U.S. NAVAL RESEARCH LABORATORY

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

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Pulsed Laser Single-Event Effects

Goals:

1. Basic understanding of PL SEE approach
2. Understanding of the various ***uses and applications*** of PL SEE approach
3. Current topics

Pulsed Laser Single-Event Effects

PL SEE is <u>complementary</u> to heavy-ion-induced SEE

➡ ***TPA and SPA are additional tools in our "SEE Toolbox"***

Pulsed Laser Single-Event Effects

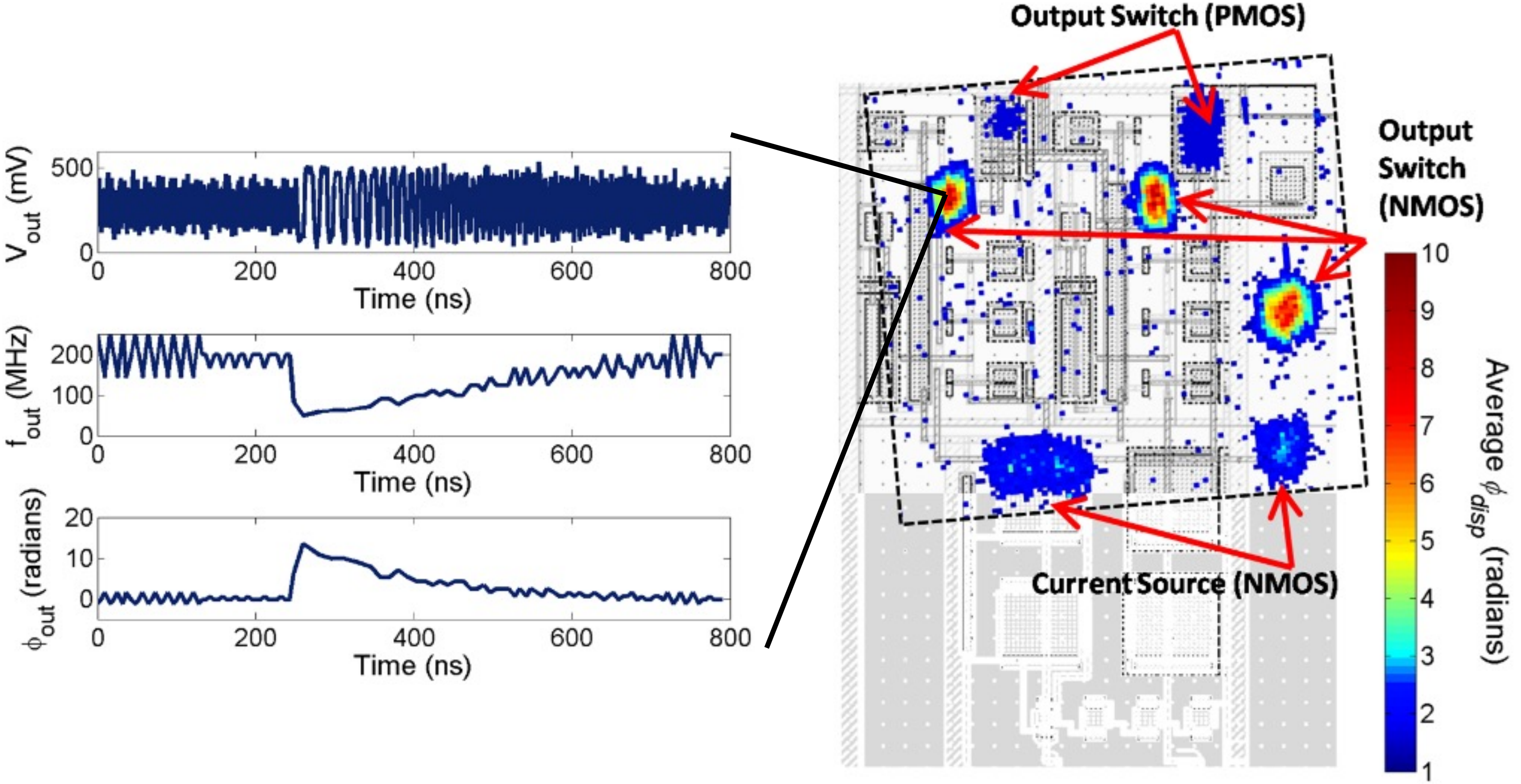
For SEE studies, the pulsed laser is a tool for ***injecting charge*** in a well-defined manner into semiconductor microelectronic and nanoelectronic structures

Pulsed Laser Single-Event Effects

Pulsed-laser SEE is used for:

- Sensitive node identification/characterization
- SEU mapping of sensitive areas
- Digital single-event transient characterization and mitigation
- Laser-induced latch-up screening/mitigation
- Analog single-event transient screening (ASETs)
- Hardened circuit (RHBD and RHBP) verification
- Dynamic SEE testing
- Experimental test setup verification
- Complex circuit evaluation/error signature identification
- Basic mechanisms studies

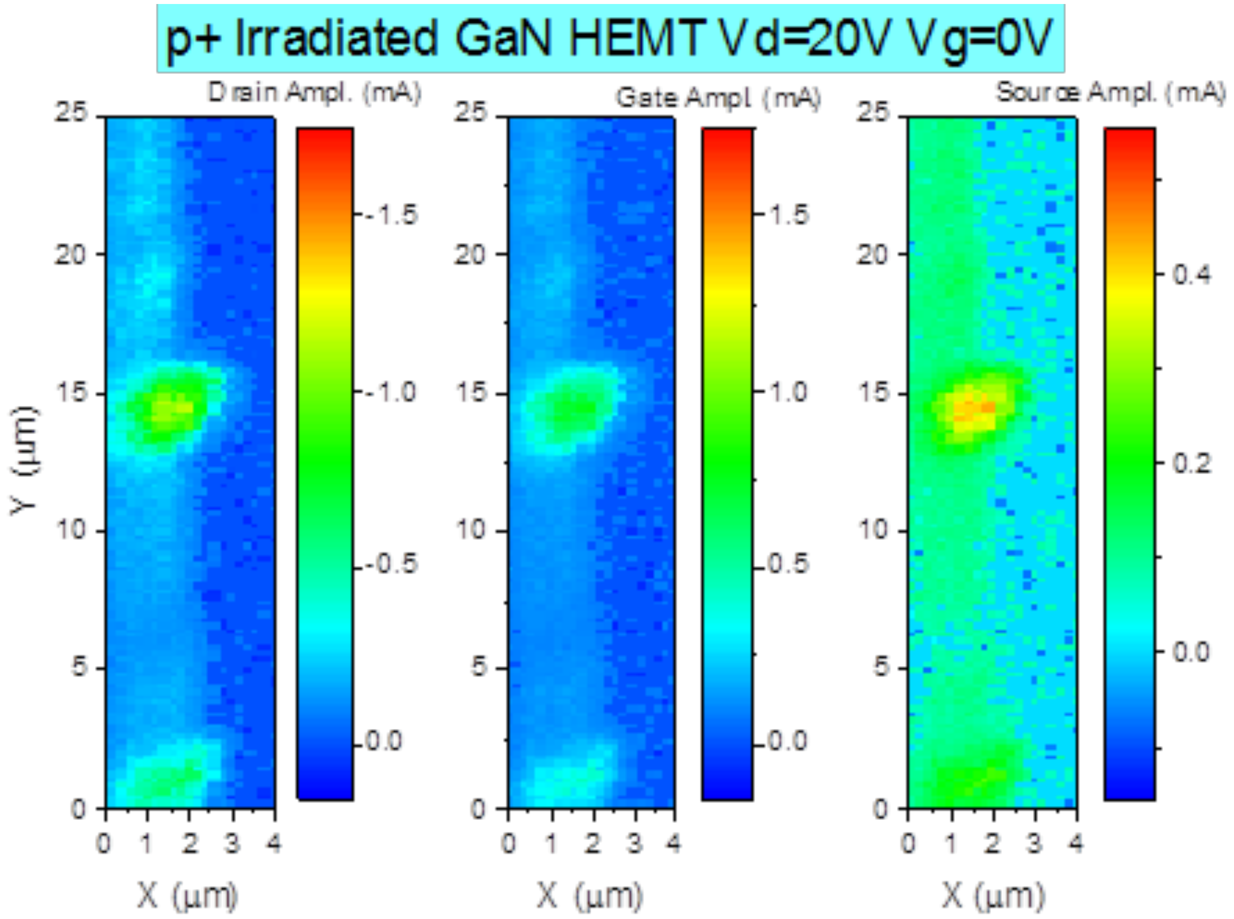
Key Feature of PL SEE: Spatial Selectivity

