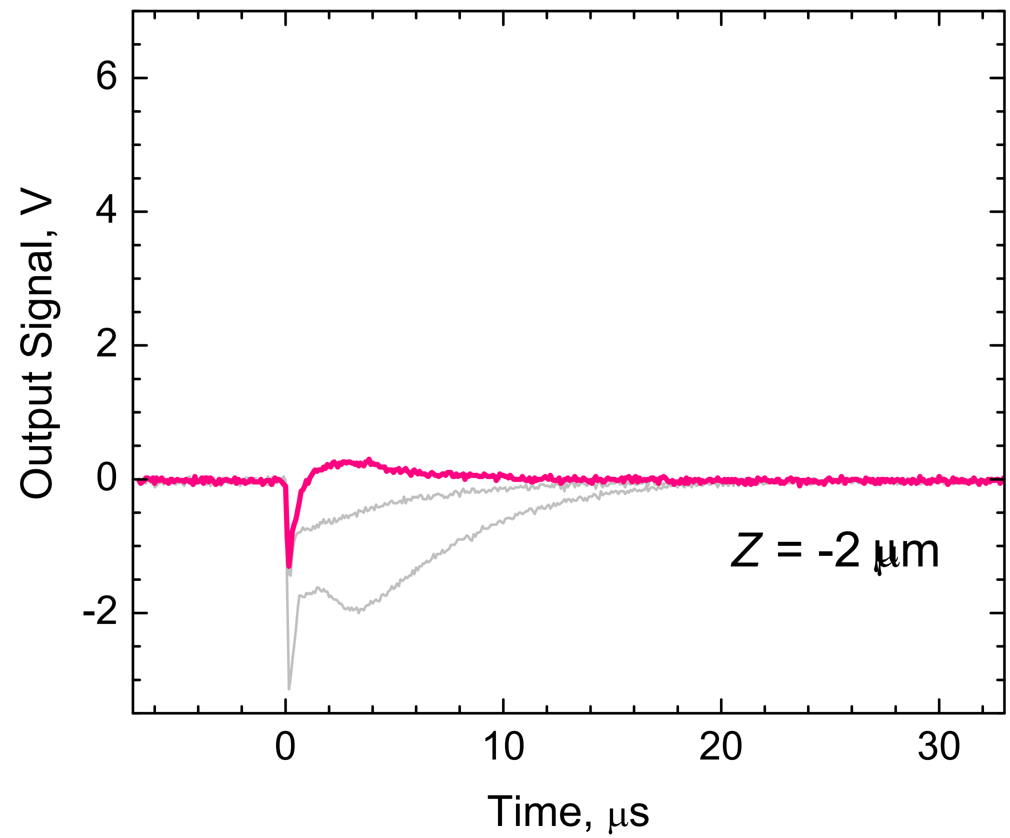




*McMorrow, et al., IEEE TNS, **50**, 2199 (2003).*

"Z" Dependence: LM124 Q20 TPA: C1-epi Junction
(Inverting Configuration; gain of 20)

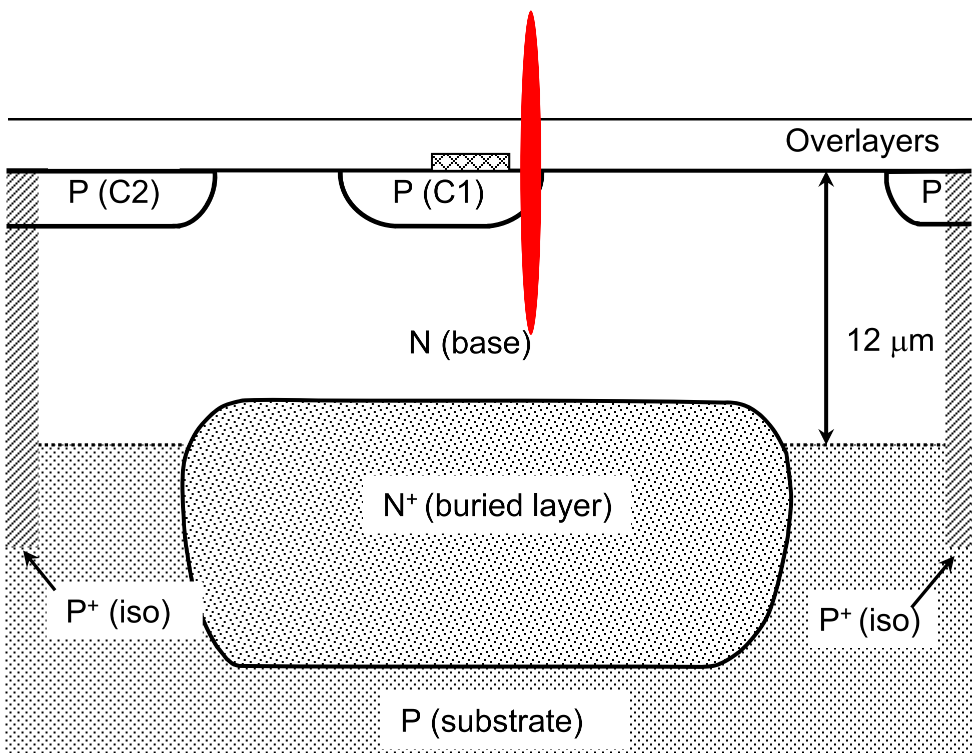


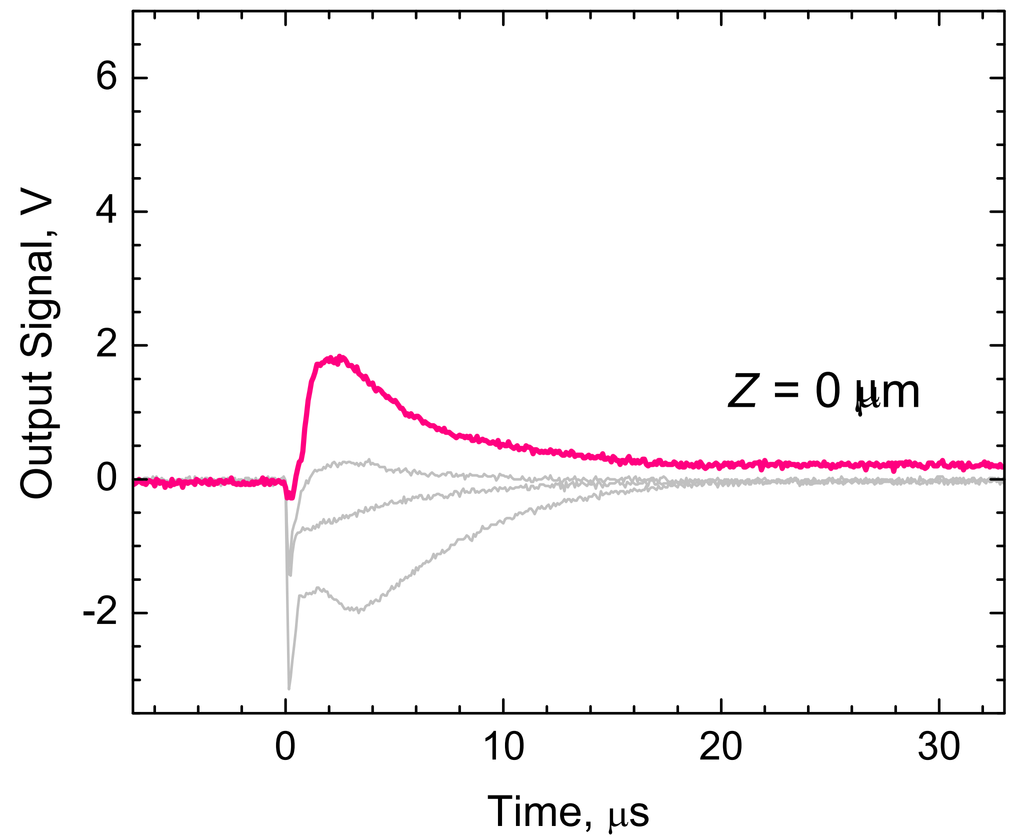


*McMorrow, et al., IEEE TNS, **50**, 2199 (2003).*

"Z" Dependence: LM124 Q20 TPA: C1-epi Junction

(Inverting Configuration; gain of 20)





*McMorrow, et al., IEEE TNS, **50**, 2199 (2003).*

"Z" Dependence: LM124 Q20 TPA: C1-epi Junction

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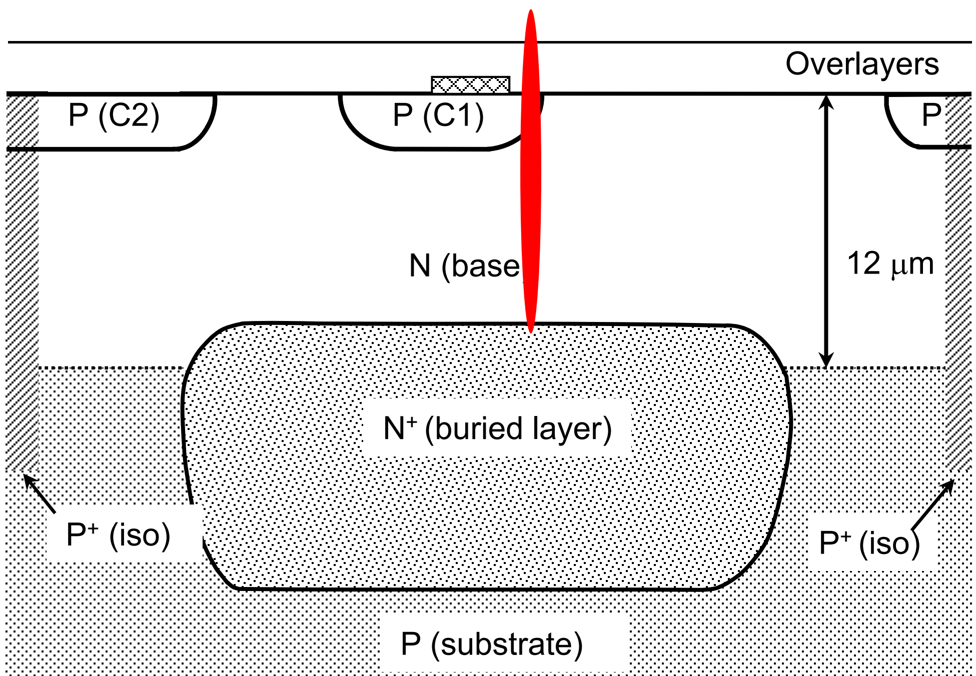

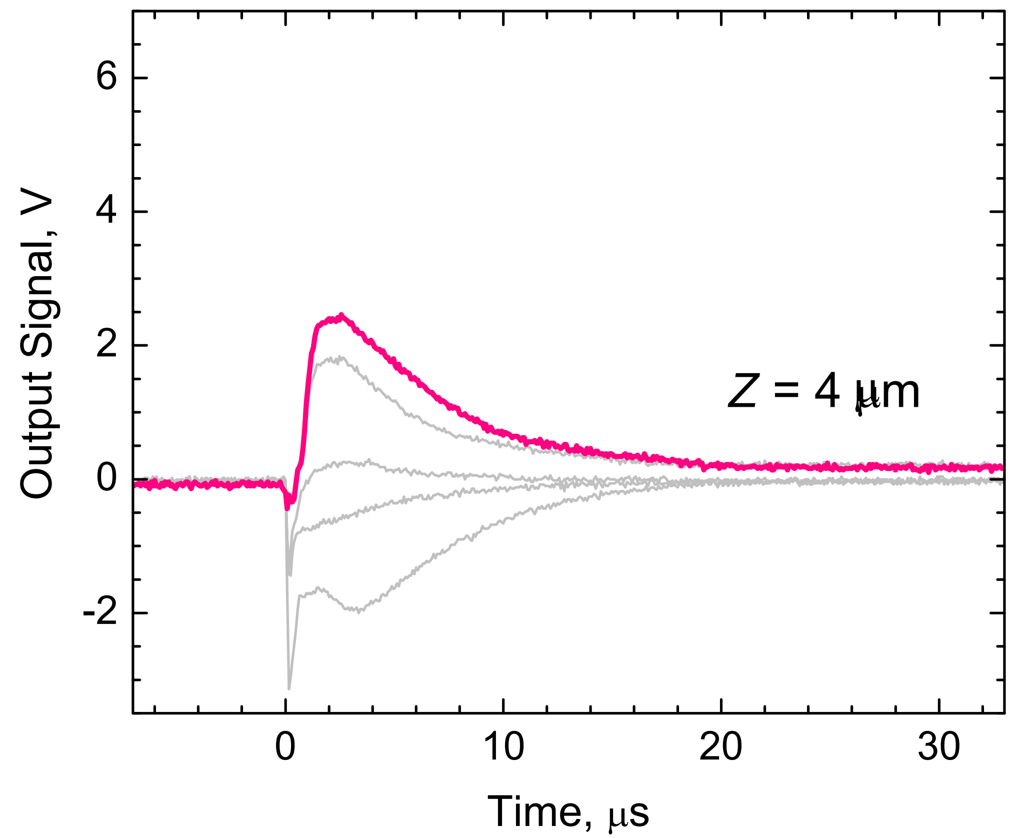

*McMorrow, et al., IEEE TNS, __**50**__, 2199 (2003).*

"Z" Dependence: LM124 Q20 TPA: C1-epi Junction

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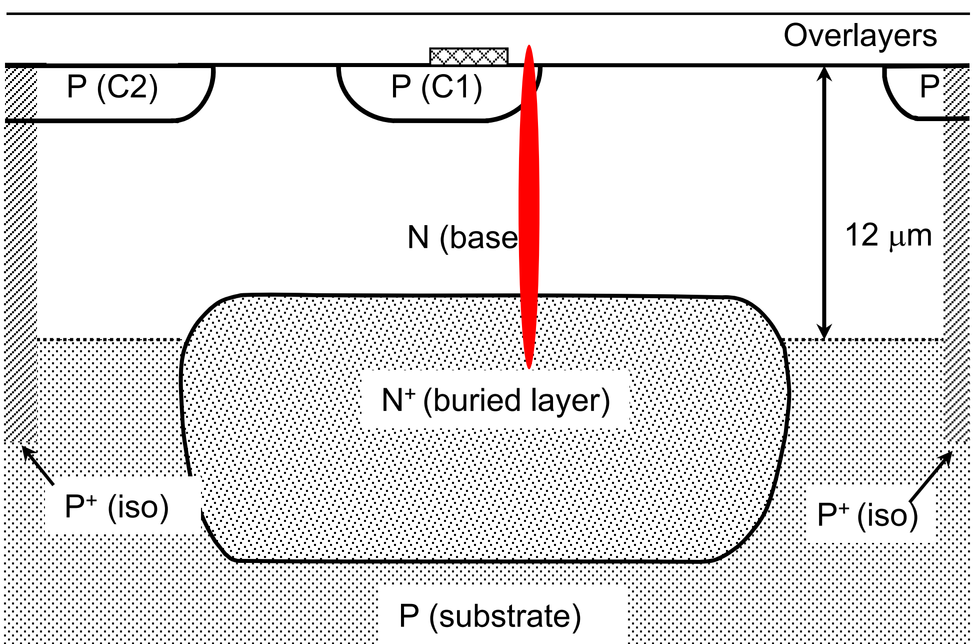
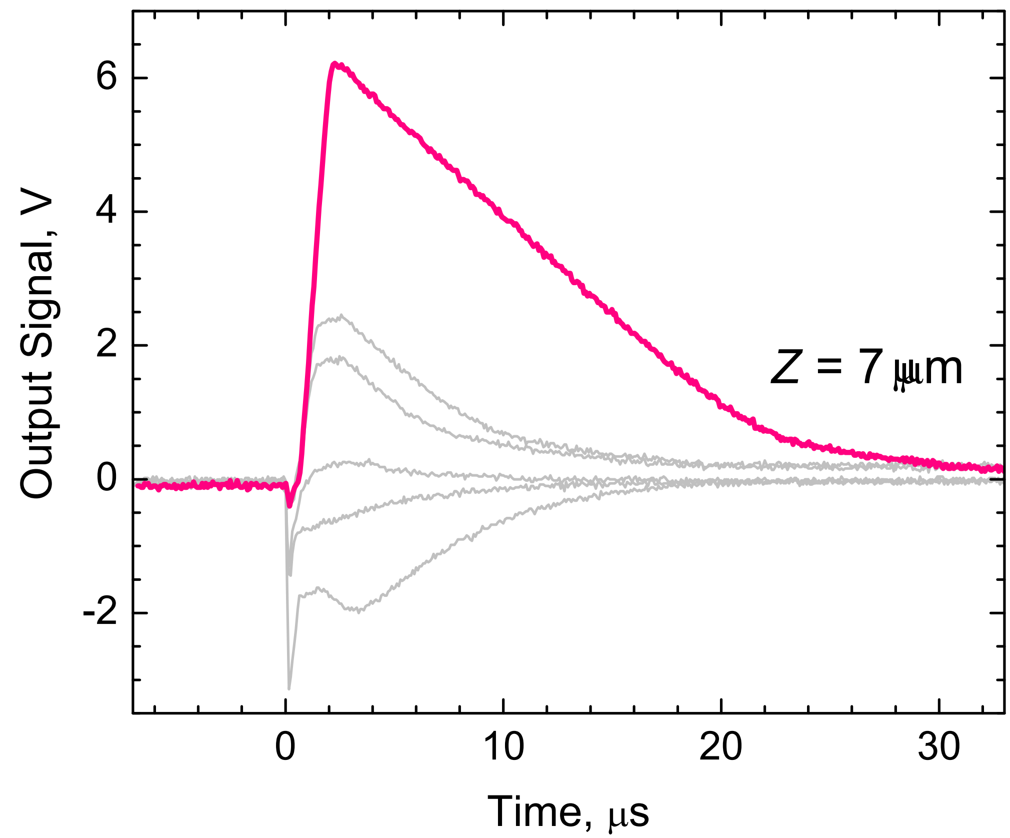
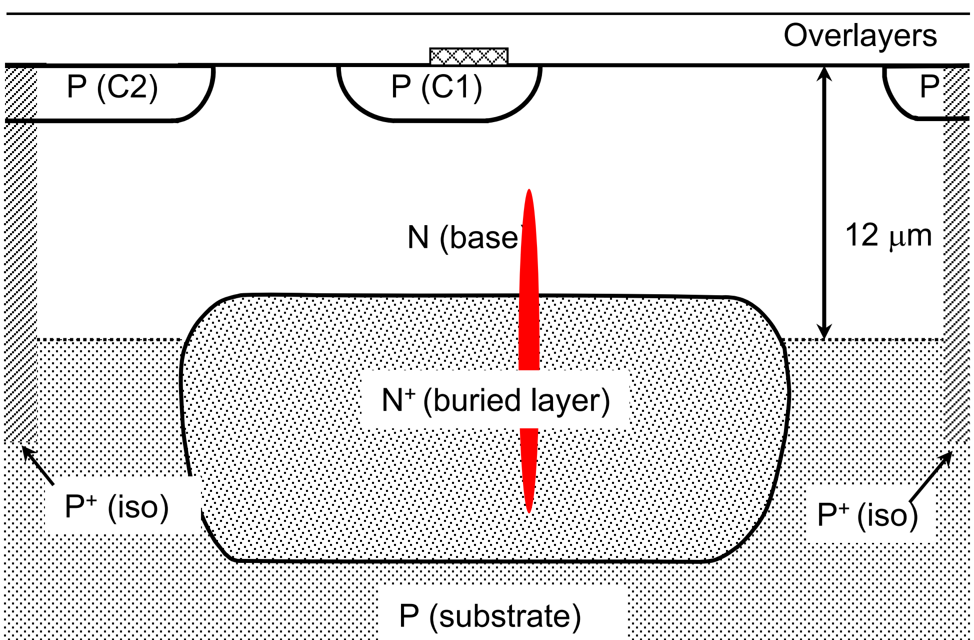