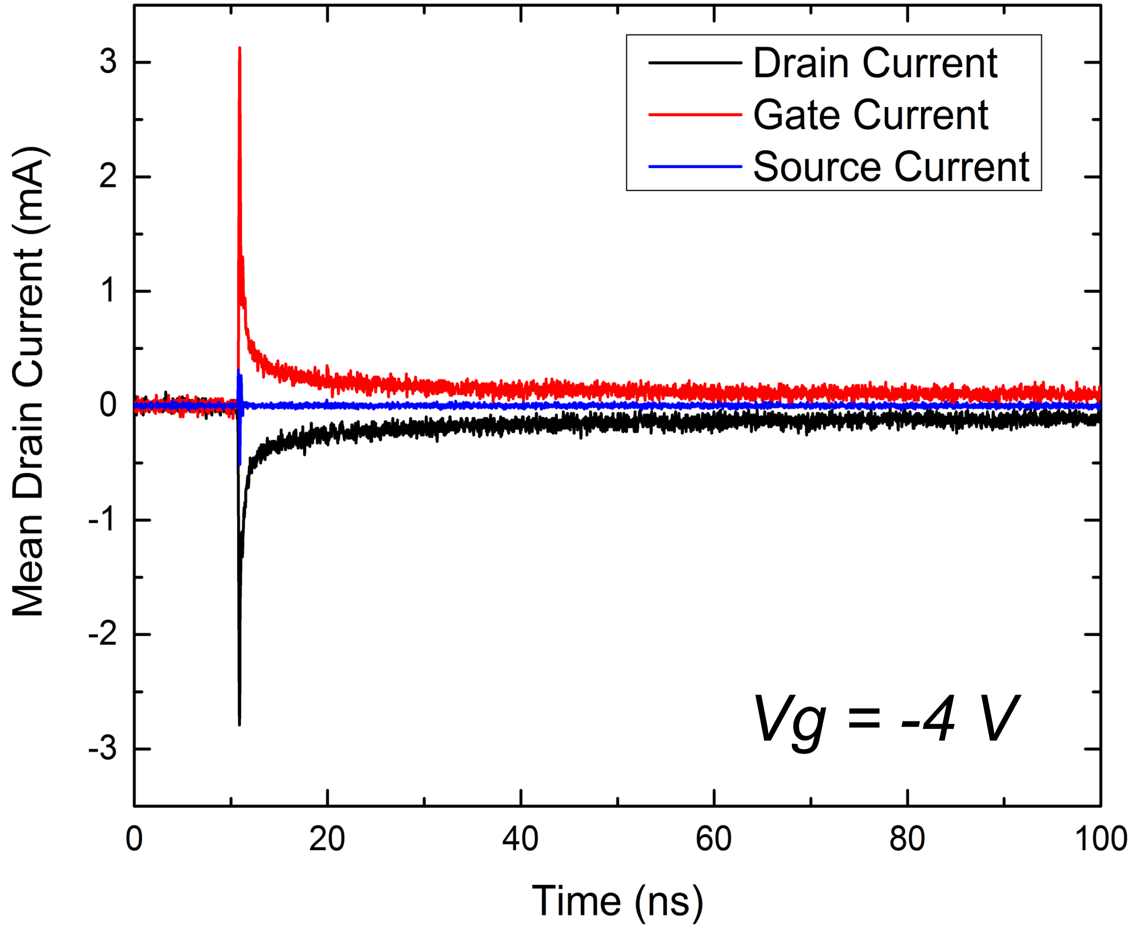


Loveless, et al., IEEE TNS 57, 2933 (2010)

Loveless, et al., NSREC 2019, Paper PB-2

Key Feature of PL SEE: Spatial Selectivity



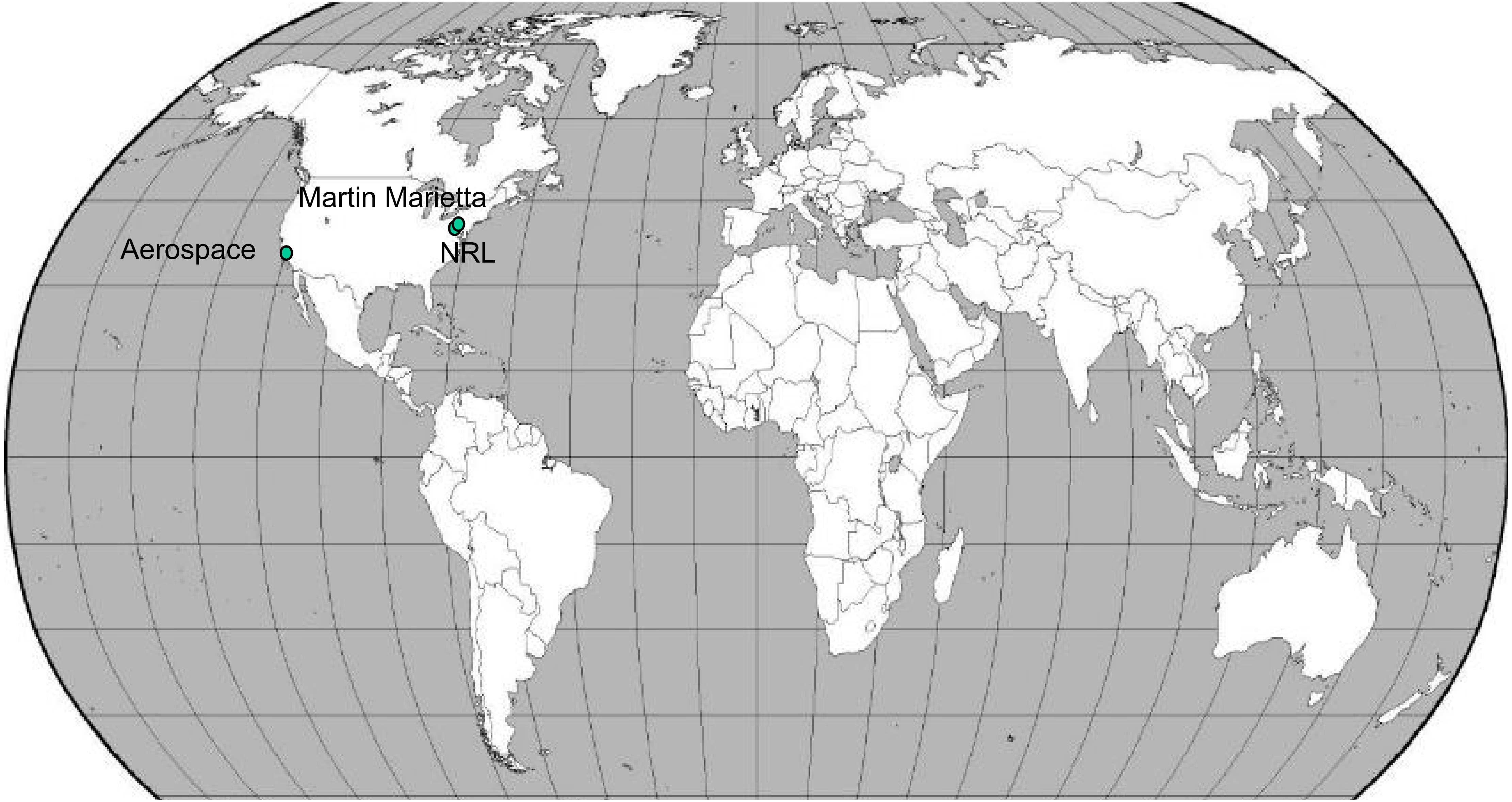


- The shapes of the transients provide insights into the nature and density of defects and traps
- Hotspots appear to arise from regions of high trap density, presumably associated with threading dislocations