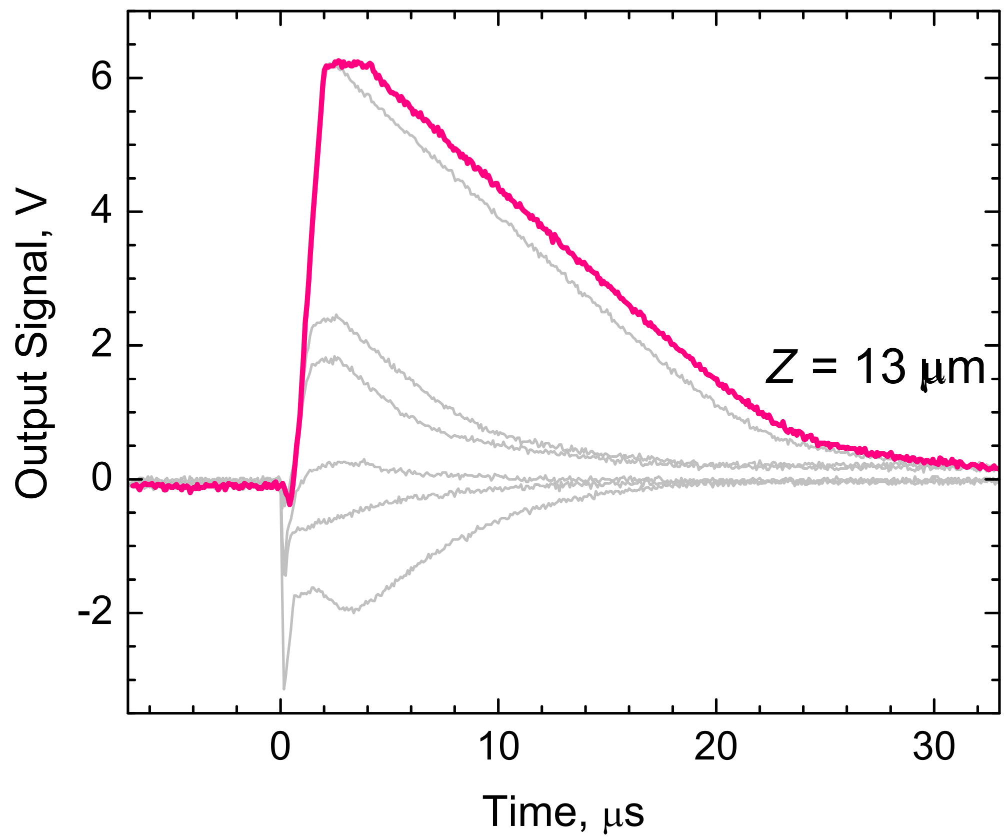


*McMorrow, et al., IEEE TNS, **50**, 2199 (2003).*

"Z" Dependence: LM124 Q20 TPA: C1-epi Junction

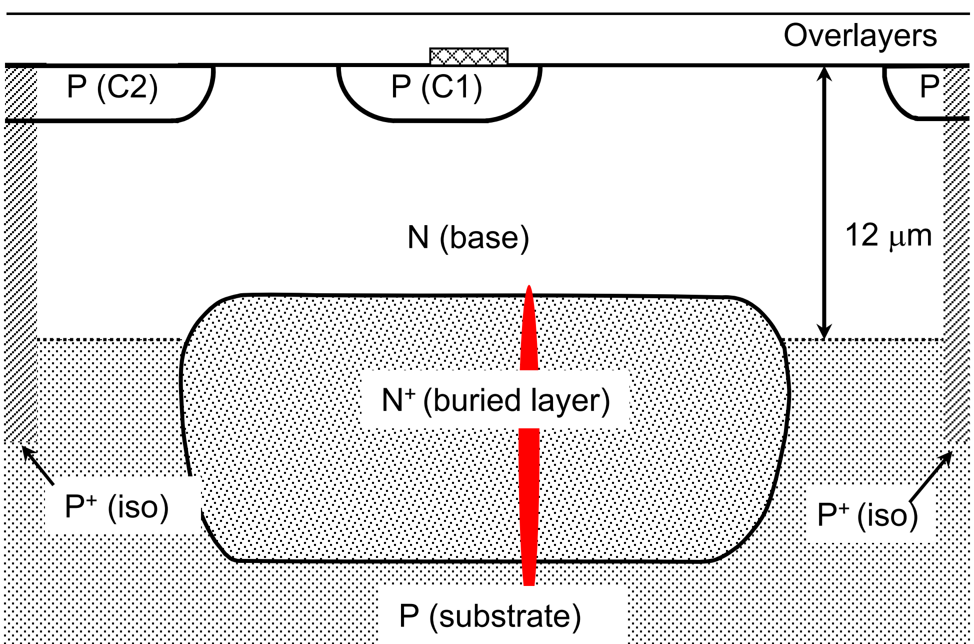
(Inverting Configuration; gain of 20)

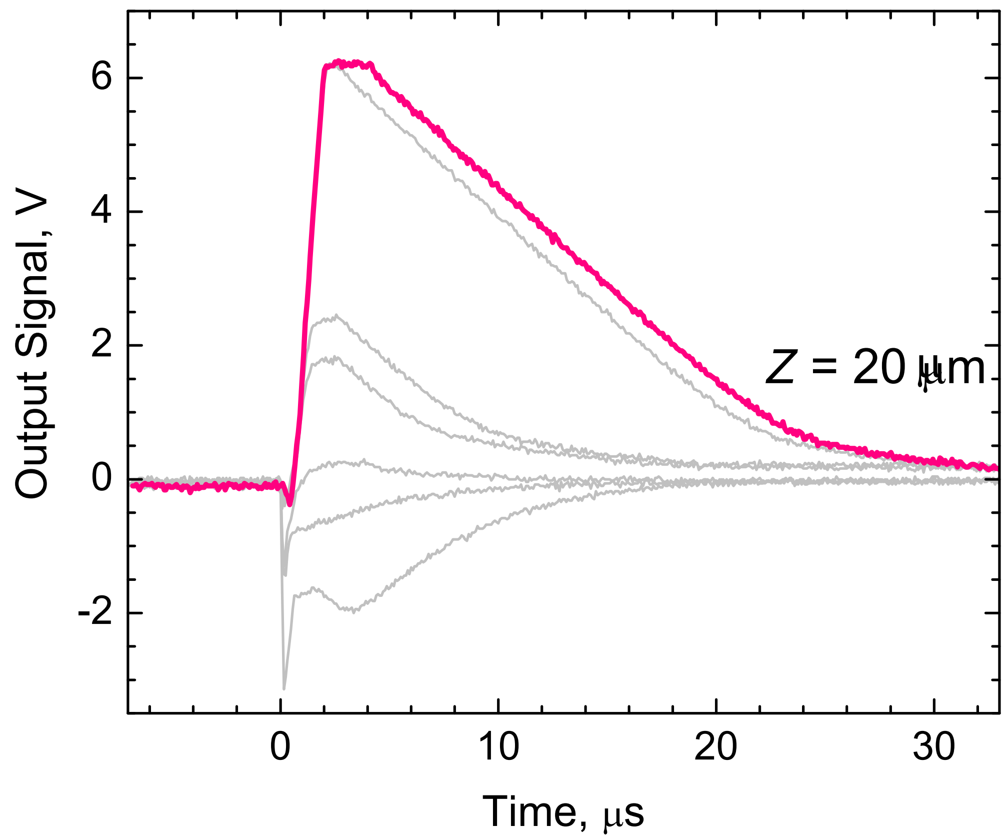




McMorrow, et al., IEEE TNS, ***50****, 2199 (2003).*

"Z" Dependence: LM124 Q20 TPA: C1-epi Junction
(Inverting Configuration; gain of 20)





McMorrow, et al., IEEE TNS, __50__, 2199 (2003).

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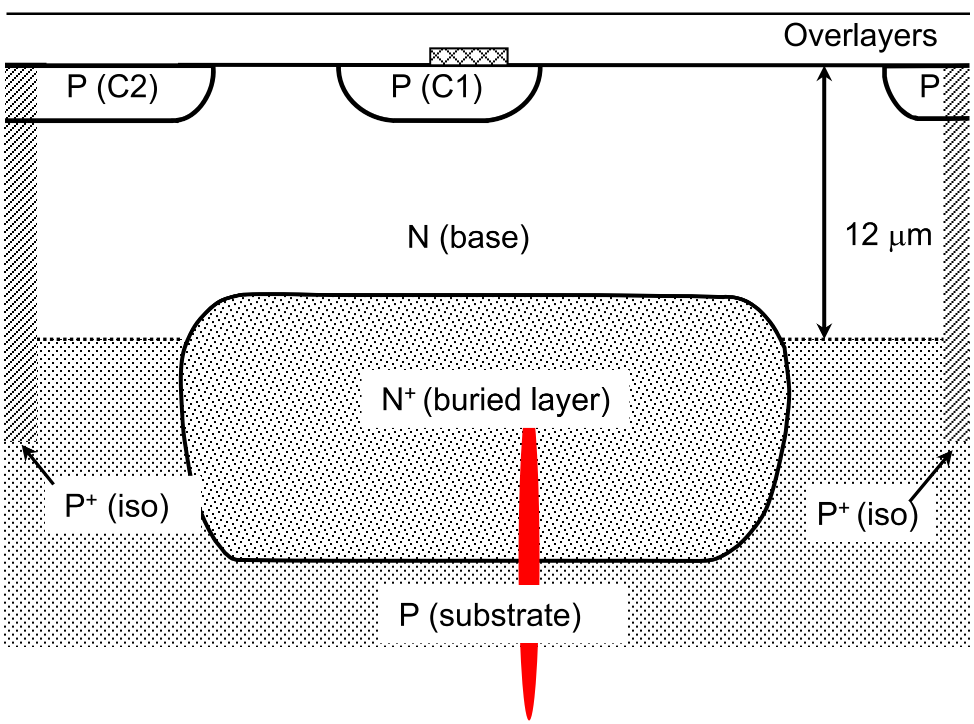
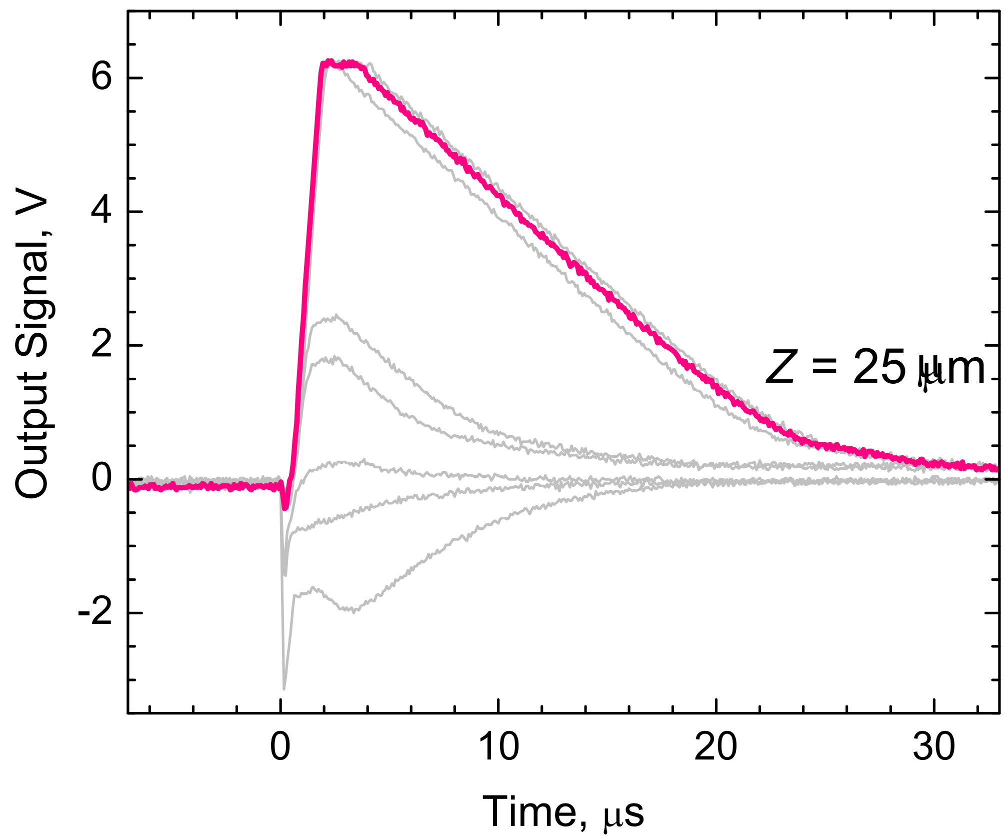
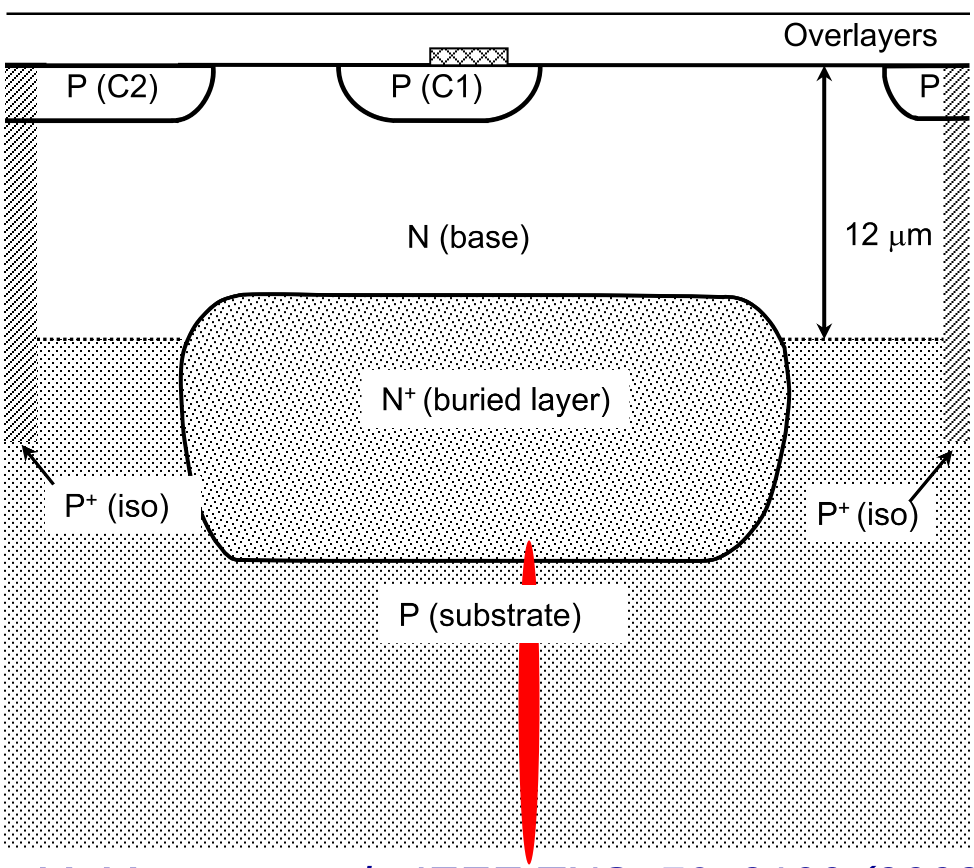
(Inverting Configuration; gain of 20)

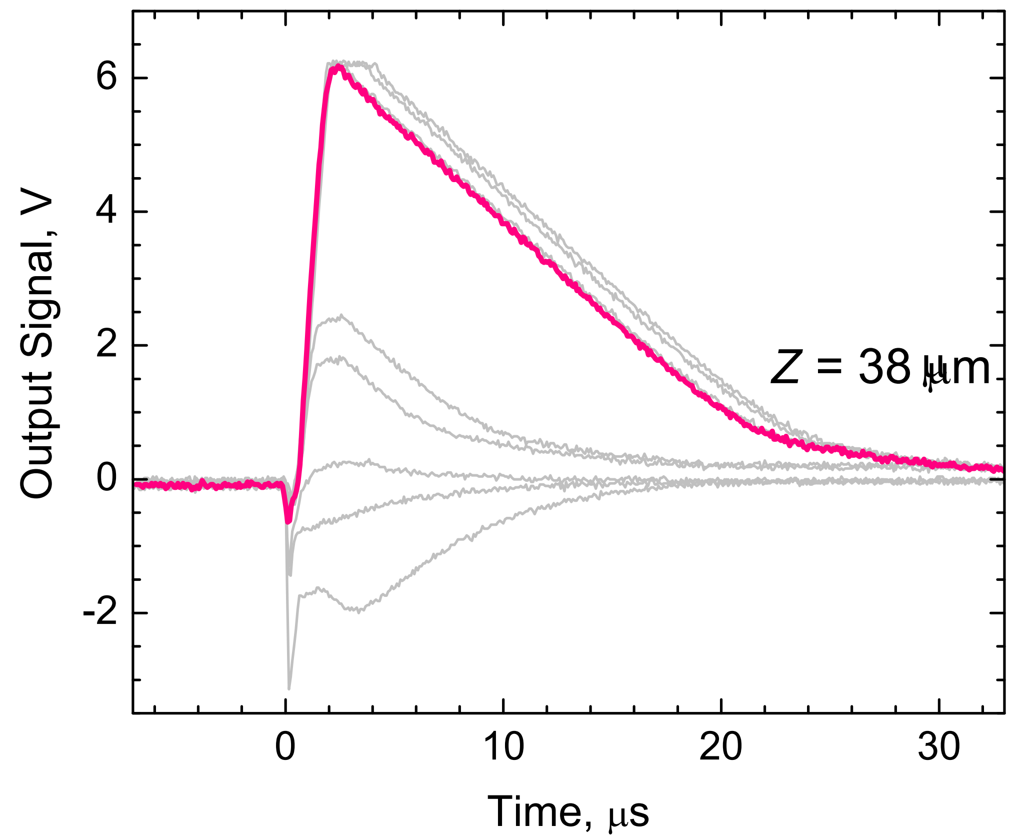




*McMorrow, et al., IEEE TNS, __**50**__, 2199 (2003).*

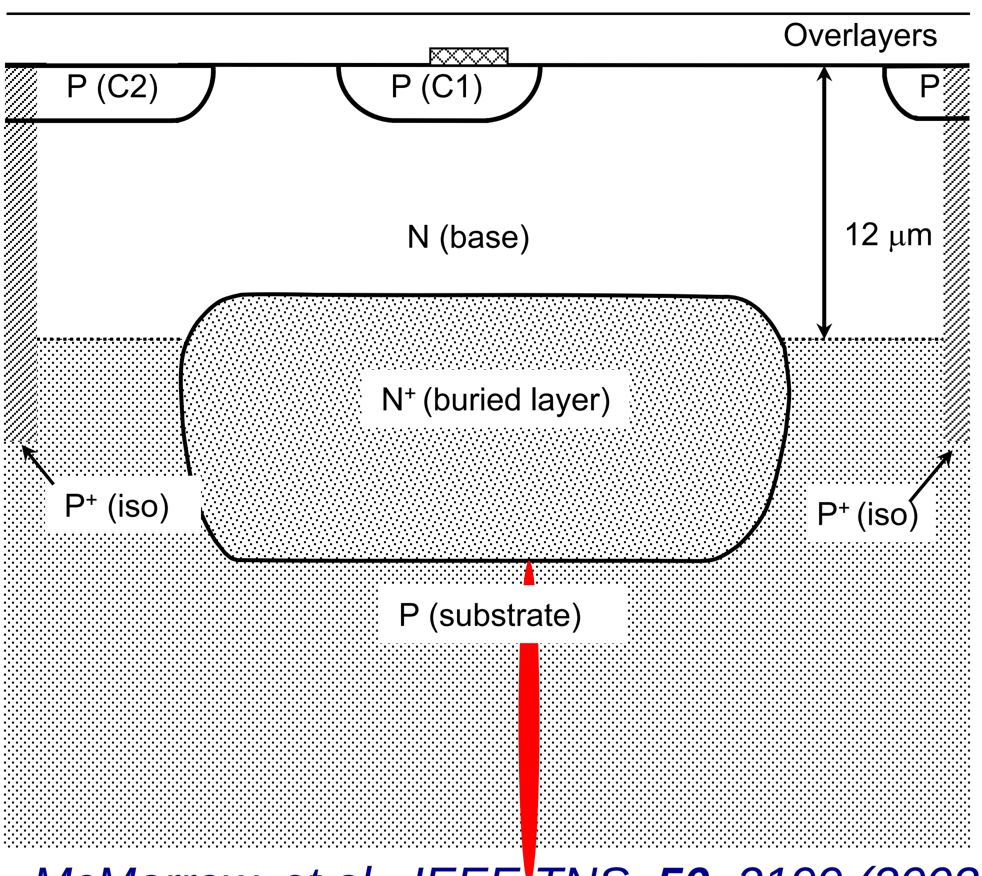
"Z" Dependence: LM124 Q20 TPA: C1-epi Junction
(Inverting Configuration; gain of 20)