Khachatrian, et al., IEEE TNS 63, 1995 (2016)

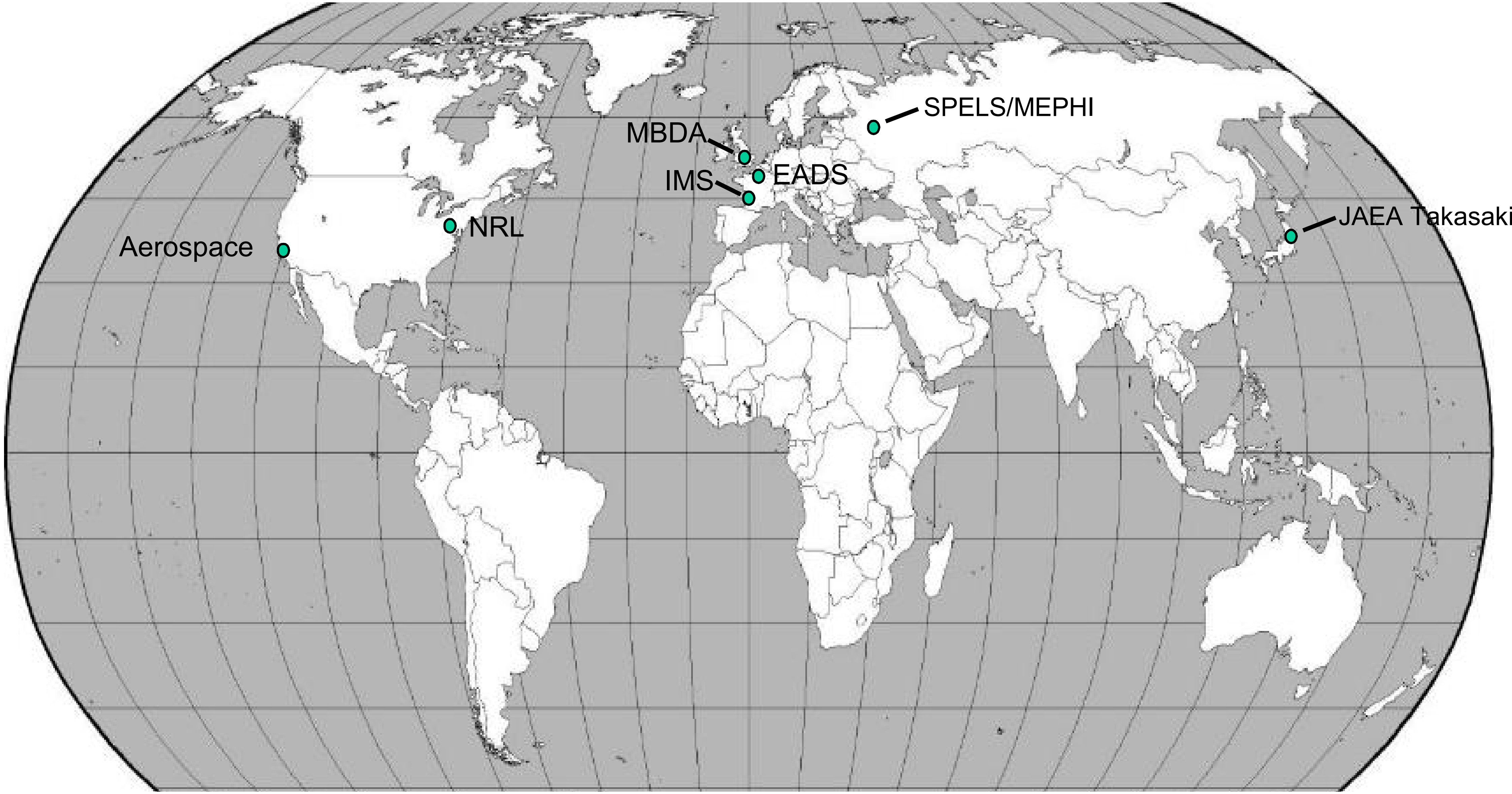
Global Laser SEE Testing Facilities

1991



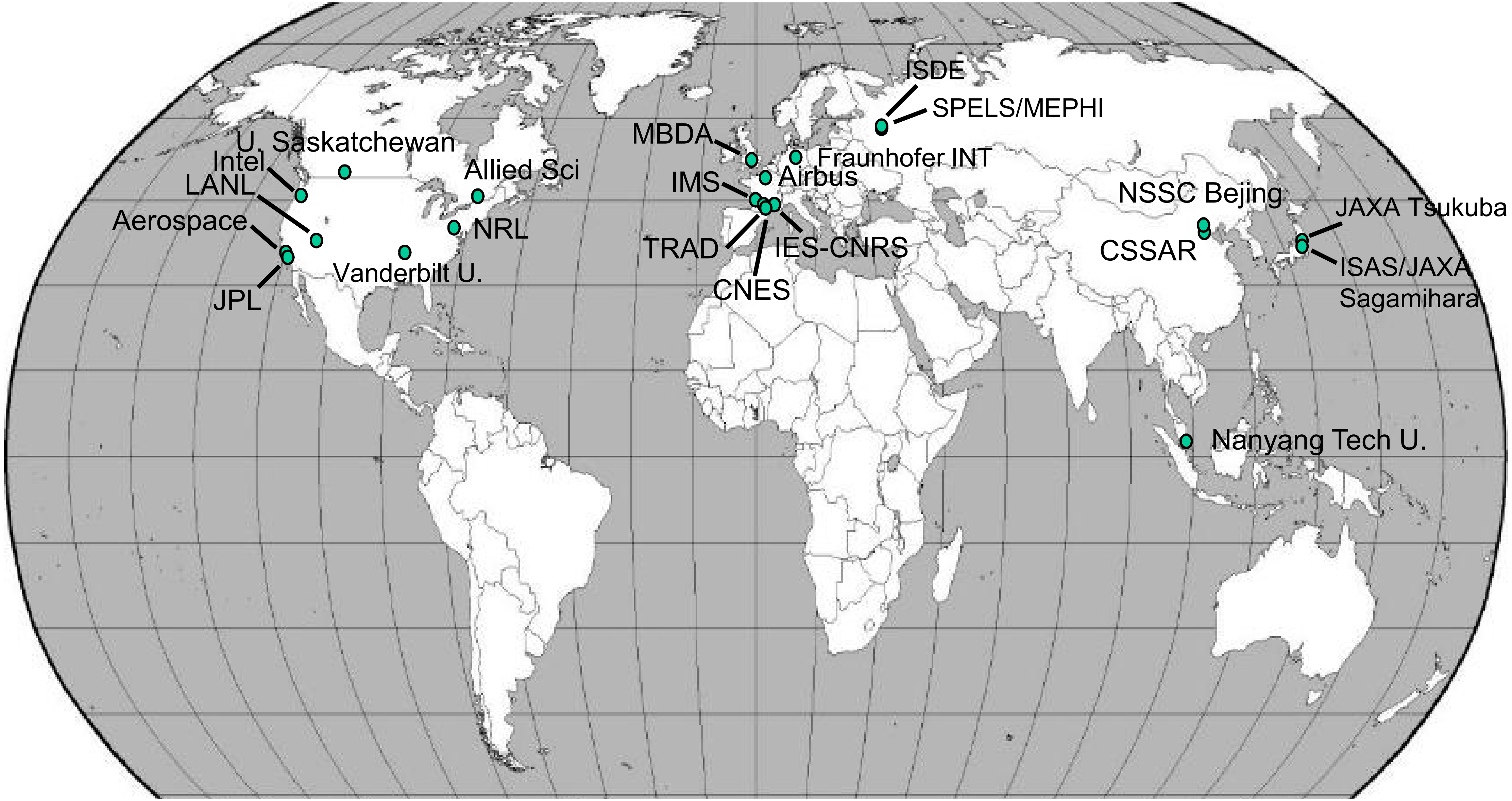
Global Laser SEE Testing Facilities

2005



Global Laser SEE Testing Facilities

2019



Pulsed Laser Single-Event Effects

- **Single-Photon Absorption (SPA)**
  - *Excitation above the semiconductor bandgap*

    Can inject:
    - a well-characterized quantity of charge
    - in a well-defined *x-y* location
    - with a well-defined charge-deposition profile
    - at a well-defined time

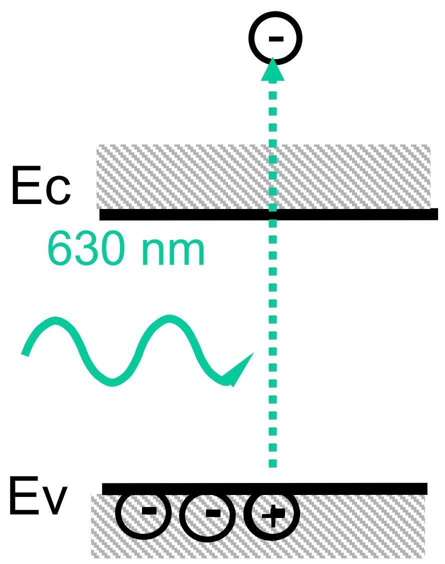
Two-Photon Absorption (TPA, 2PA)

- *Excitation (typically) below the semiconductor bandgap*

  Can inject charge:
  - a well-characterized quantity of charge
  - in a well-defined *x-y-z* location
  - with a well-defined charge-deposition profile
  - at a well-defined time
  - and can propagate through silicon wafers
  - more difficult to quantify

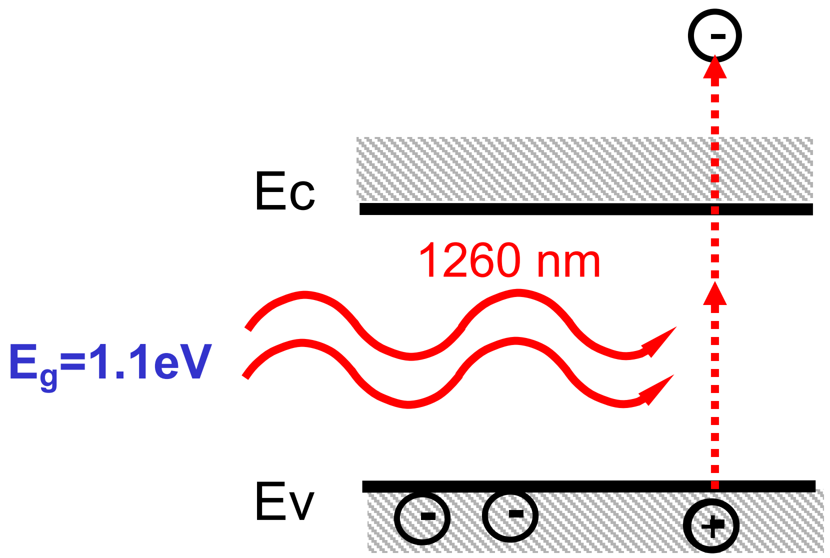
Optical Excitation of Carriers in Silicon

<u>**1-Photon**</u>



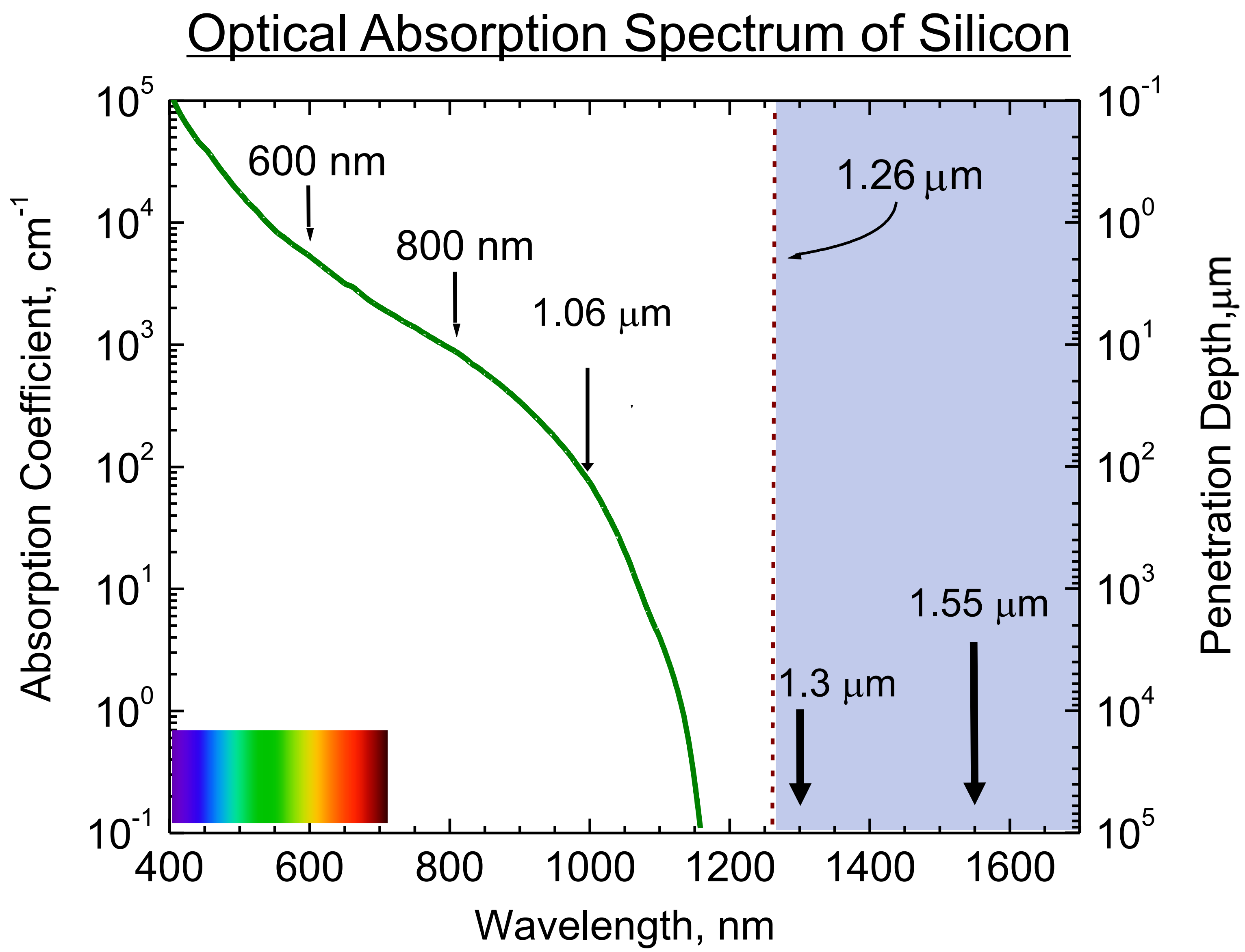
- ***Single photon absorbed***
- ***By the material (silicon)***
- ***Creates a single e-h pair***