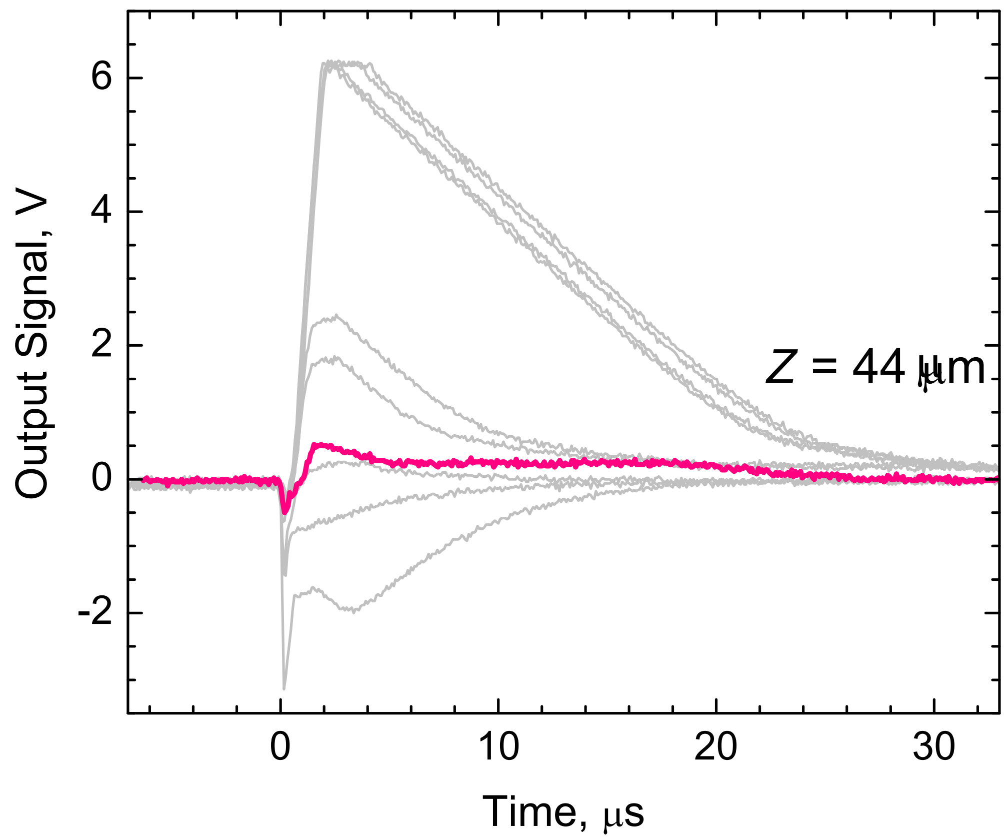




*McMorrow, et al., IEEE TNS, **50**, 2199 (2003).*

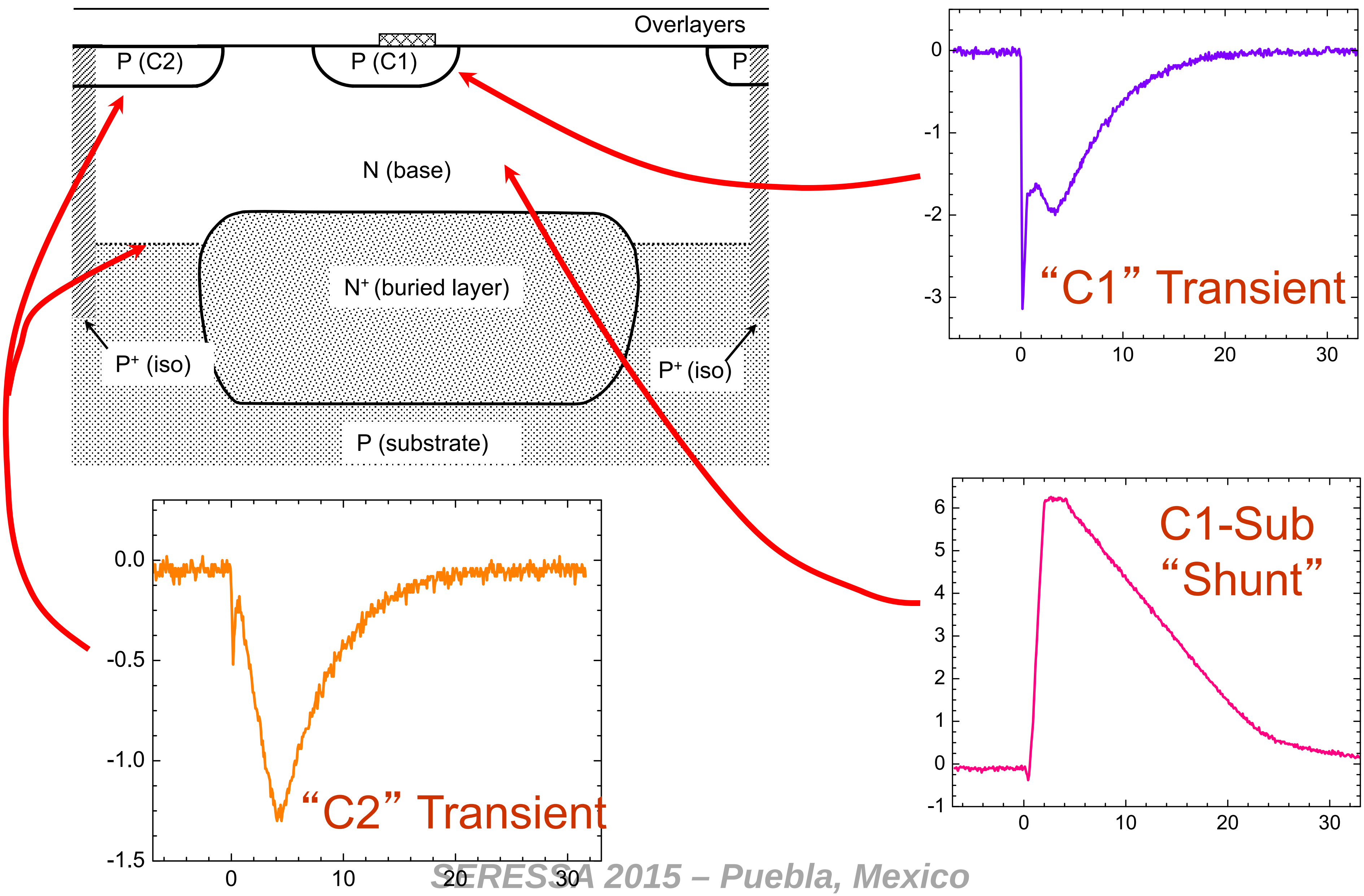
"Z" Dependence: LM124 Q20 TPA: C1-epi Junction
(Inverting Configuration; gain of 20)





*McMorrow, et al., IEEE TNS, __**50**__, 2199 (2003).*

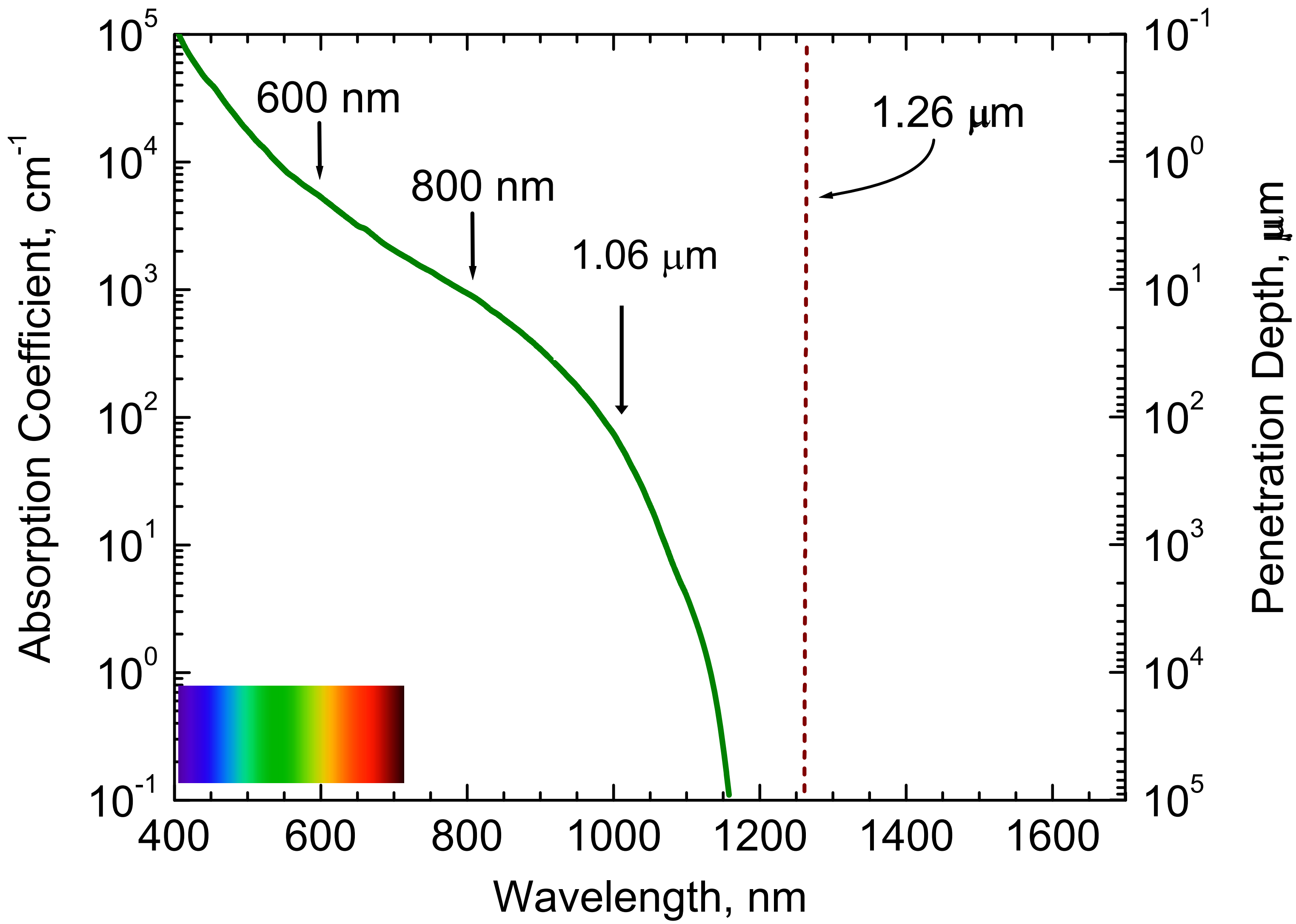
LM124 Q20 TPA SET: "Z" Dependence



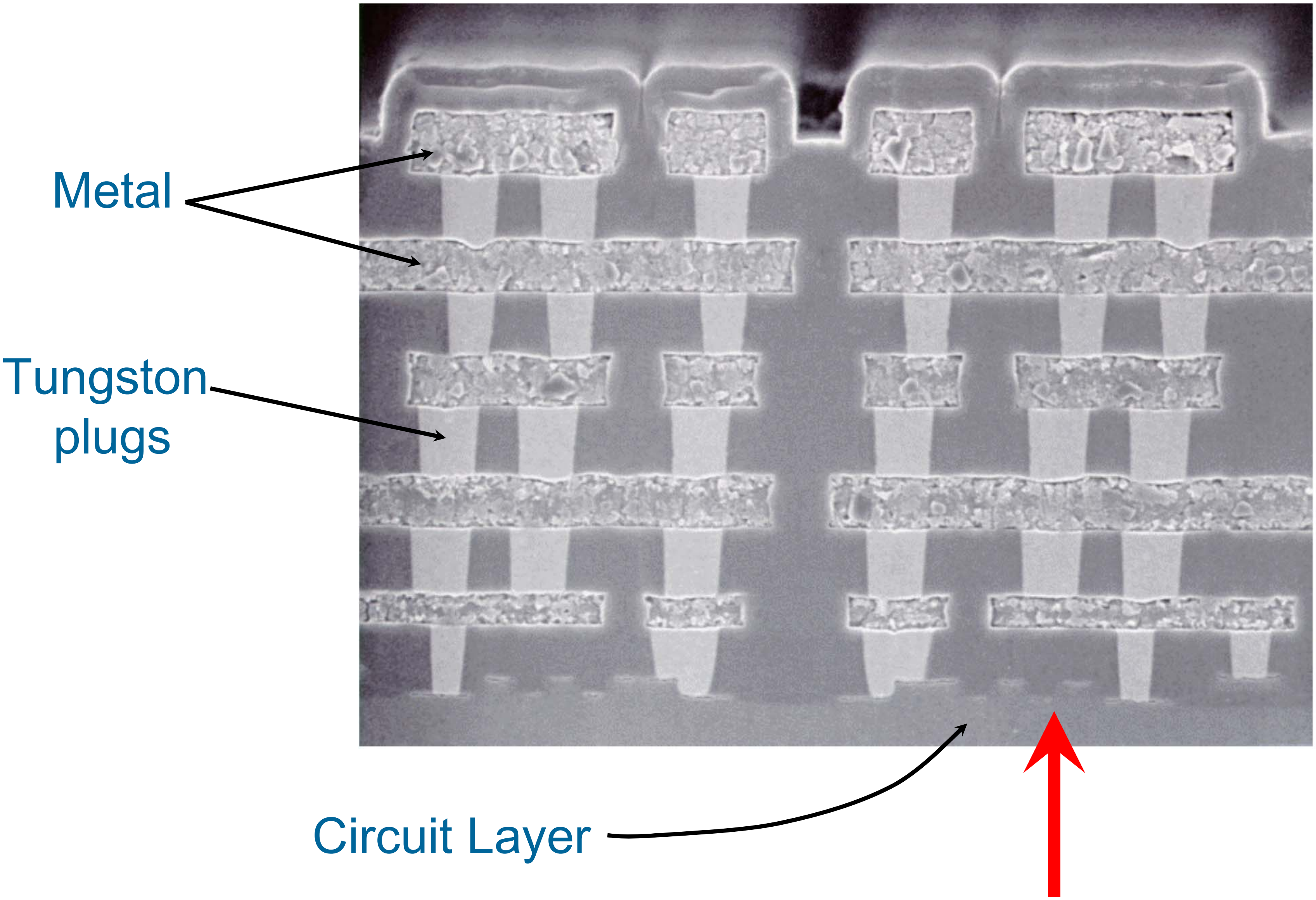
CASE STUDY 8

Backside, Through-Wafer, Two-Photon-Induced Single-Event Effects

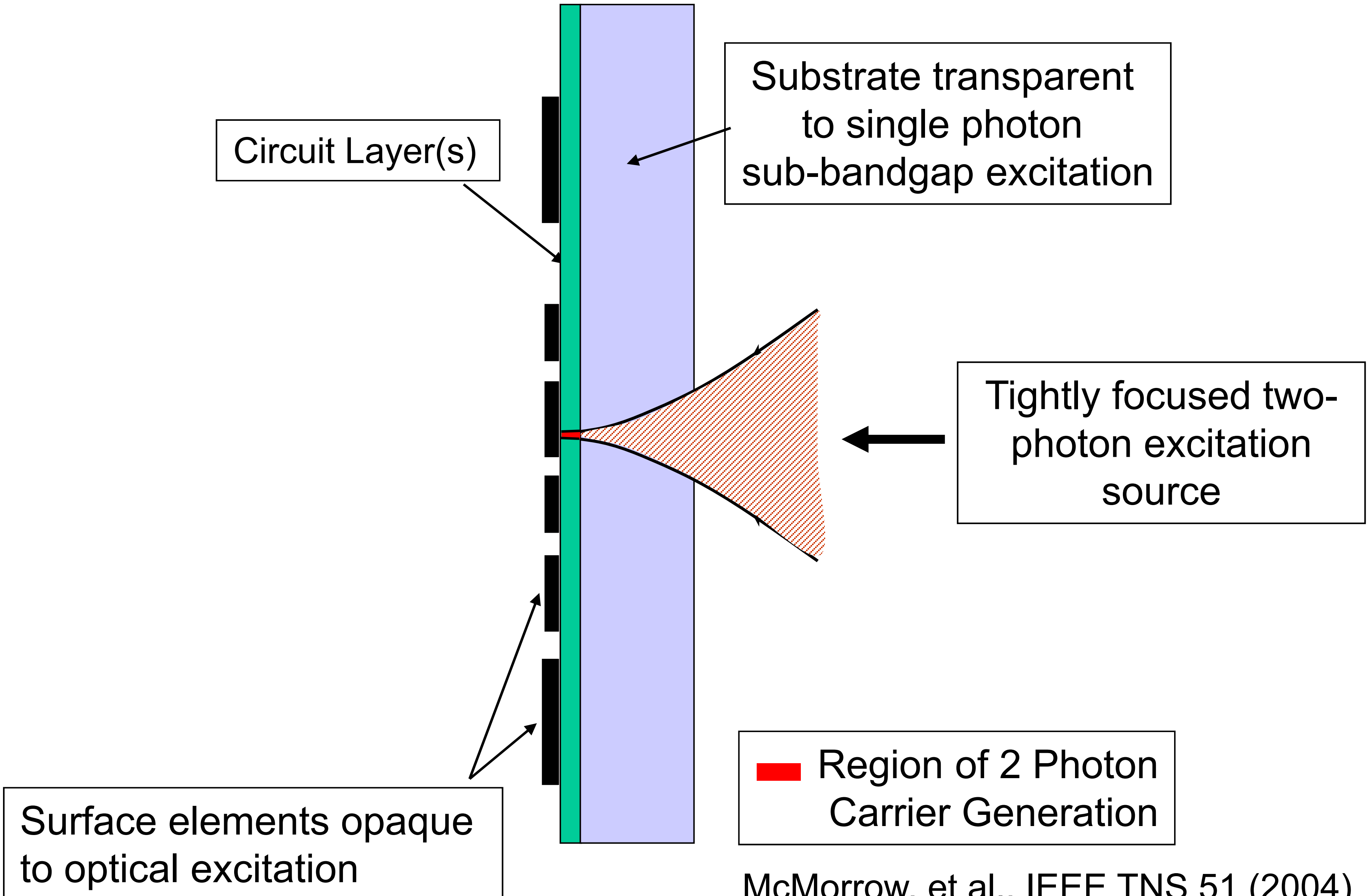
Backside "Through-Wafer" TPA Illumination



Cross Section of Modern Device



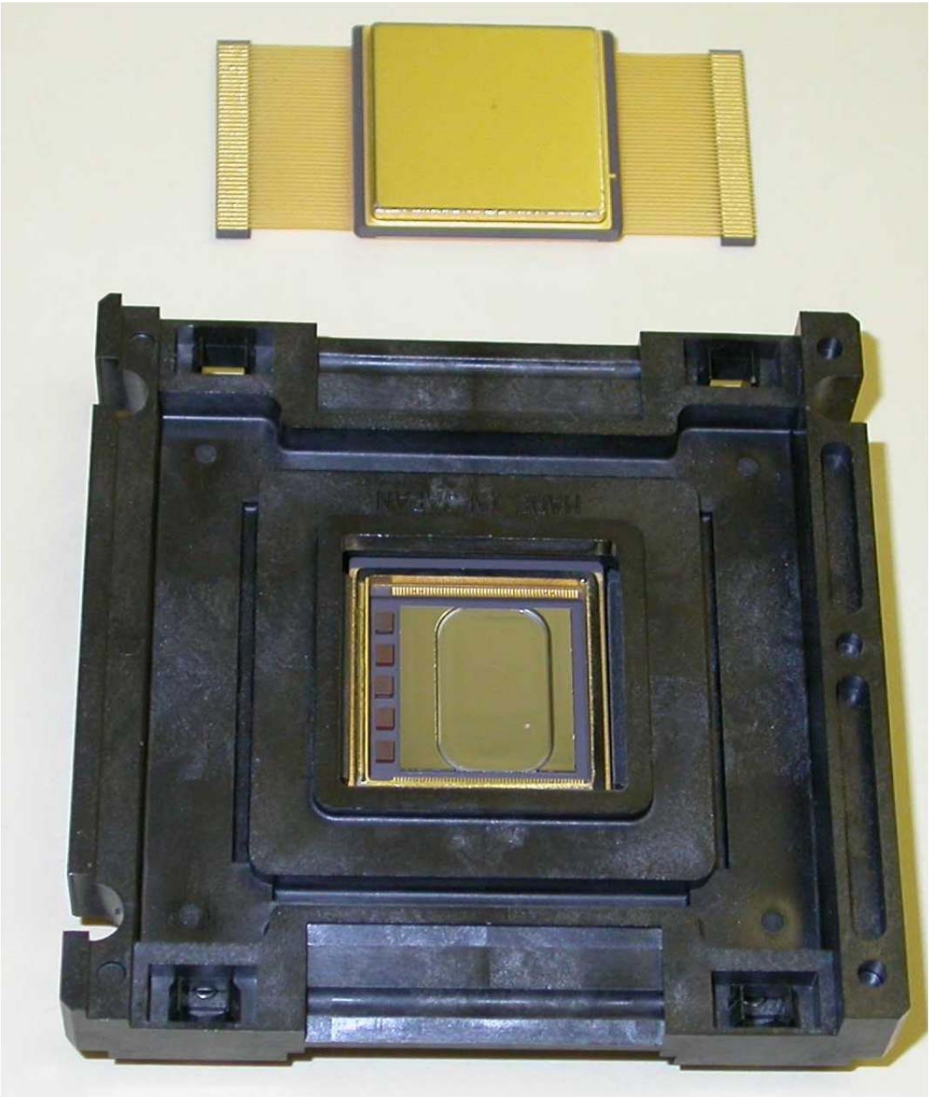
Backside "Through-Wafer" TPA Illumination



McMorrow, et al., IEEE TNS 51 (2004)