<u>**2-Photon**</u>

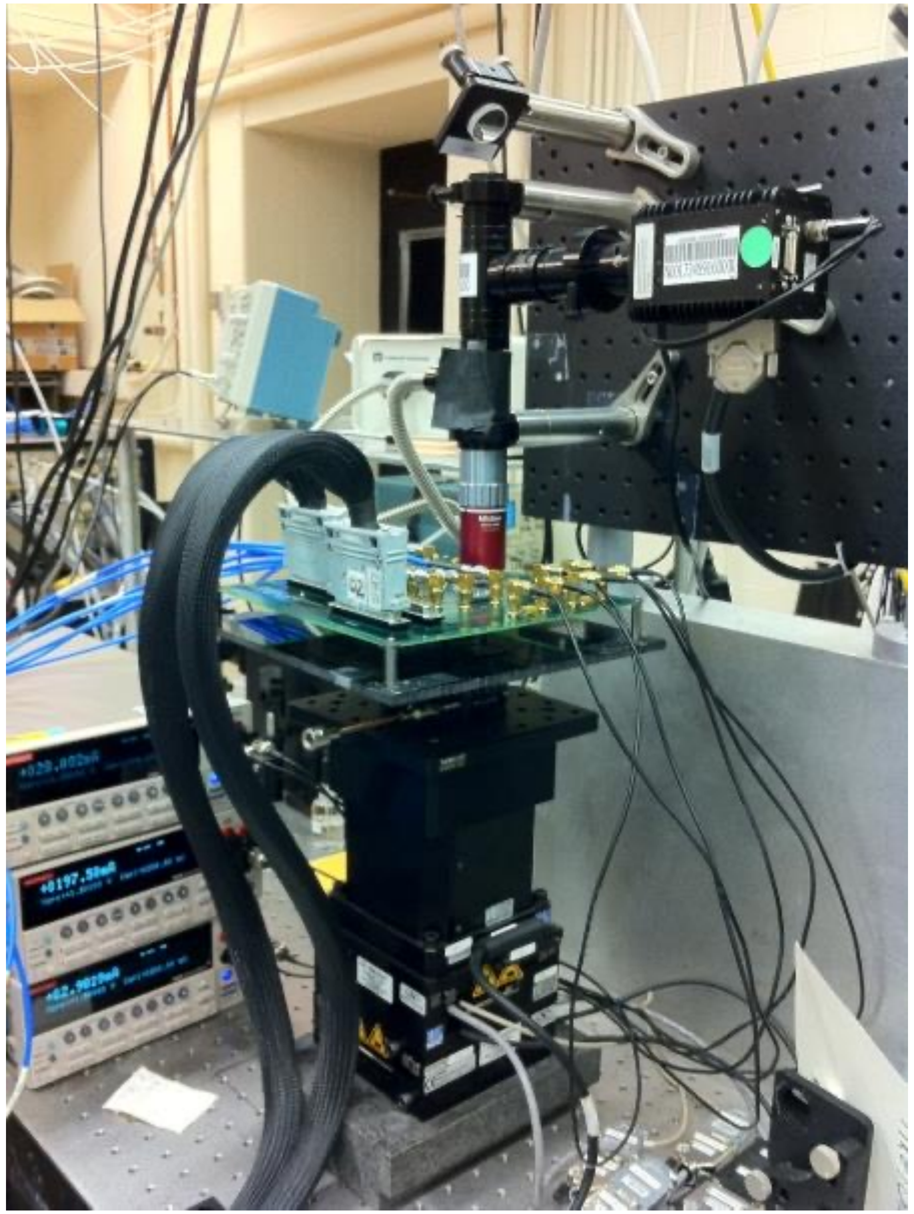


- ***Two photons absorbed***
- ***By the material (silicon)***
- ***Simultaneously***
- ***Creates a single e-h pair***