Backside "Through-Wafer" TPA Illumination

BAE 4 Mb SRAM Flip Chip Test Structure

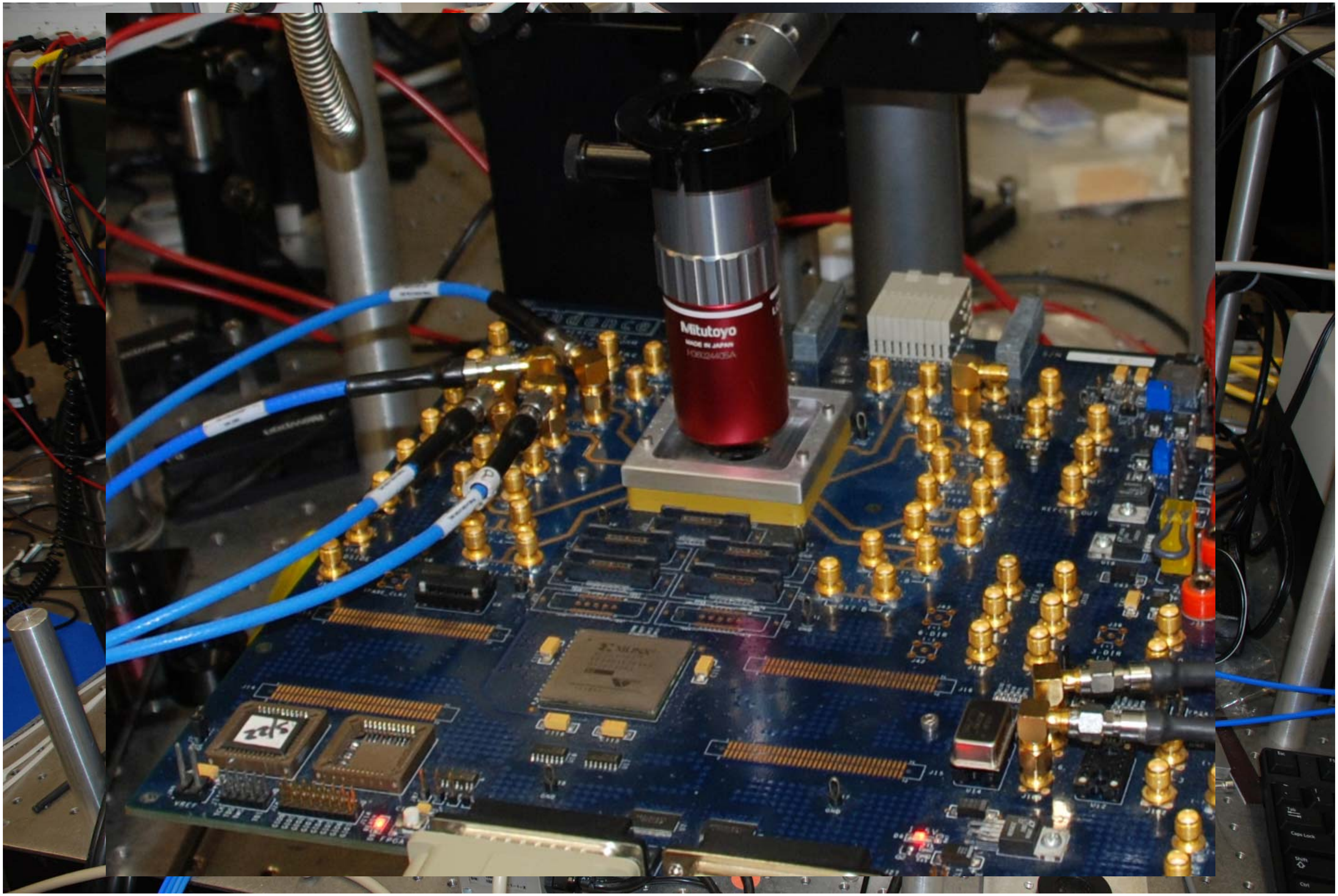


Package with lid-on

SRAM chip in test socket with lid removed and back-side of 4Mb SRAM milled

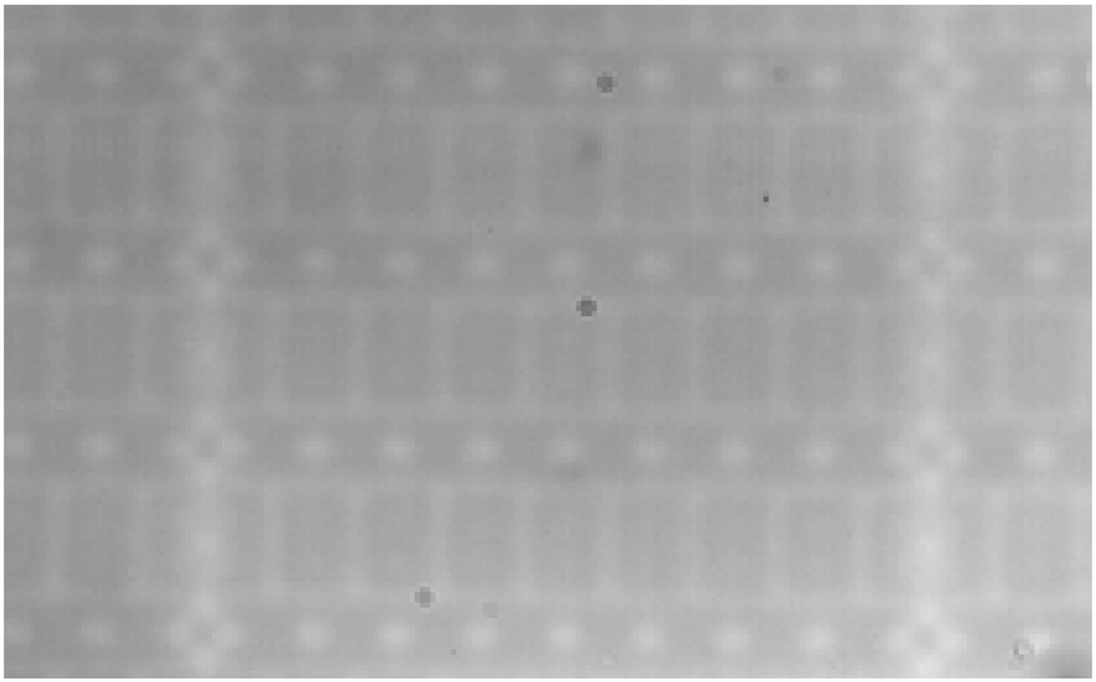
McMorrow, et al., IEEE TNS 52, 2412 (2005)

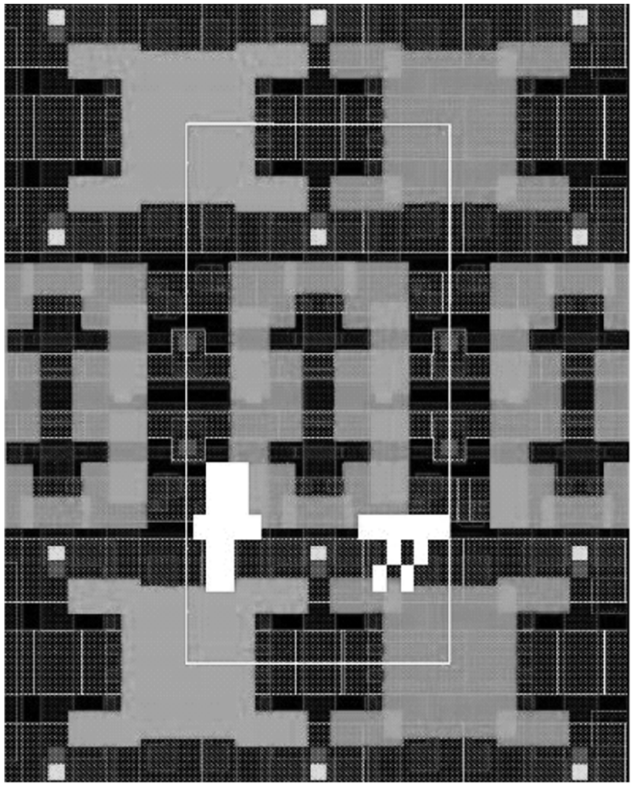
Pulsed Laser-Induced SEE Experiment



Backside "Through-Wafer" TPA Illumination
BAE 4 Mb SRAM Flip Chip Test Structure

BAE SRAM chip through-wafer image and SEU map





McMorrow, et al., IEEE TNS 52, 2412 (2005)

Evaluation of RHBD Approaches
SEE Hardened Phase-Locked Loop

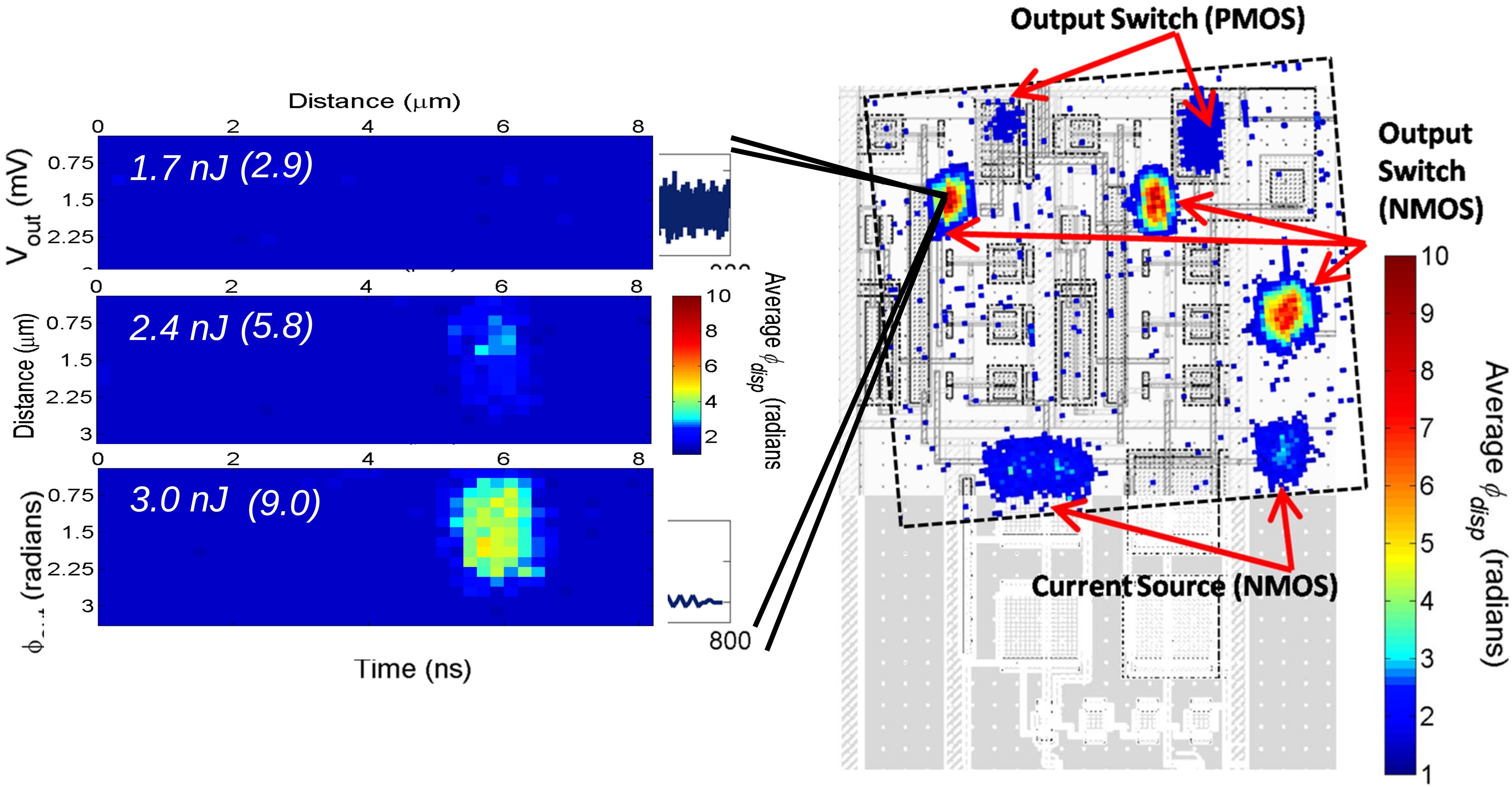
- Daniel Loveless: Vanderbilt University
- Lloyd Massengill, Robert Reed, Bharat Bhuva, William Holman: Vanderbilt University

- Experimental study to compare SEE performance of conventional (current-based) charge pump with RHBD voltage-based charge pump

VANDERBILT UNIVERSITY School of Engineering

Evaluation of RHBD Approaches

Phase-Locked Loop



Loveless, et al., IEEE TNS 57, 2933 (2010)

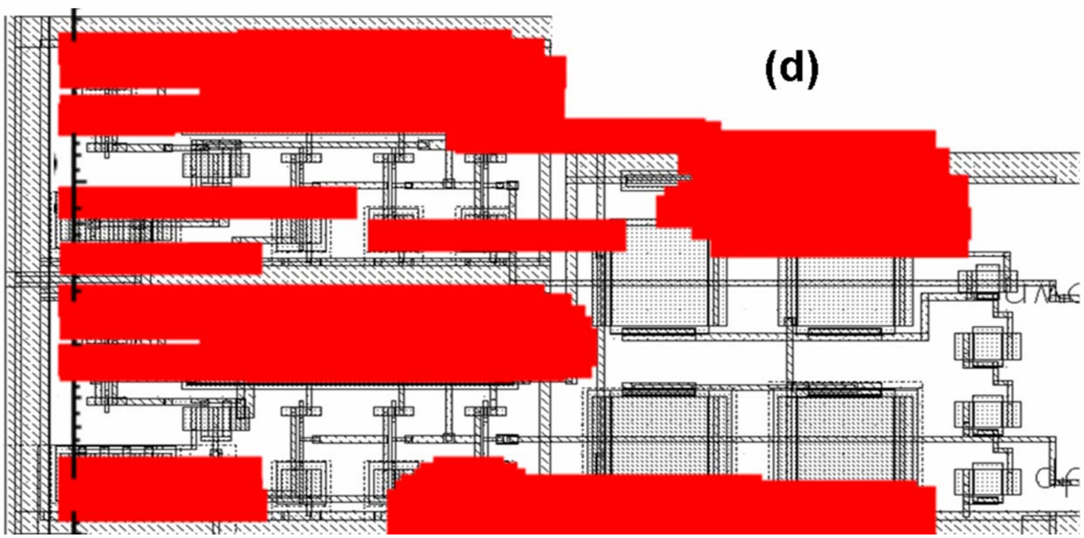
Evaluation of RHBD Approaches

SEE Hardened Phase-Locked Loop

7.0 nJ

54, NO. 6, DECEMBER 2007

2 μm



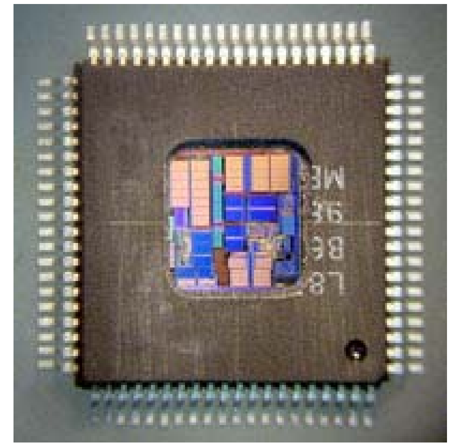
Loveless, et al., IEEE TNS 54, 2012 (2007).

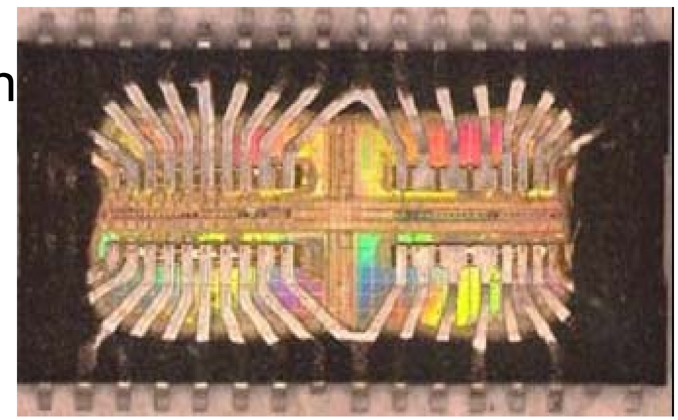
CASE STUDY 9

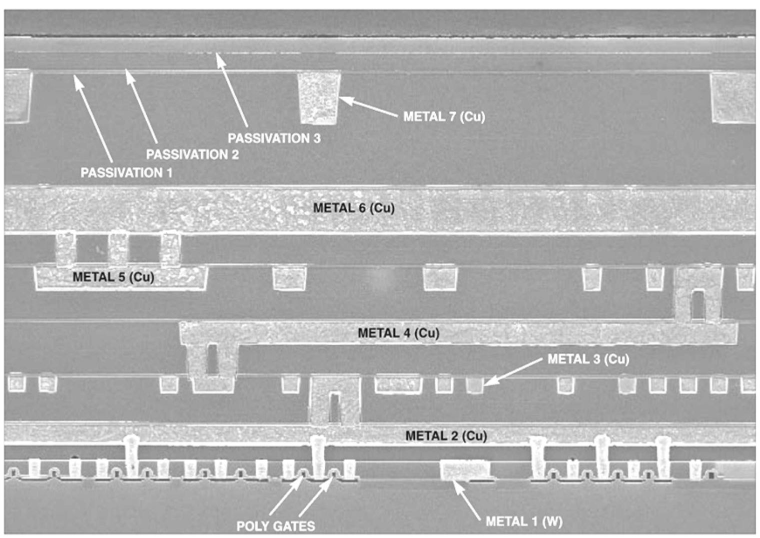
Single-Event Effects in Substrate-Etched SOI/CMOS Devices

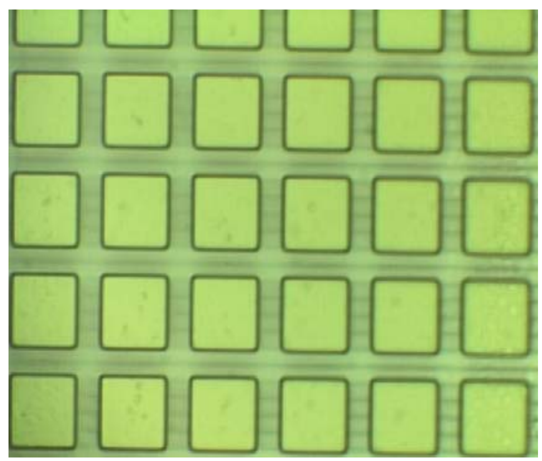
Testing of Modern, Highly-Scaled Technology

- **Packaging**
  - Ceramic or plastic opening
  - Lead frame masking => repackaging
  - Flip-chip
- **Modern process technologies**
  - Many interconnections layers
  - Metal lines, tungsten plugs
  - Dummy cells: metal filling for process planarization
- **Effect heavy-ion and laser testing in different ways**







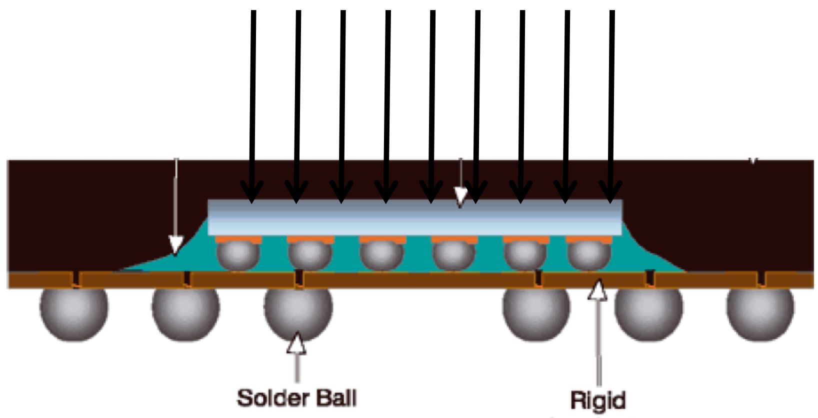


New approaches are required

Single-Event Effects in Substrate-Etched SOI Devices

New Approach:

- ***Complete removal of the Si substrate*** in an SOI Device

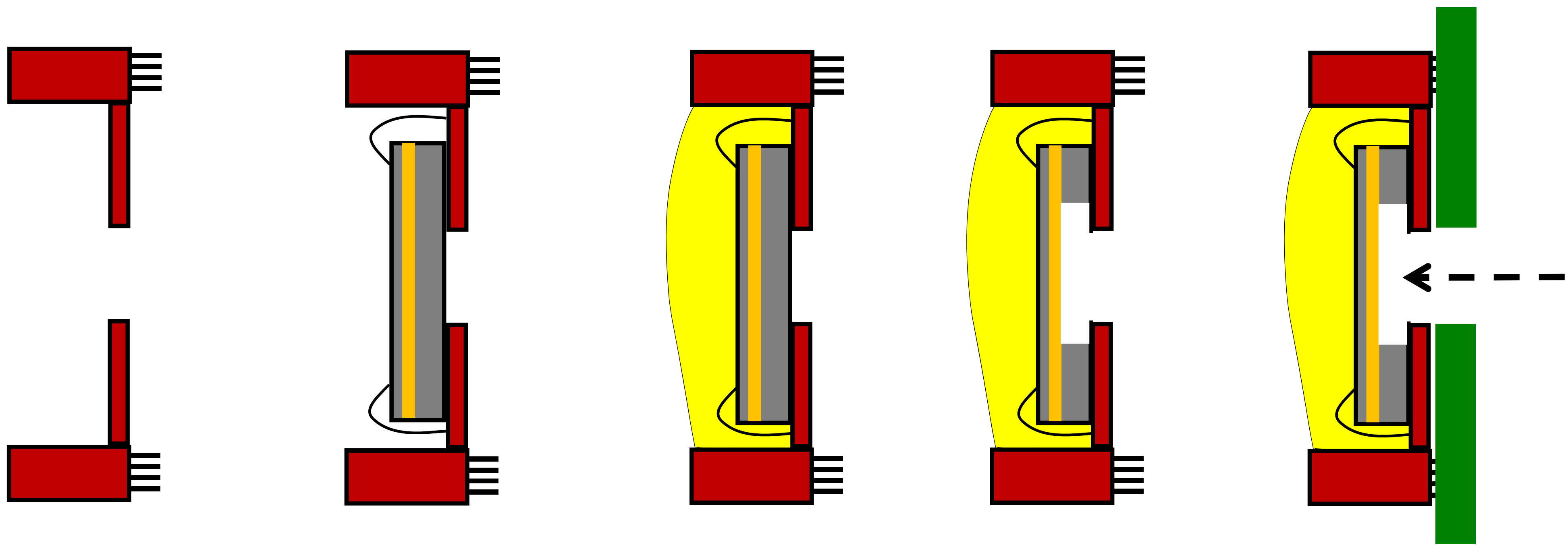


- Initial demonstration: application to a ***90 nm Freescale SRAM***

Single-Event Effects in Substrate-Etched SOI/CMOS Devices

- NRL has adapted a ***standard XeF_2 etching procedure*** involving chemical vapor etching of silicon
- The process involves ***no mechanical polishing*** that can introduce stresses
- The device is ***stabilized in epoxy***
- The remaining Si/SiO_2 structure is suitable for ***back side SEE testing*** with heavy ions, protons, and pulsed laser light
- Can be adapted to flip-chip devices using standard mask procedures

Single-Event Effects in Substrate-Etched SOI/CMOS Devices



Cut a hole in the packge with laser

Mount device directly over hole

Stabilize device by embedding it in epoxy

Completely remove Silicon substrate with XeF_2 etch

Mount package on test board containing a hole coincident with hole inpackage

Silicon thickness = 700 A

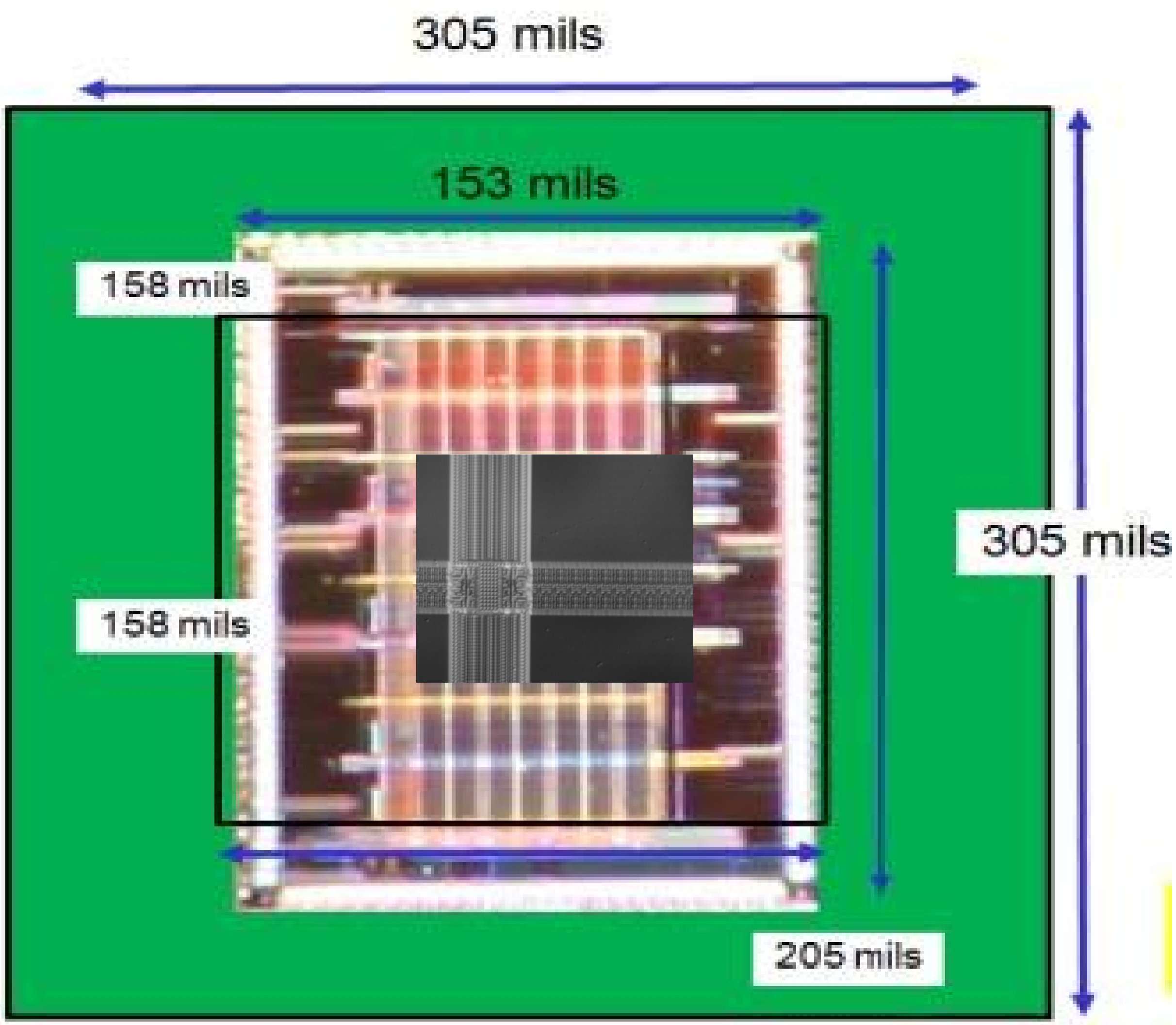
Silicon Dioxide thickness = 1450 A

Overlayers = 5 microns

Kanyagoro, IEEE TNS, 58, 3414 (2010).

Single-Event Effects in Substrate-Etched SOI/CMOS Devices

Backside View



Kanyagoro, IEEE TNS, 58, 3414 (2010).

Single-Event Effects in Substrate-Etched SOI/CMOS Devices

Advantages:

- Potential for ***smaller spot size*** by using ***blue or UV light***
- ***Accurate knowledge of deposited charge for SPA***
- Calibration of Two-Photon Absorption by Single-Photon Absorption
- ***Reduction in LET uncertainties*** for back-side heavy-ion irradiation
- Reduction in LET uncertainties for ***low-energy proton measurements***
- Permits heavy ion testing at ***low-energy accelerators*** since penetration depth is not an issue

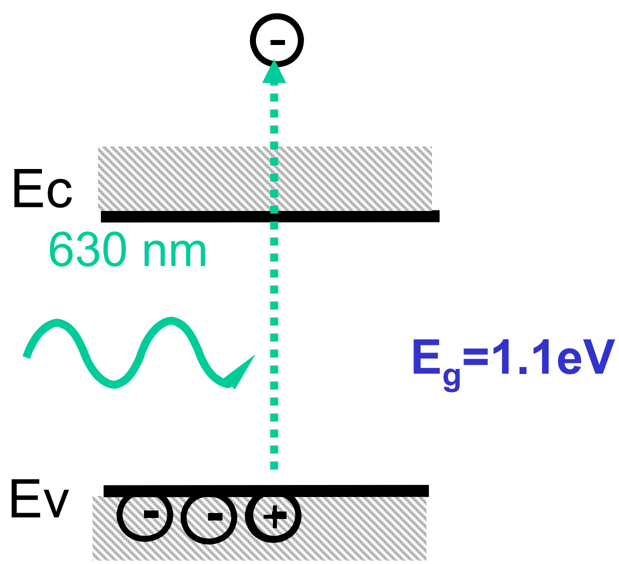
Single-Event Effects in Substrate-Etched SOI/CMOS Devices

Initial Concerns:

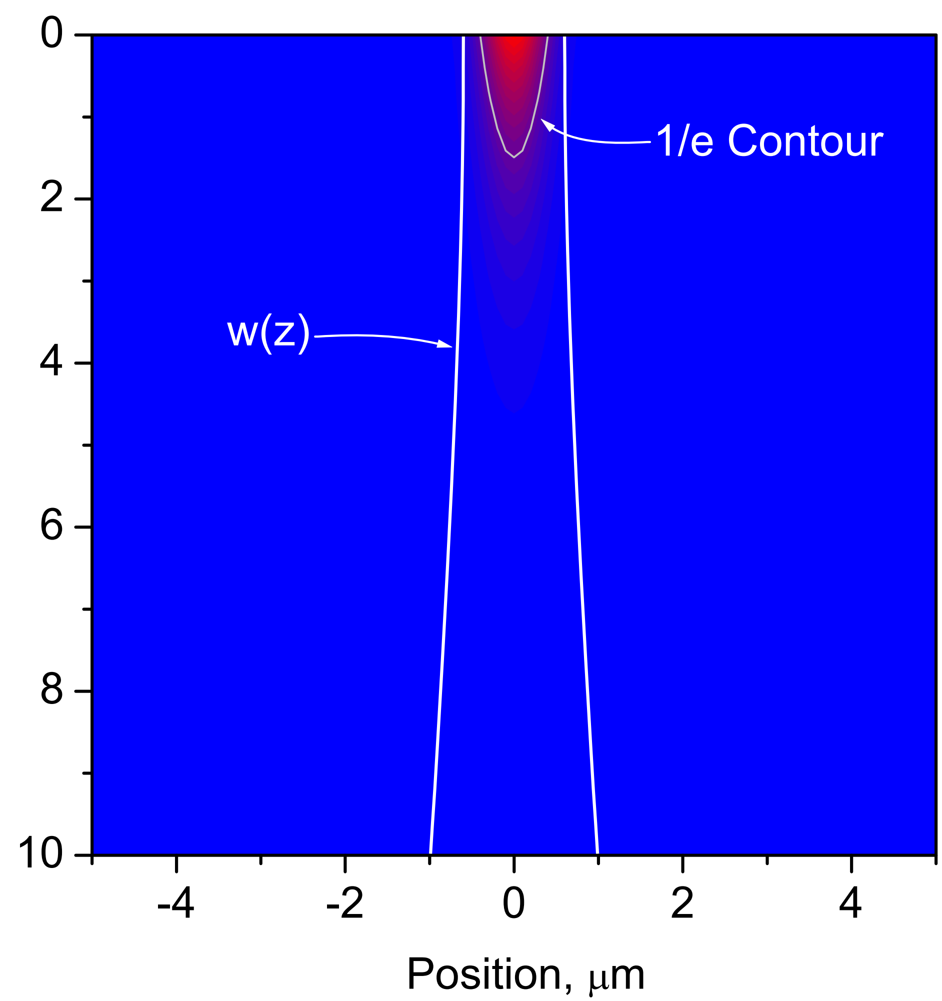
- Device functionality
- Heat dissipation
- SEU performance

Optical Excitation of Carriers

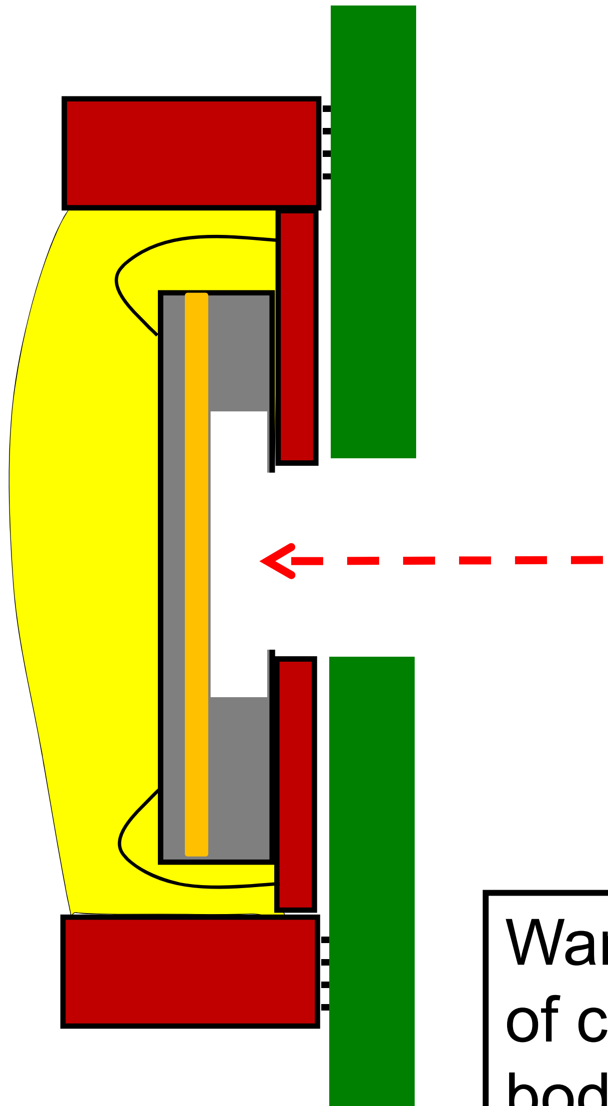
1-Photon



- ***Single photon absorbed***
- ***By the material (silicon)***
- ***Creates a single e-h pair***



Optical Excitation of Carriers



90 nm SRAM

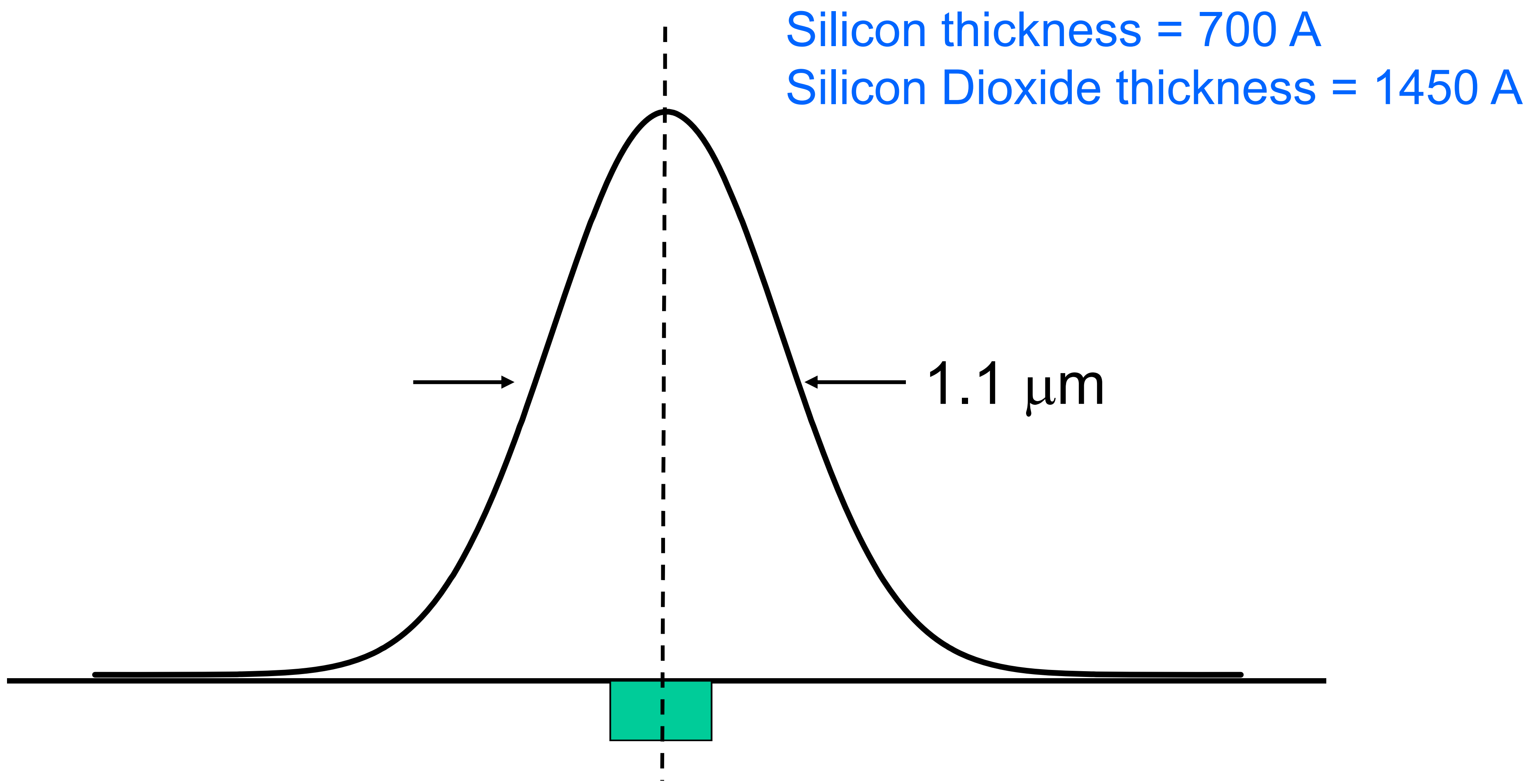
SEU Threshold

590 nm

SPA_{th} = 0.77 pJ

Want to calculate the amount of charge deposited in the body for 0.77 pJ of incident laser pulse energy