Linear and Nonlinear Optical Absorption in Si

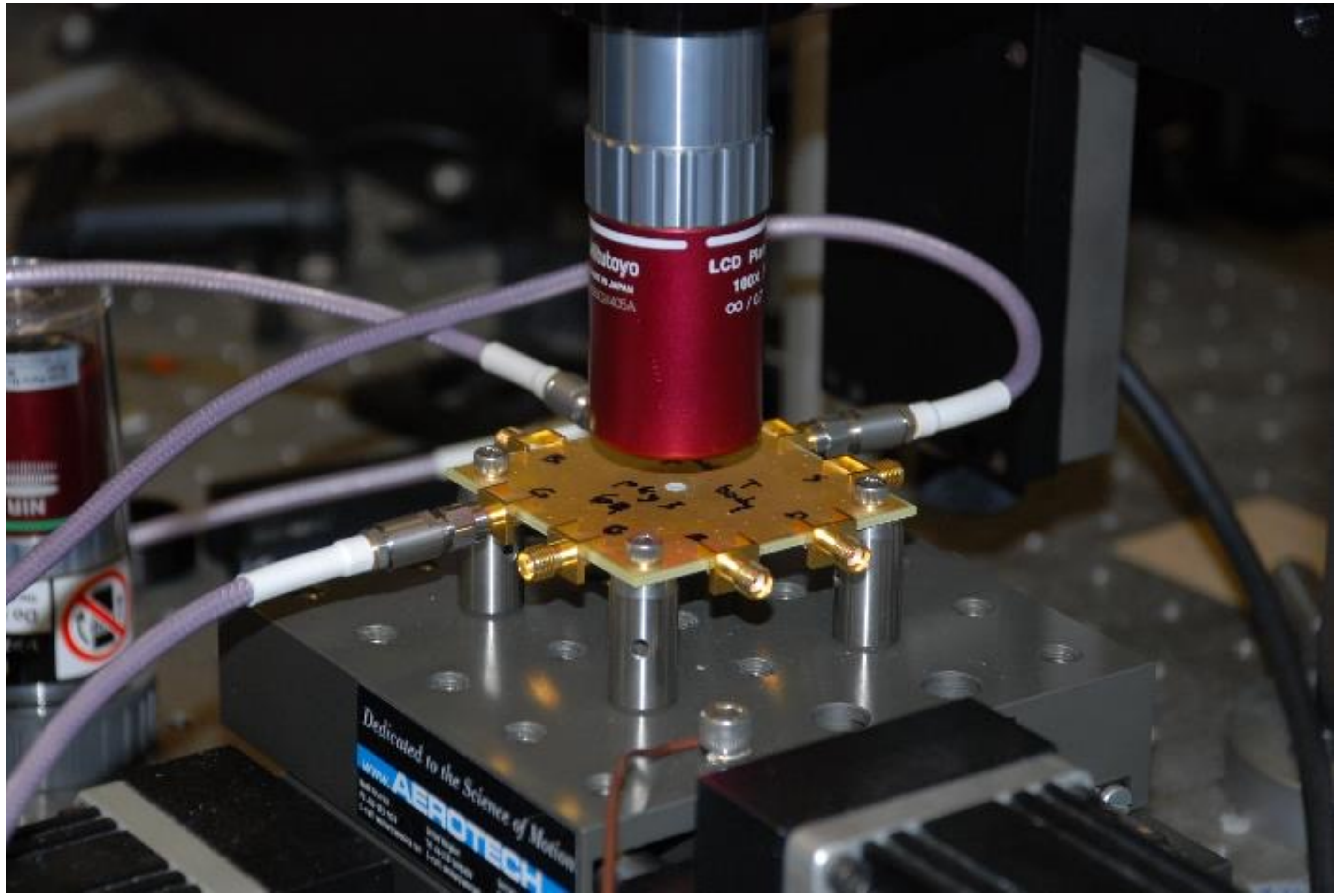


Pulsed Laser Single-Event Effects

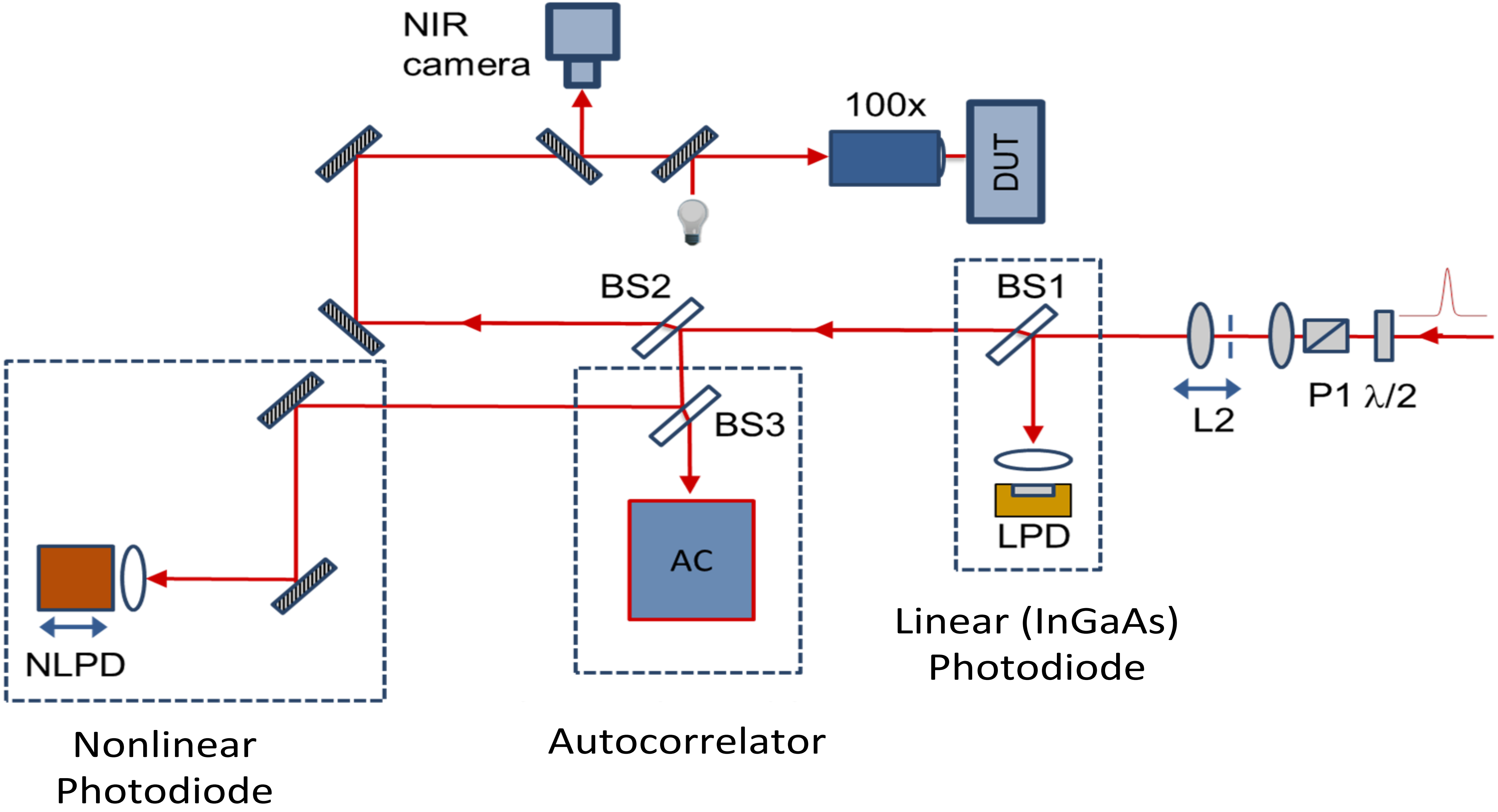


45 nm RHBD
PLL test

Pulsed Laser Single-Event Effects



Pulsed Laser Single-Event Effects



Pulsed Laser Single-Event Effects
Nonlinear Beam Propagation

Optical beam propagation, optically thin media:

Carrier generation equation:
$$\frac{dN(r,z,t)}{dt} = \frac{\alpha I(r,z,t)}{(hc/\lambda)} + \frac{1}{2}\frac{\beta_2 I(r,z,t)^2}{(hc/\lambda)}$$

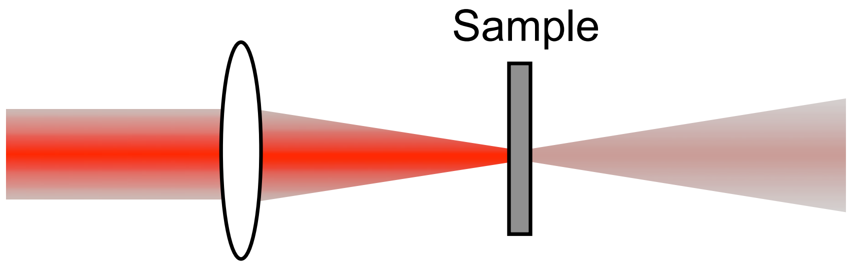
Irradiance equation:
$$\frac{dI(r,z,t)}{dz} = -\alpha I(r,z,t) - \beta_2 I(r,z,t)^2 - \sigma_{FCA} N(r,z,t) I(r,z,t)$$

Phase equation:
$$\frac{d\Phi(r,z,t)}{dz} = k_0 n_0 + k_0 n_2 I(r,z,t) - \sigma_{FCR} N(r,z,t)$$

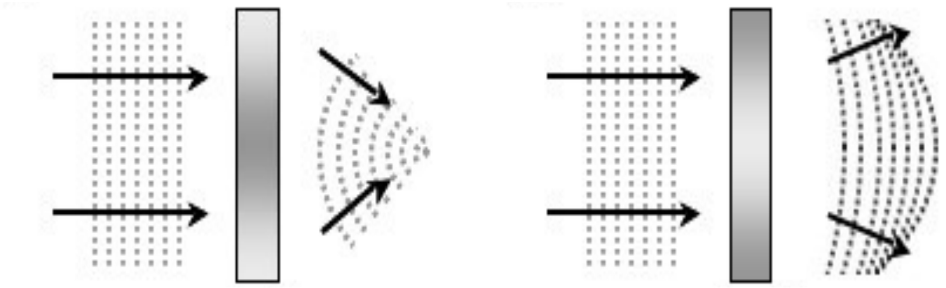
α	*linear absorption coefficient*
β_2	*two-photon absorption coefficient*
n_o	*index of refraction*
n_2	*nonlinear index of refraction*
σ_{FCA}	*free carrier absorption cross section*
σ_{FCR}	*free carrier refraction cross section*

Pulsed Laser Single-Event Effects
Nonlinear Beam Propagation

Two-photon absorption (TPA), β

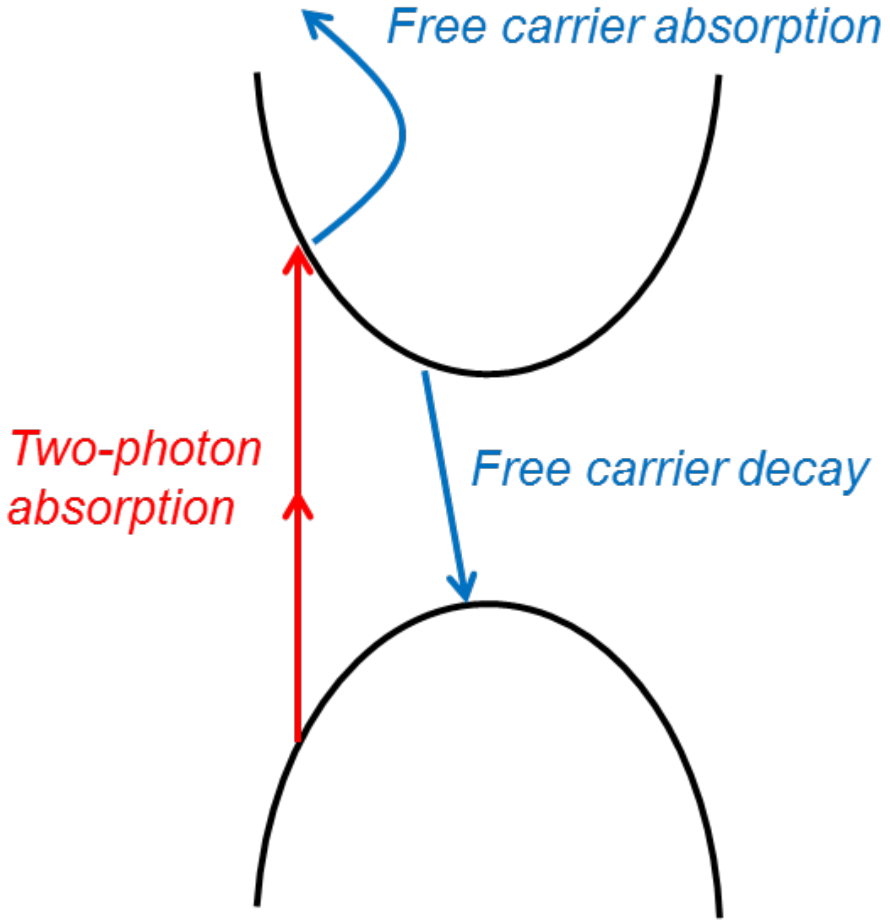


Nonlinear refraction (NLR), n_2
Free-carrier refraction (FCR),



$n_2 > 0$ $\sigma_{FCR} < 0$

Free-carrier absorption (FCA), σ_{FCA}



Modeling TPA Charge Deposition: More Rigorous Approach Required

Table I

Comprehensive Approaches for Simulating Laser-Generated CDs

	NLOBPM	Gaussian Matrix	Lumerical
Developed	NRL, 2014	U. Montpellier, 2013	Vanderbilt, 2018
Algorithm	FDTD	ABCD Matrix Method	FDTD
Strengths	• Comprehensive NLO • Comprehensive focusing • Validated	• Comprehensive NLO • Computation speed • Facile implementation	• Comprehensive NLO • Comprehensive focusing • Nanophotonic effects
Limitations	• Cylindrical symmetry • Inaccessible source code	• Only Gaussian beam • Paraxial approximation	• Computation resources/time • Commercial cost
References	• [44, 48, 55, 59]	• [60]	• [61-63]