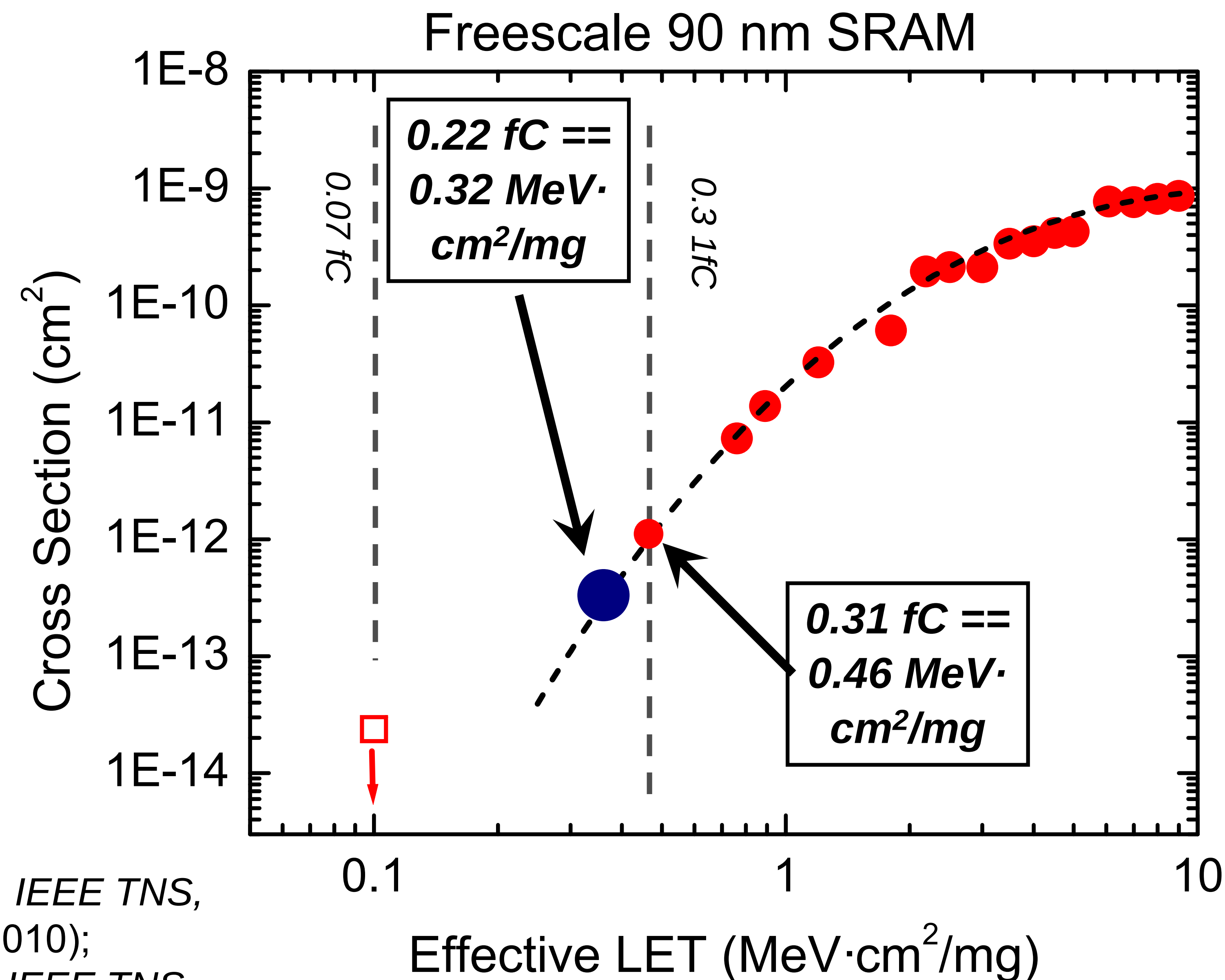
Carrier Excitation in Small Volume



$$E_{dep} = 0.77\ pJ\ (T \times F_{overlap} \times A_{0.07})$$

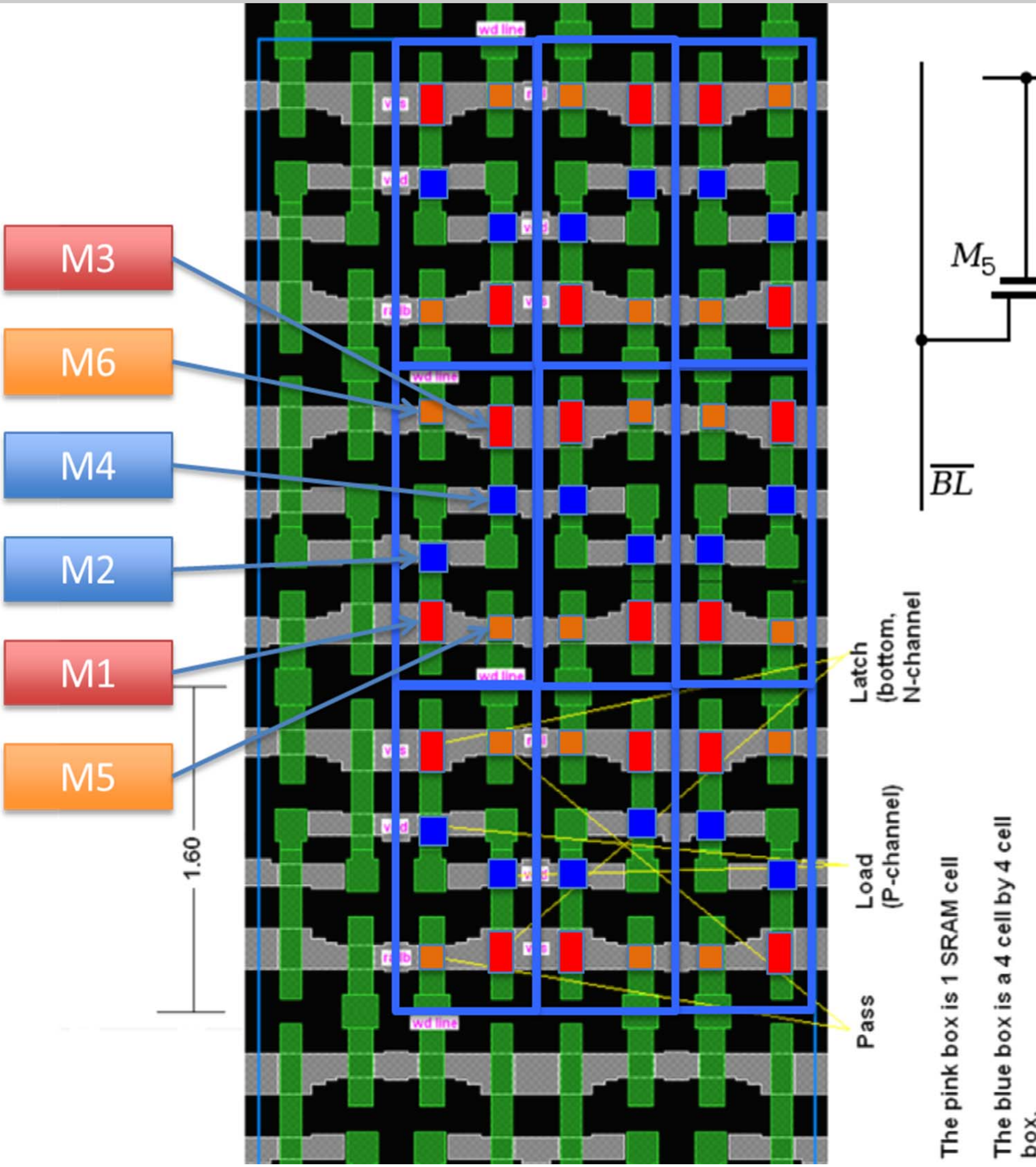
Kanyagoro, IEEE TNS, 58, 3414 (2010).

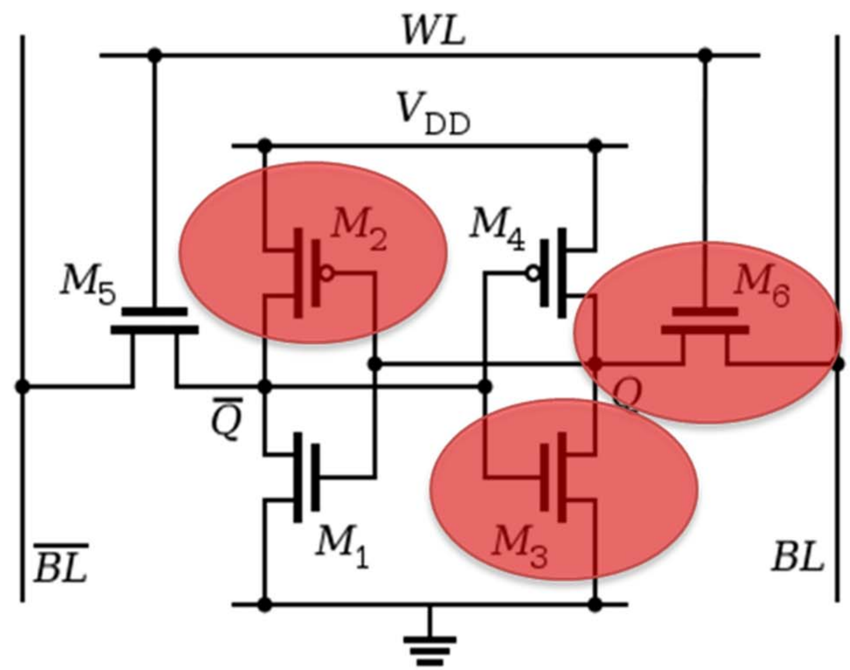
Heavy-Ion SEU Response: Quantitative Prediction of the SEU Threshold



Kanyagoro, IEEE TNS, 58, 3414 (2010); *McMorrow, IEEE TNS,* 60, 4184 (2013).

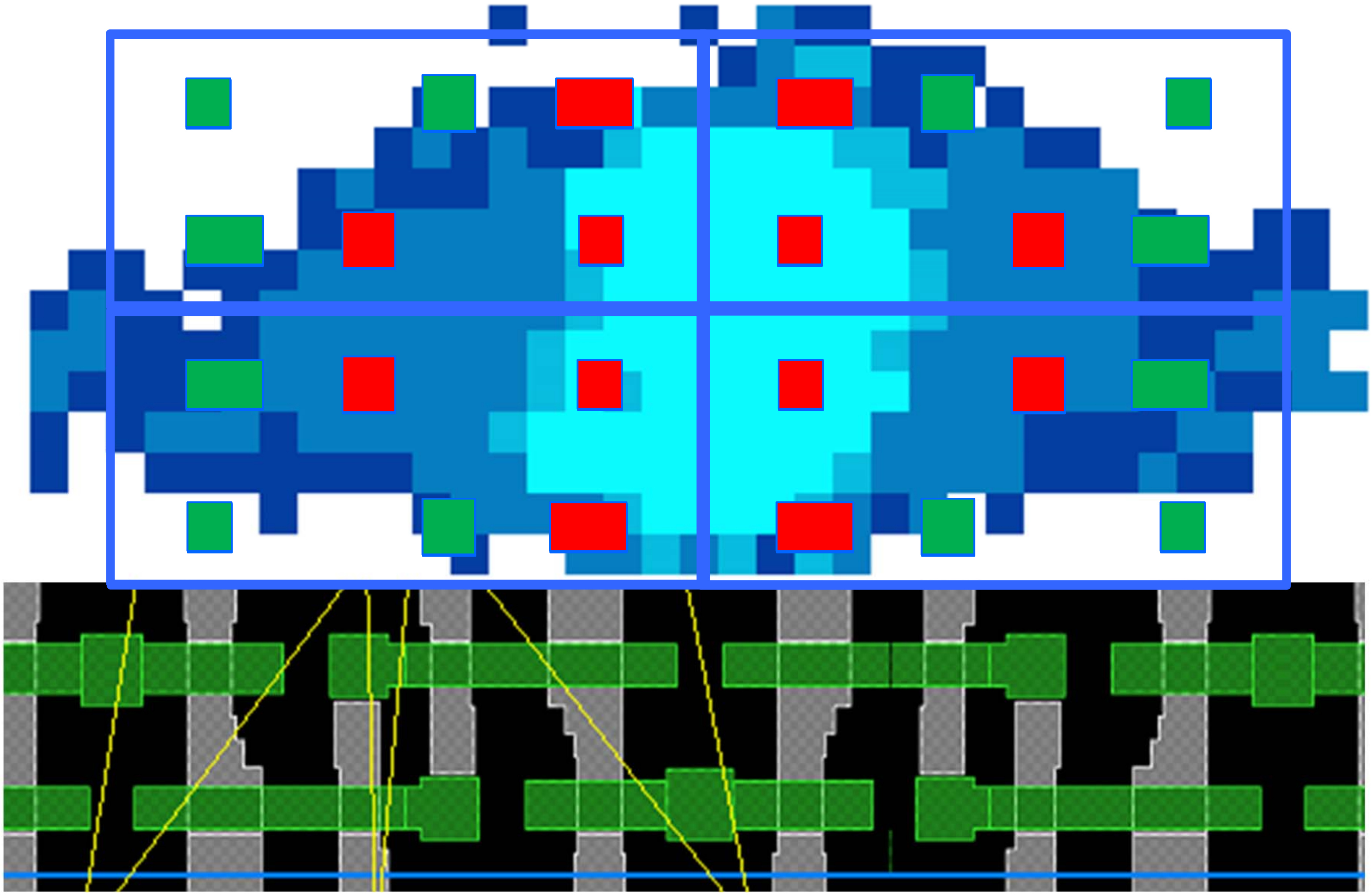
SRAM Cell Design





M3 and M1	Latch (N-channel)
M4 and M2	Load (P-channel)
M6 and M5	Access

2D Error Mapping of SOI SRAM



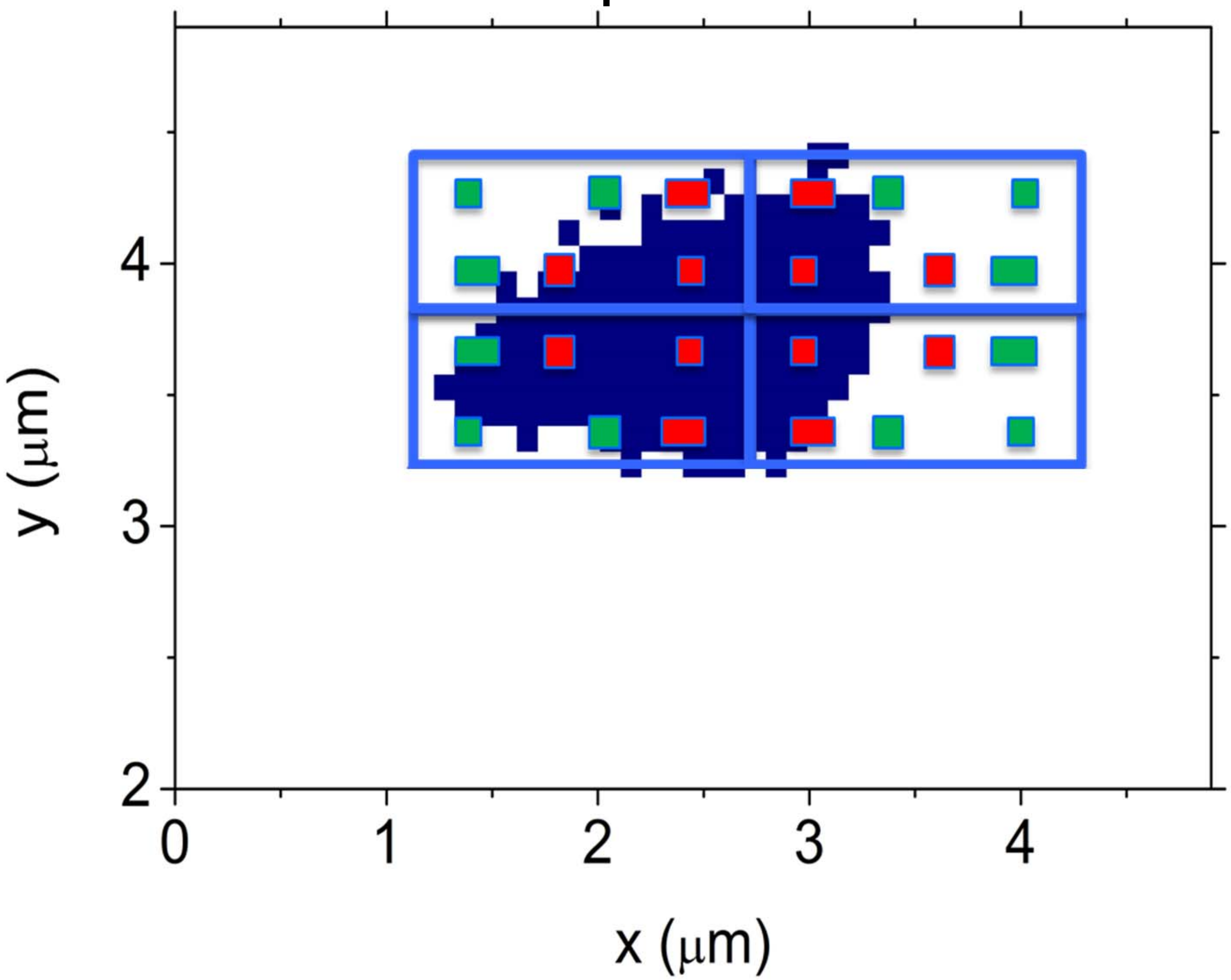
Sensitive transistors for all 1's highlighted in RED

McMorrow, IEEE TNS, 60, 4184 (2013).

2D Mapping with 293 nm Laser Pulse

25% above threshold

Multiple bit errors

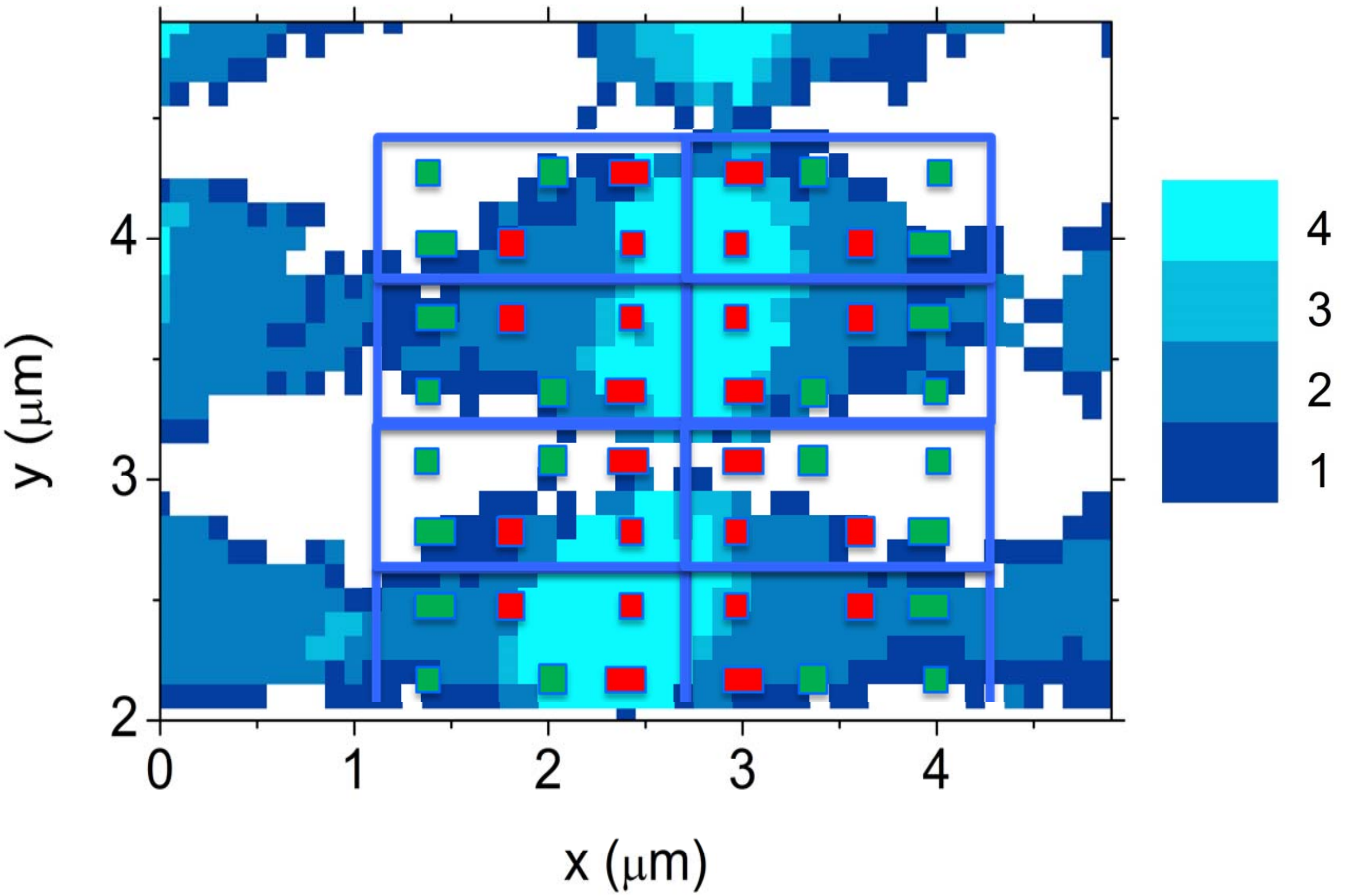


Error Map for Bits 1, 2 and 3

McMorrow, IEEE TNS, 60, 4184 (2013).

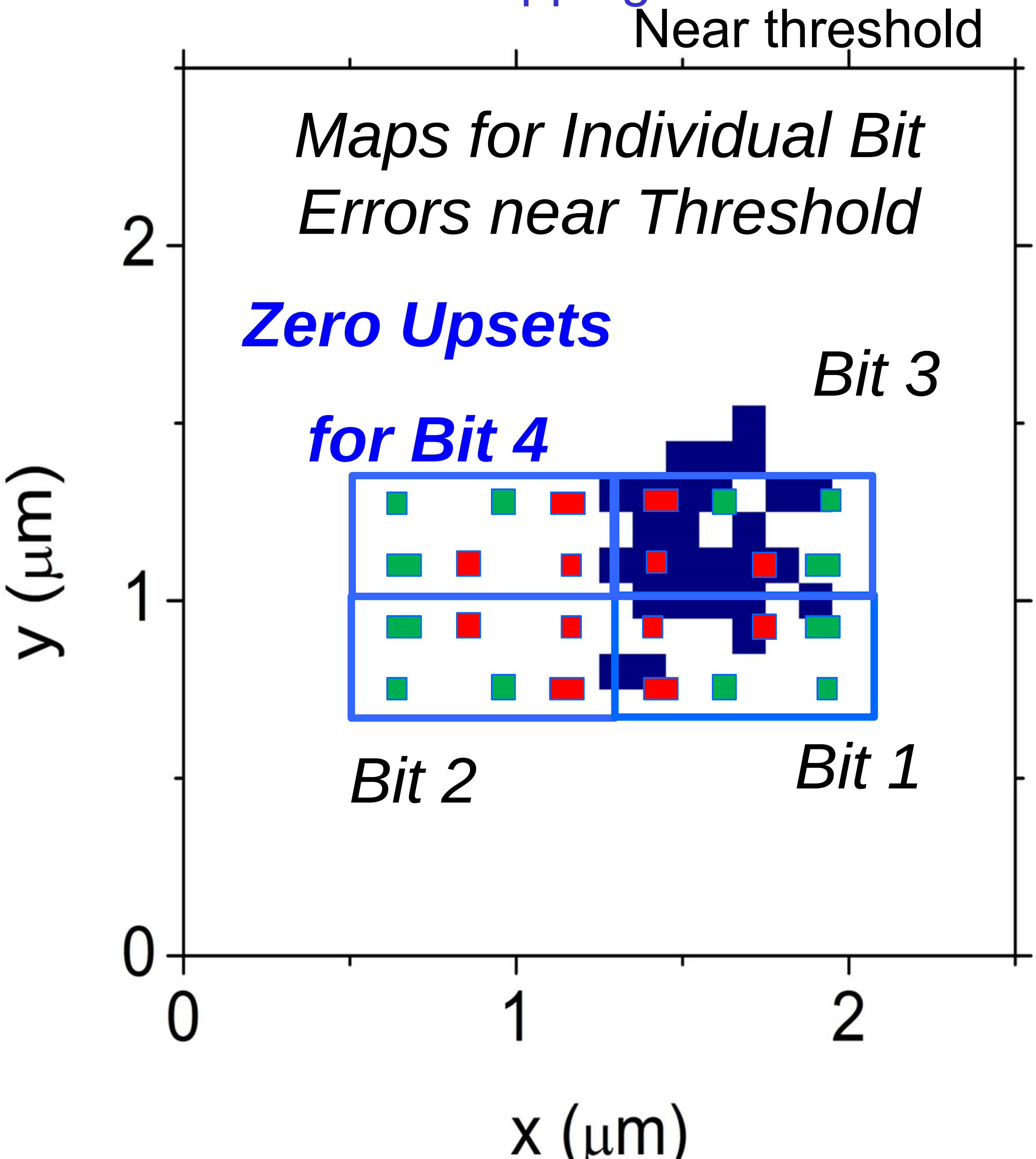
2D Mapping with 293 nm Laser Pulse
25% above threshold

4-bit errors are common



McMorrow, IEEE TNS, 60, 4184 (2013).

2D Mapping with 293 nm Laser Pulse



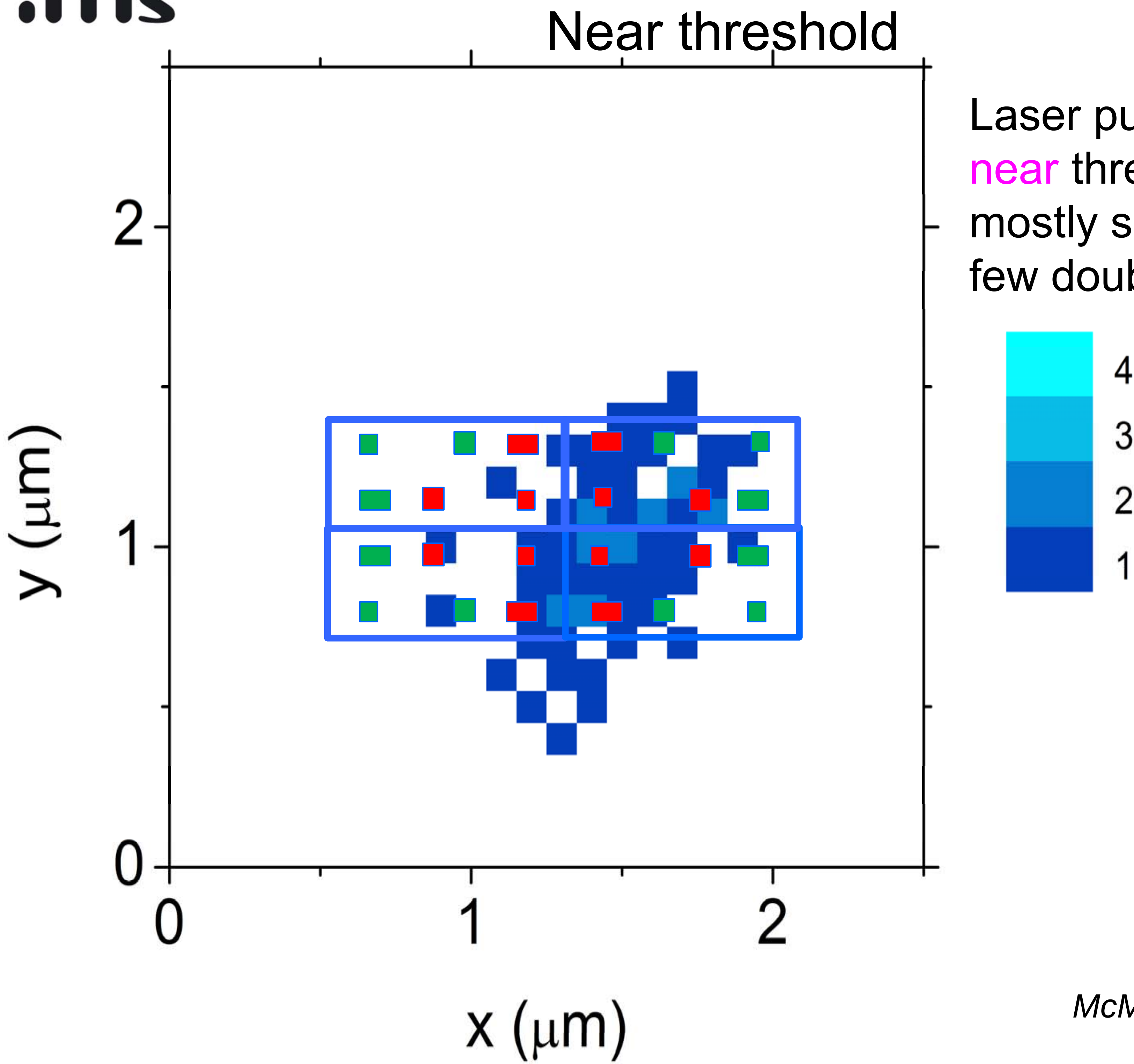
Laser pulse energy near threshold—mostly single, and a few double-bit errors

KEY RESULT:

- Direct observation of *cell-to-cell variations in upset sensitivity*
- ***Consequence of process variations***

McMorrow, IEEE TNS, 60, 4184 (2013).

2D Mapping with 293 nm Laser Pulse



Laser pulse energy near threshold—mostly single, and a few double-bit errors

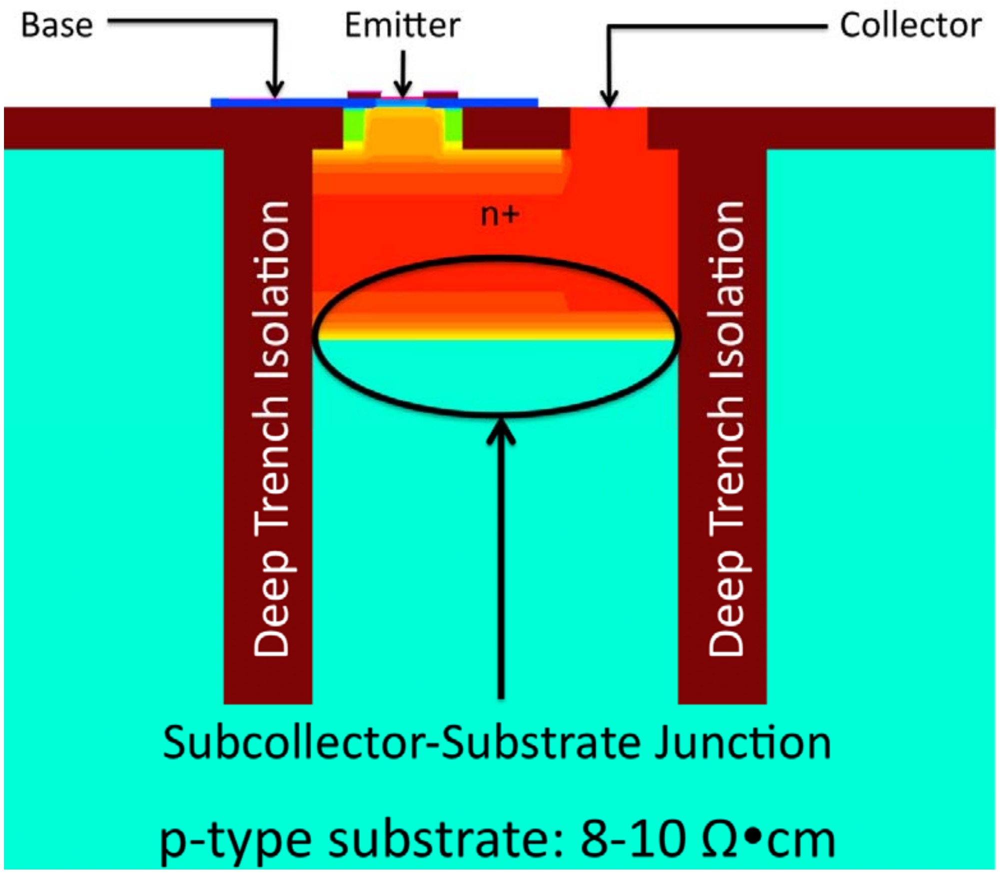
McMorrow, IEEE TNS, 60, 4184 (2013).

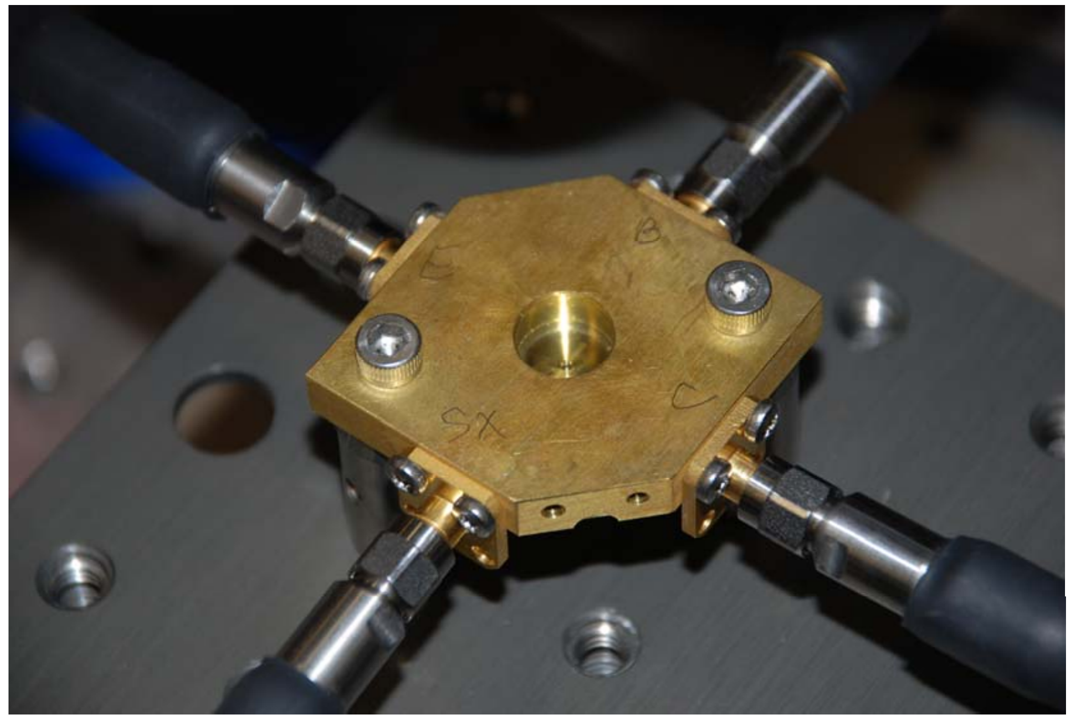
CASE STUDY 10

Two-Photon-Induced Single-Event Effects:

Basic Mechanisms in SiGe

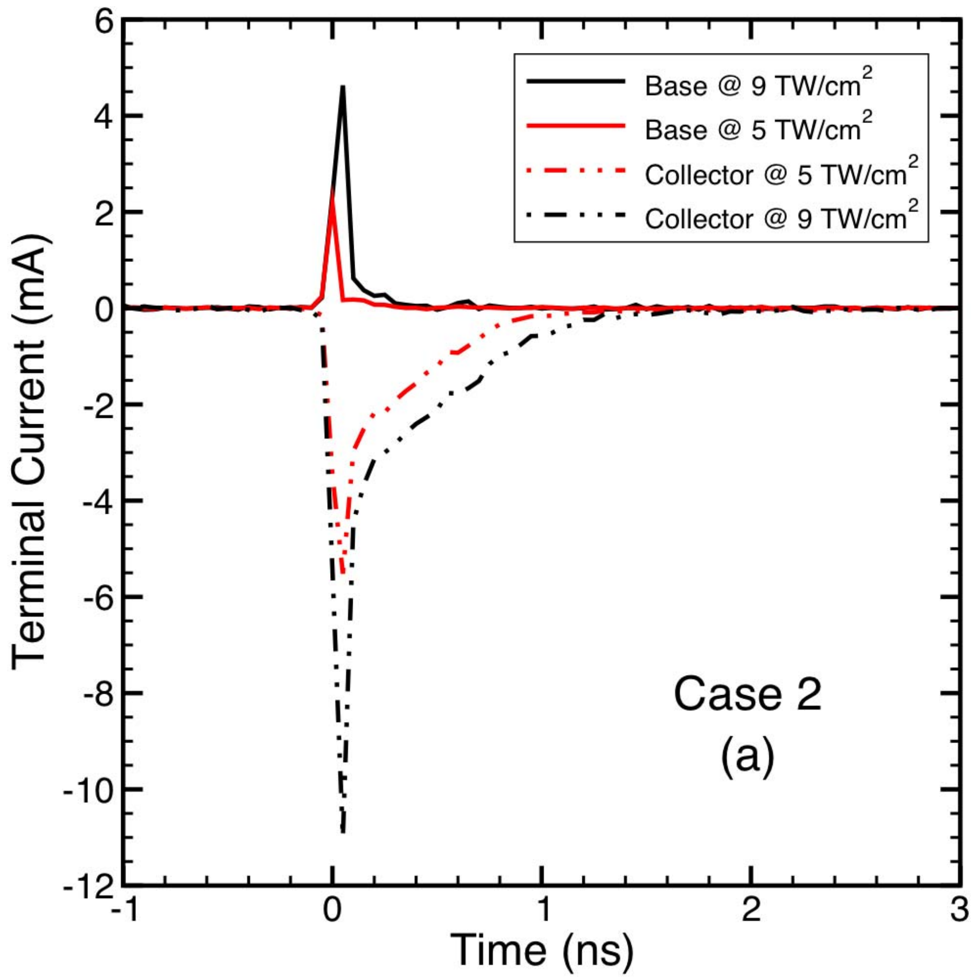
Basic Mechanisms: Single-Event-Induced Charge Collection in SiGe HBTs

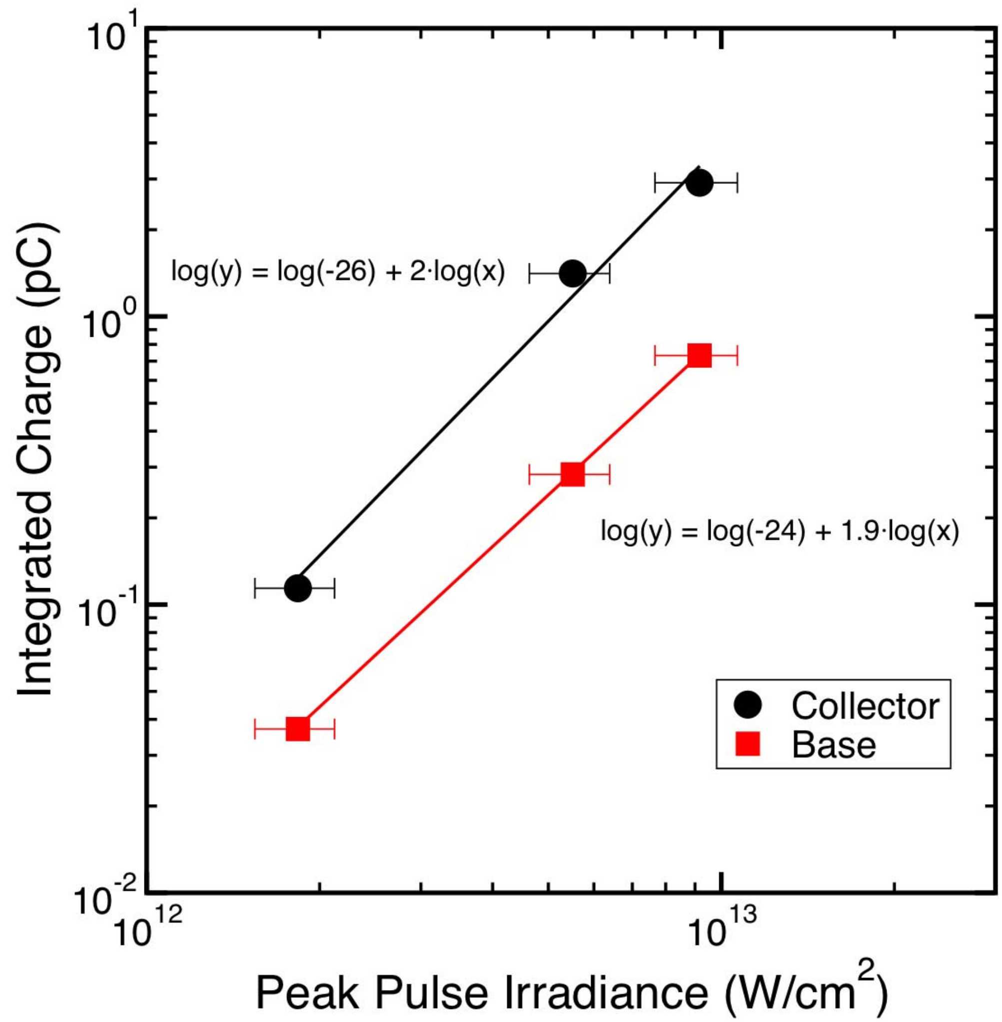




Pellish, et al., IEEE TNS, 55, 2936 (2008)

Basic Mechanisms: Single-Event-Induced Charge Collection in SiGe HBTs

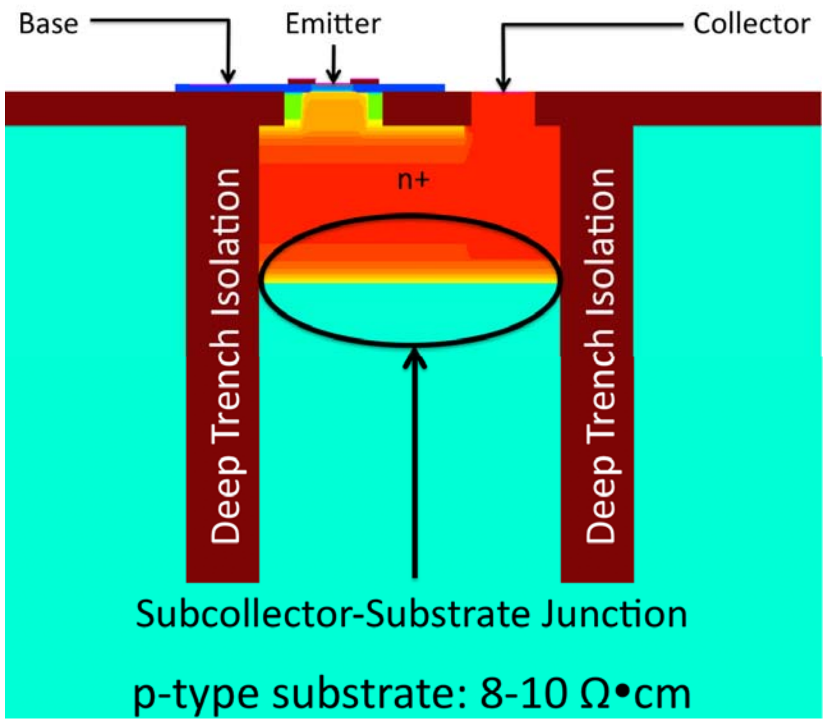


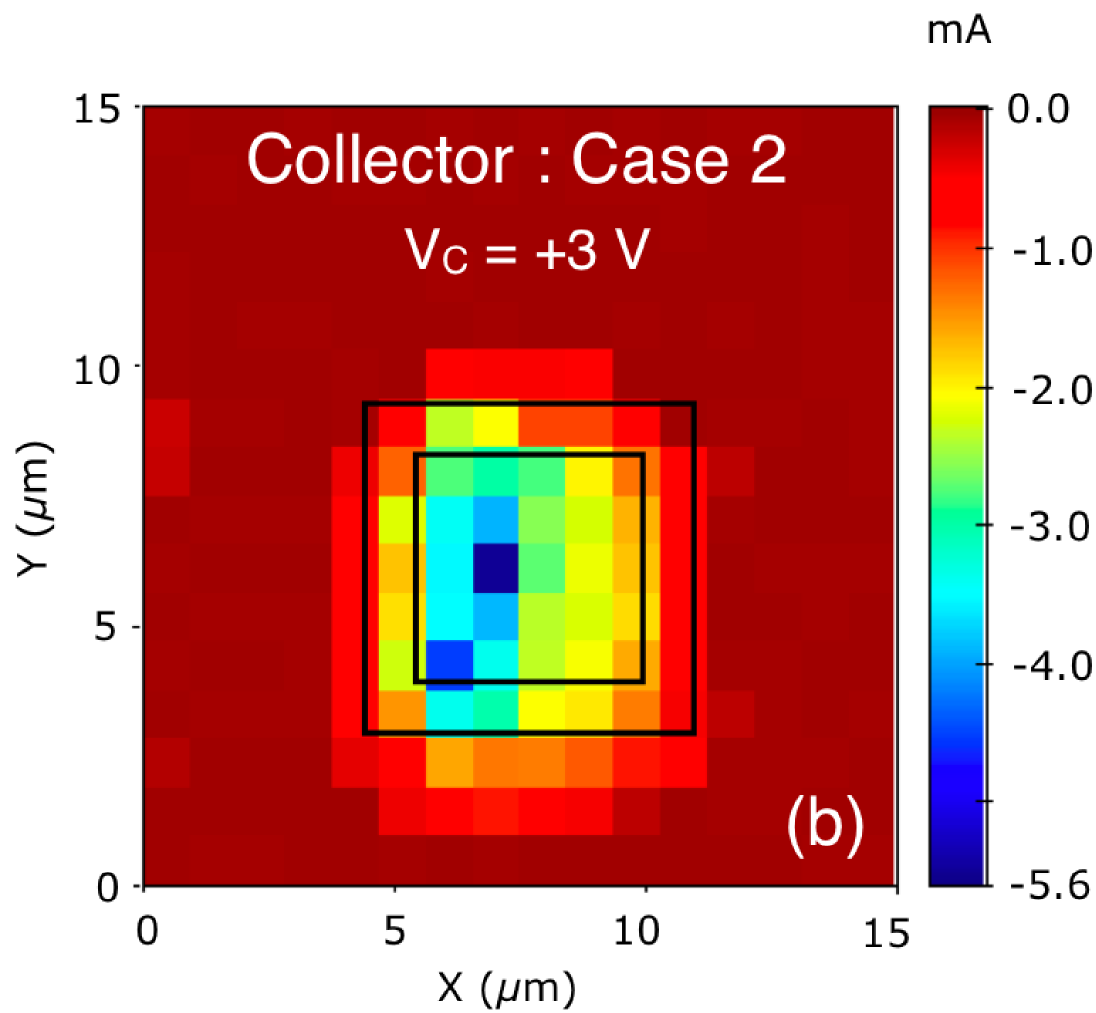


MODEL VALIDATION AND CALIBRATION

Pellish, et al., IEEE TNS, 55, 2936 (2008)