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:

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

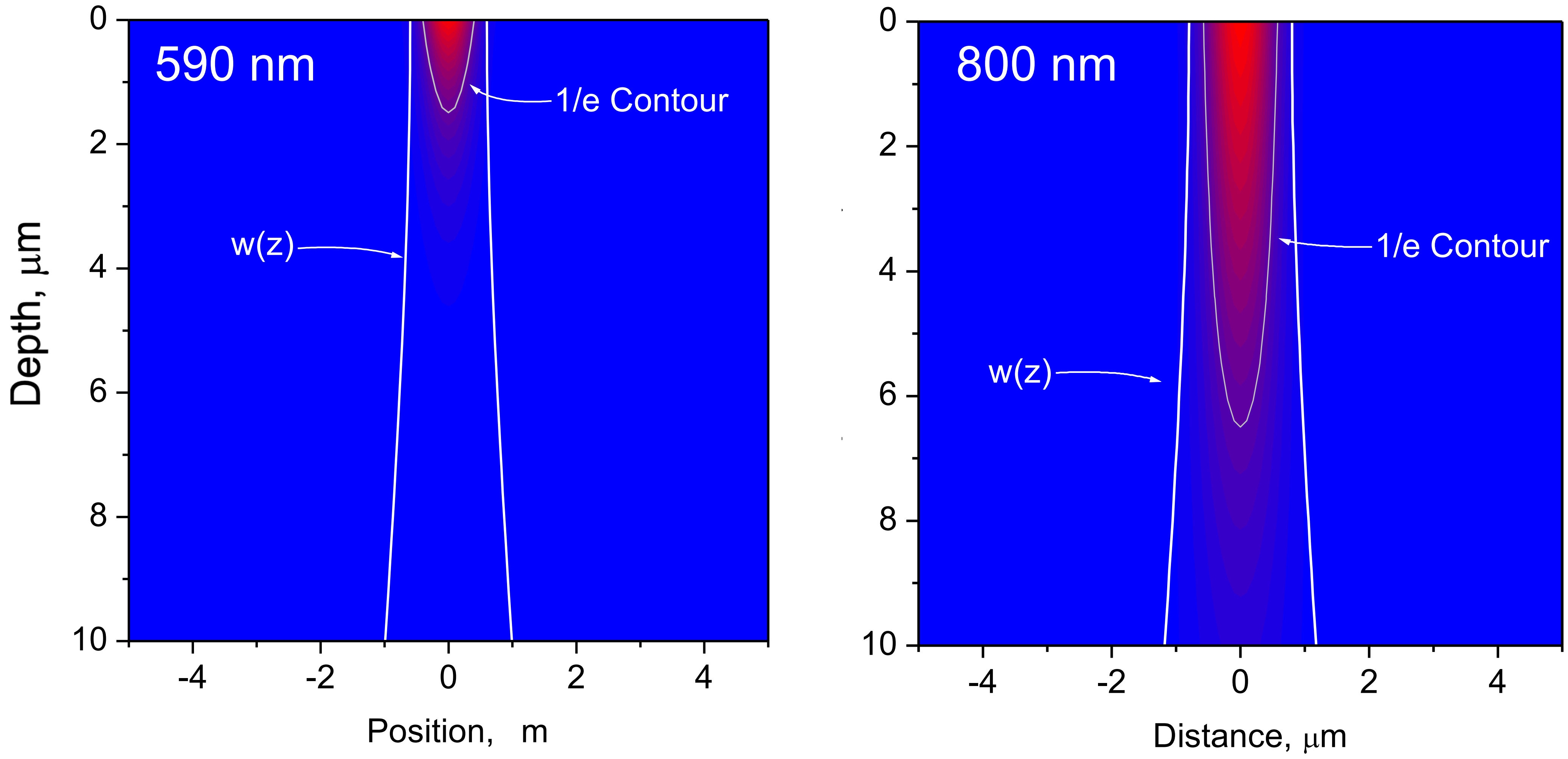
Carrier Generation:

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

Beer-Lambert Law

Carrier Density Distribution
Above-Band-Gap Single Photon Absorption

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



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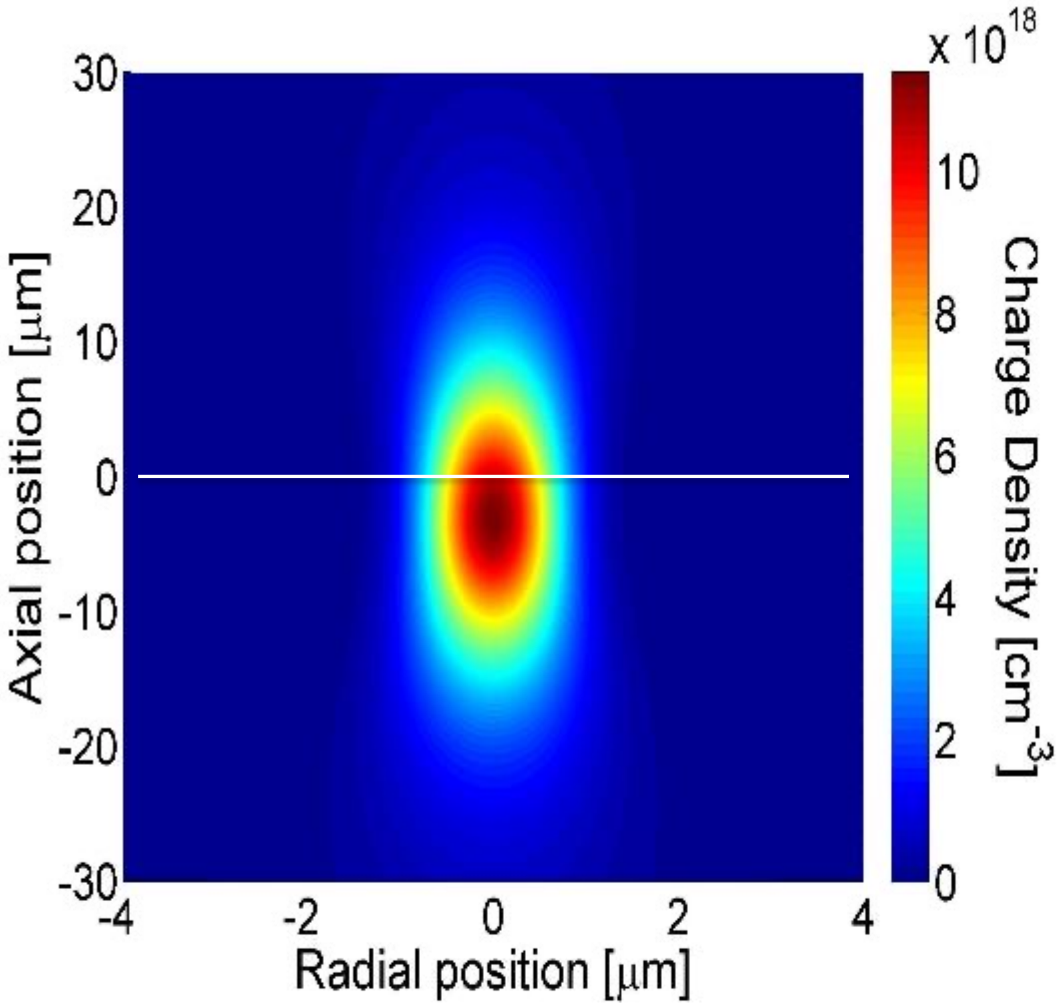
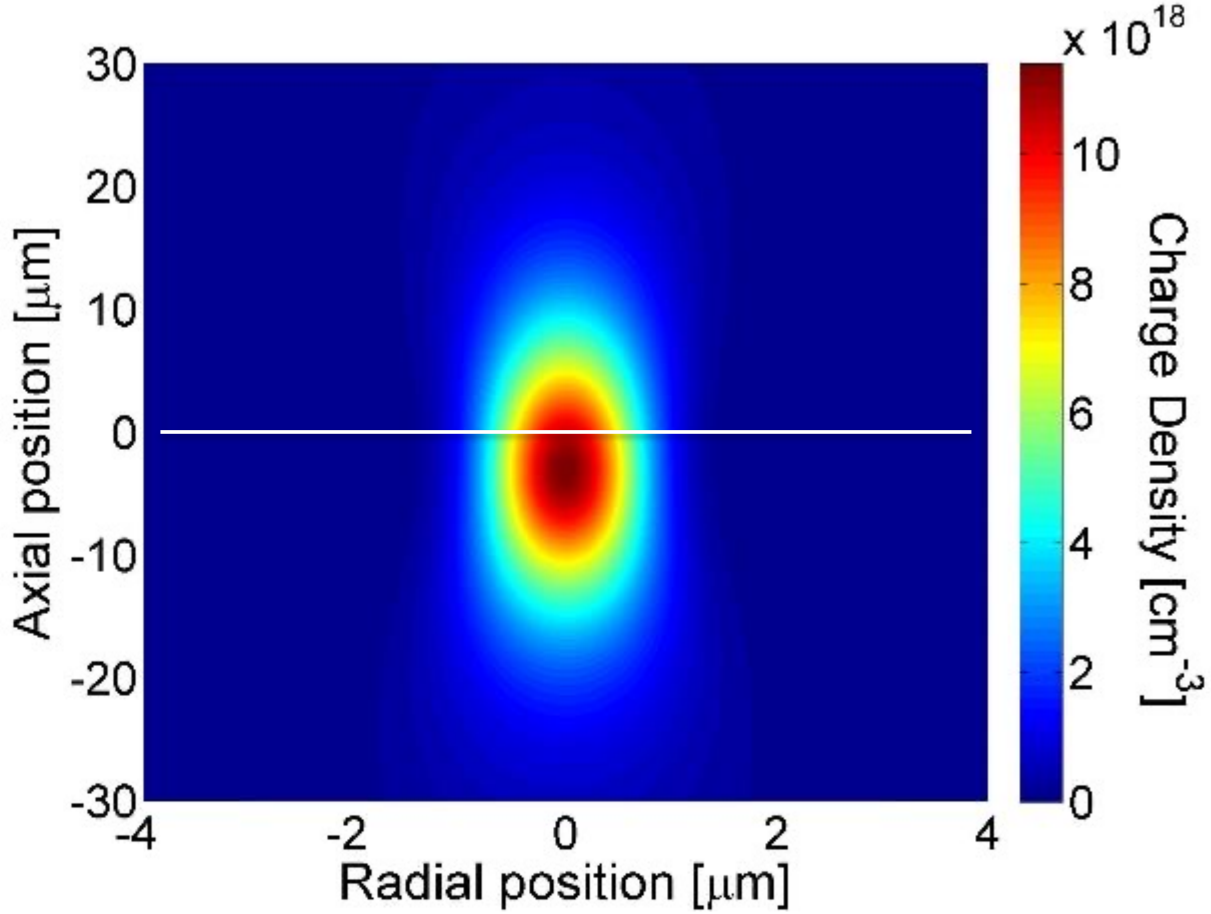
Beer-Lambert Law