Basic Mechanisms: Single-Event-Induced Charge Collection in SiGe HBTs





Pellish, et al., IEEE TNS, 55, 2936 (2008)

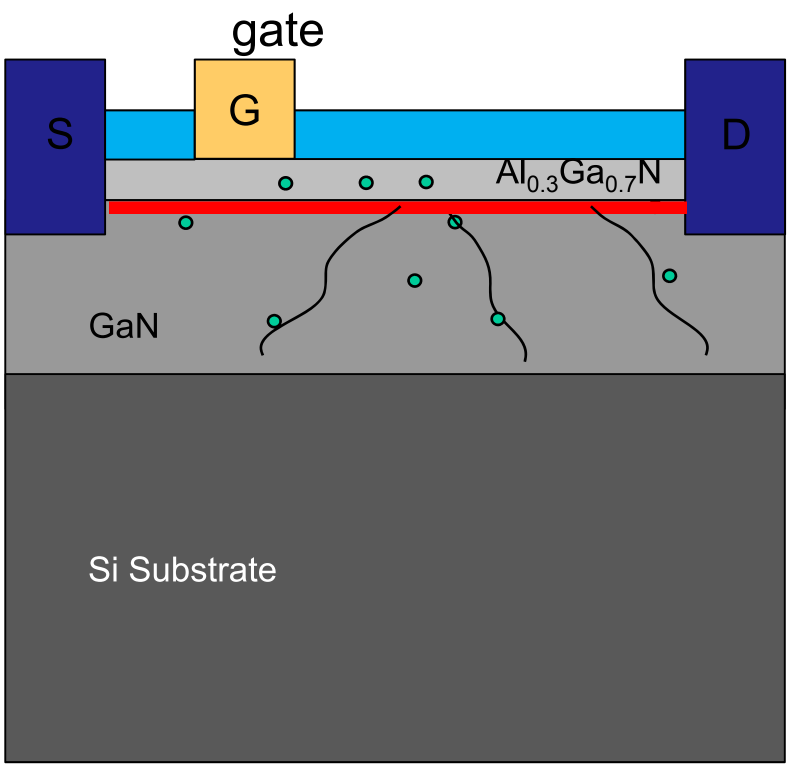
CASE STUDY 11

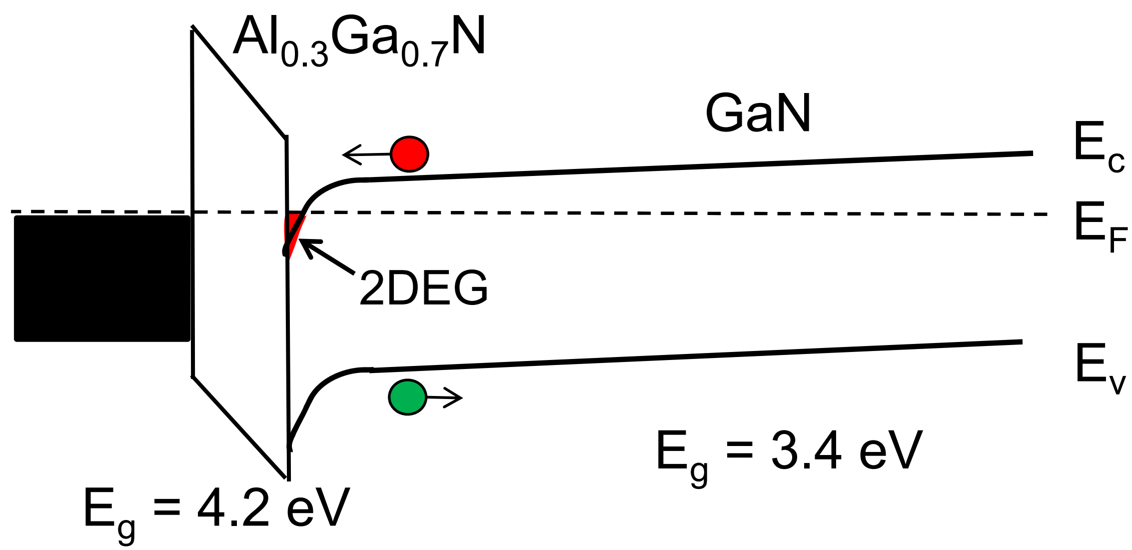
Laser-Induced Single-Event Effects:

Basic Mechanisms of SEE in GaN HEMTs

Basic Mechanisms: Single-Event-Induced Charge Collection in GaN HEMTs

Schottky barrier



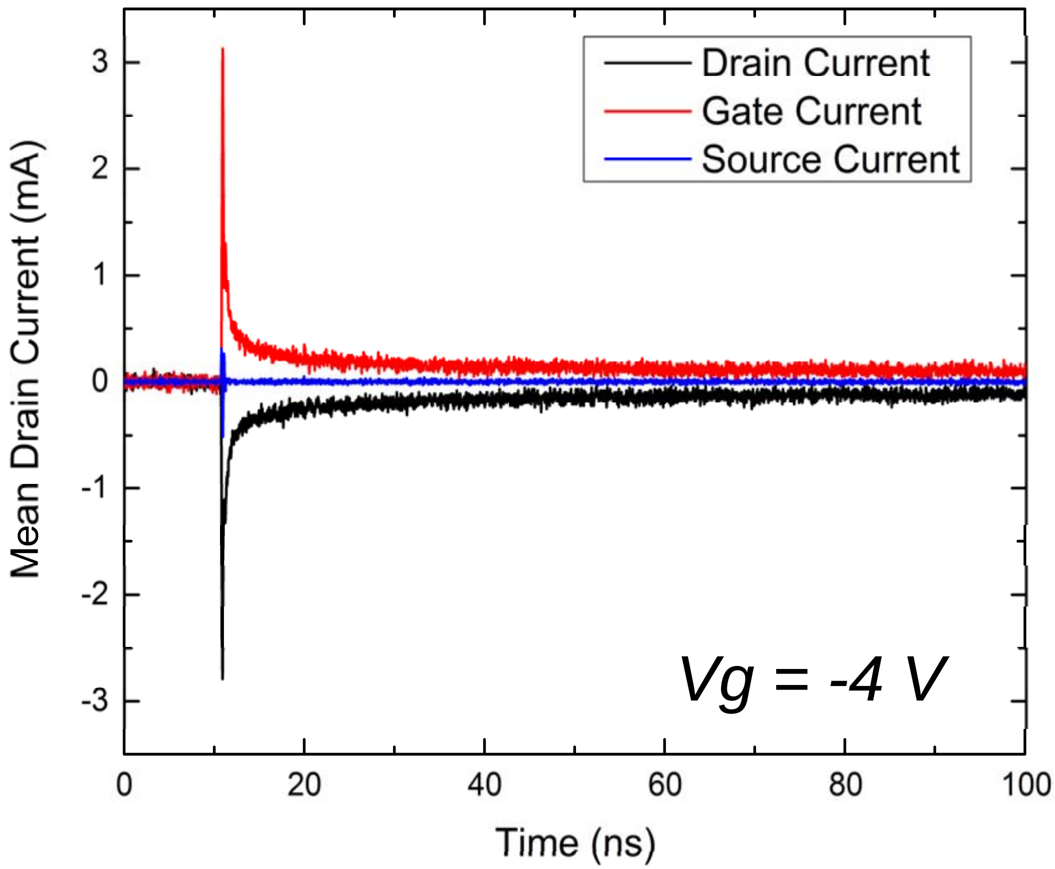


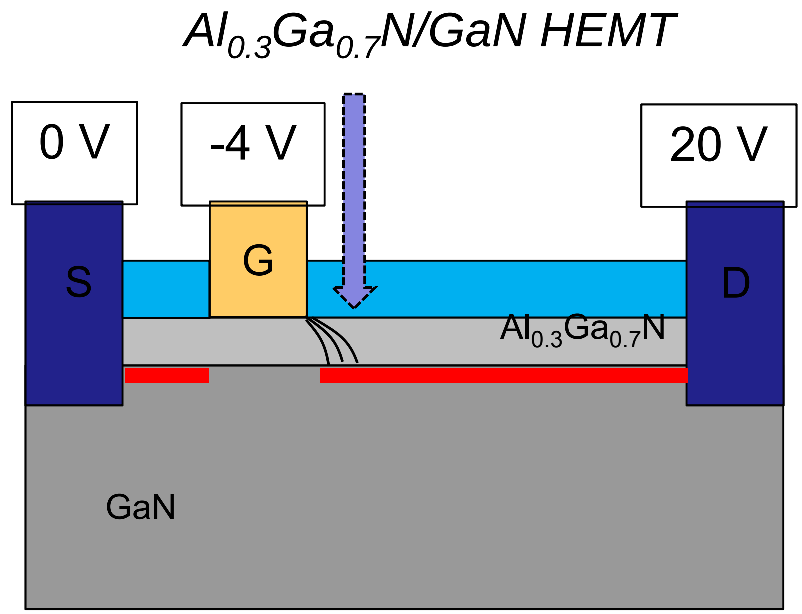
Basic Mechanisms: Single-Event-Induced Charge Collection in GaN HEMTs

Investigation into the SET mechanisms of GaN HEMTs:

- The first demonstration of laser-induced SEEs in $Al_{0.3}Ga_{0.7}N/GaN$ HEMTs
  - TPA using visible pulses
  - SPA using UV optical pulses
- We present *charge-collection transients* measured as a function of position, device bias conditions, and exposure to proton irradiation
- These results provide unique insights into *native* and *radiation-induced defects* in the material

Basic Mechanisms: Single-Event-Induced Charge Collection in GaN HEMTs



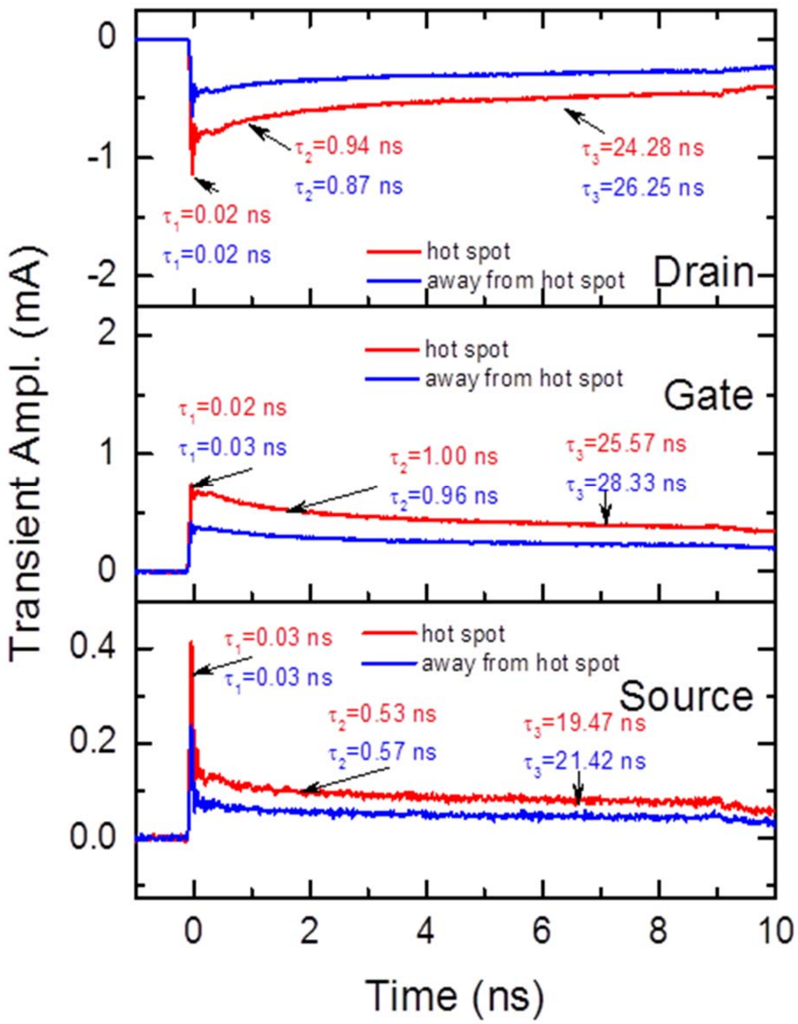


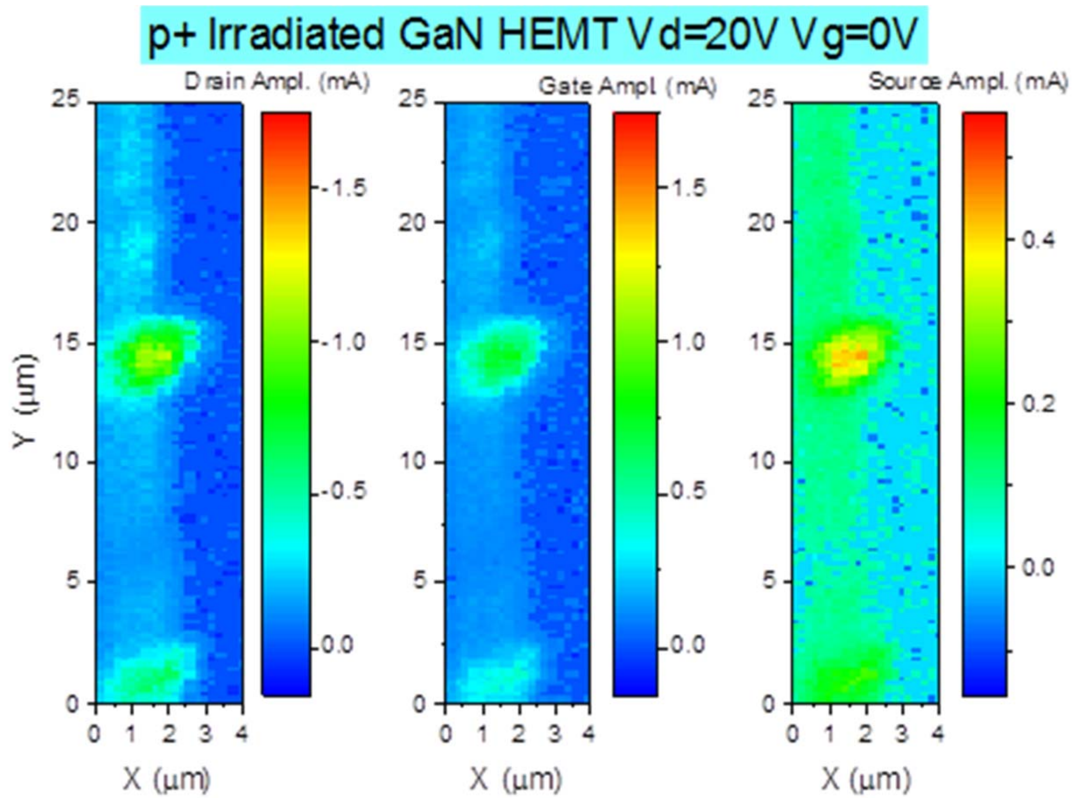
Electric field in AlGaN depends on the Al composition and on Vgd

- TPA-induced SETs on the drain and gate
- The device is biased "off"
- *Significant Gate-Drain current flow!*
- *Fast and slow contributions evident*

Roche, et al., IEEE TNS Dec. 2015, In press

GaN UV SPA Transient Amplitude Maps (p+)





- *Vg = 0 V; biased "on"*

- The shapes of the transients provide insights into the nature and density of defects
- Analysis of the transients is consistent with traps with lifetimes ranging up to 30 ns
- Consistent with *radiation-induced Nitrogen vacancies*

Khatchartian, et al., IEEE TNS 2016, In press

Some mature applications of laser testing

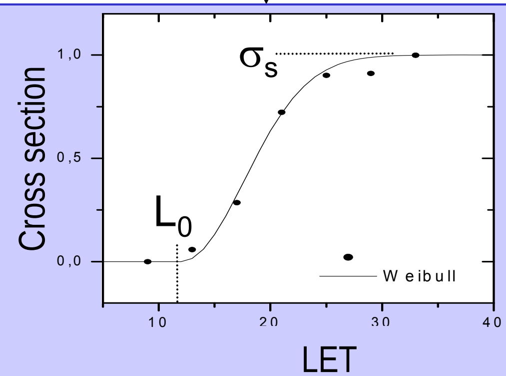
SEU / MBU	- Compare thresholds of different devices from similar technologies - Evaluate error multiplicity and EDAC options - Descramble the logical address vs physical bit location
Digital SET	- Evaluate clock frequency effects and critical time window - Analyze propagation / capture mechanisms
SEL	- Screen out sensitive devices, keep the hard ones for radiation testing - Estimate cross section - Localize sensitive areas for re-design
SEFI	- Enumerate / Classify failure modes of complex devices before radiation testing - Localize / analyzes rare events for optimizing system hardening strategies - Estimate relative thresholds and cross sections of different events
Analog SET	- Enumerate waveforms types and estimate respective probabilities - Extract amplitude vs duration distribution plots - Estimate relative thresholds and cross sections for different electrical setups
SEB	- Evaluate Safe Operating Area (SOA) - Estimate sensitive depth

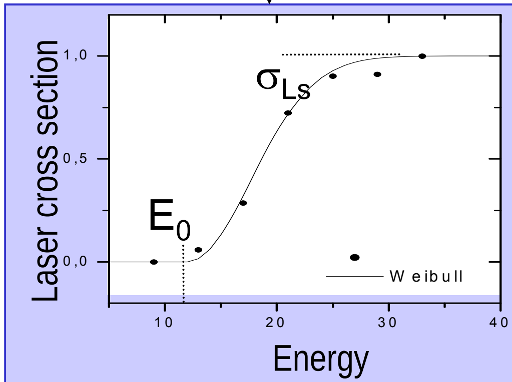
Conclusions

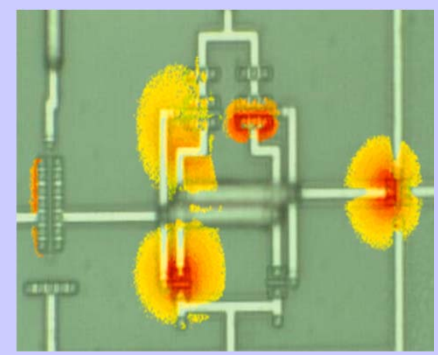
Single-Event Effects testing

Particle accelerator

Pulsed laser







Rate prediction

Designs comparison

Parametric evaluation

Screening

Complex case studies

Rare events analysis

Rad-hard design

Questions

What should I use for :	Heavy ions	Laser	
		Single Photon	Two-photon
Screening devices with different designs in the same technology node for SEU-MBU	+	++	(+)
Accurate SEU cross section vs LET measurement for a memory device	++		
Testing fault-tolerant system level solutions	+	++	+
Analyzing deep charge collection mechanisms	+	+	(++)
Mapping SEL sensitive area of a flip-chip device		+	++
Validating an SEL-free design	+ +	+	
Studying rare SEFI events in a recent digital device		++	++
Defining design margins for analog SET in linear devices	+	++	+
Validating the radiation hardening efficiency of a design update	+	++	+
Obtain a 3D view of charge collection volumes			++