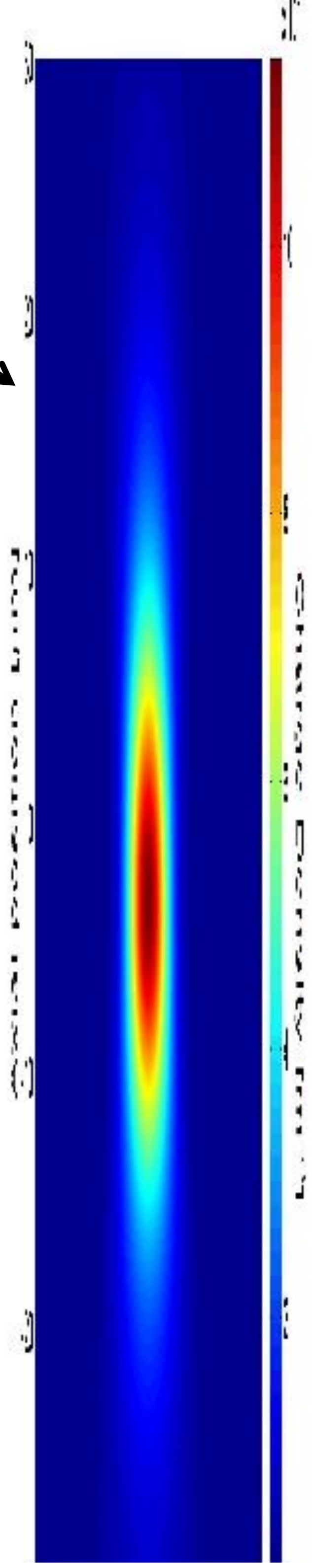
Charge Generation by Two-Photon Absorption



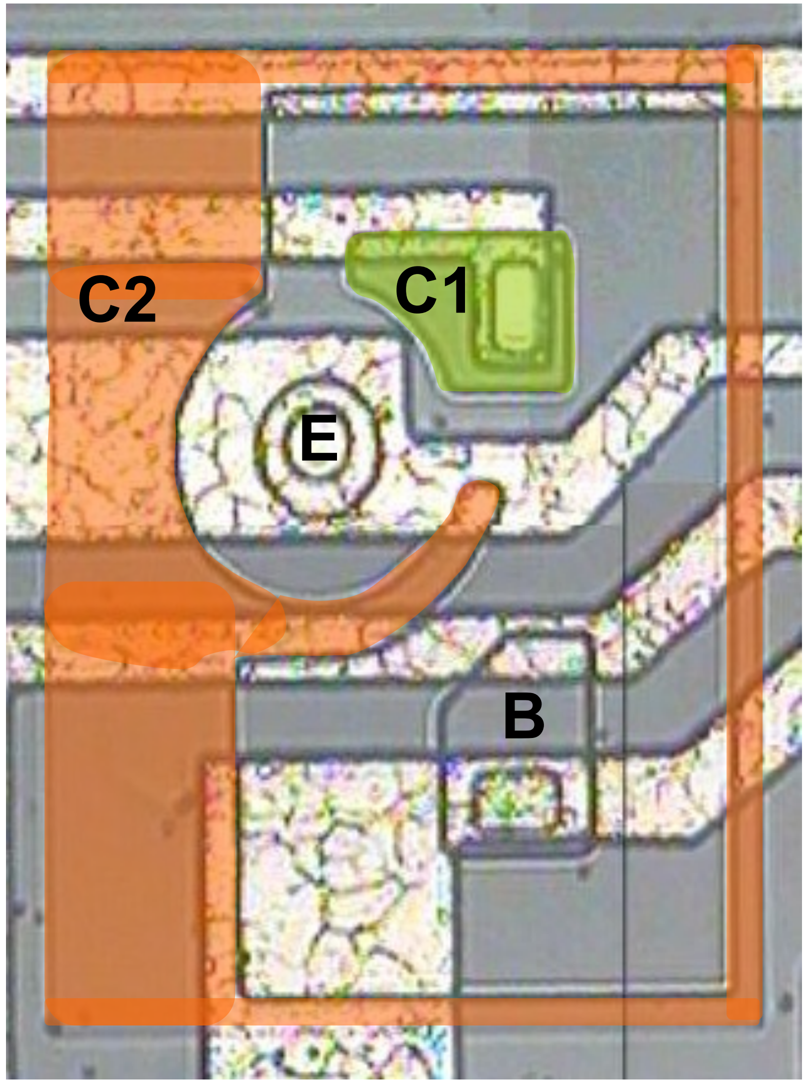
- Most efficient in *the high-irradiance region* near the focus of the beam
  - Because of I^2 dependence
  - Lack of exponential attenuation
- Carriers can be ***injected at any depth*** in the material
- Optimizing TPA generation:
  - Tight focus
  - Short pulse (~150 fs)
  - High pulse energy

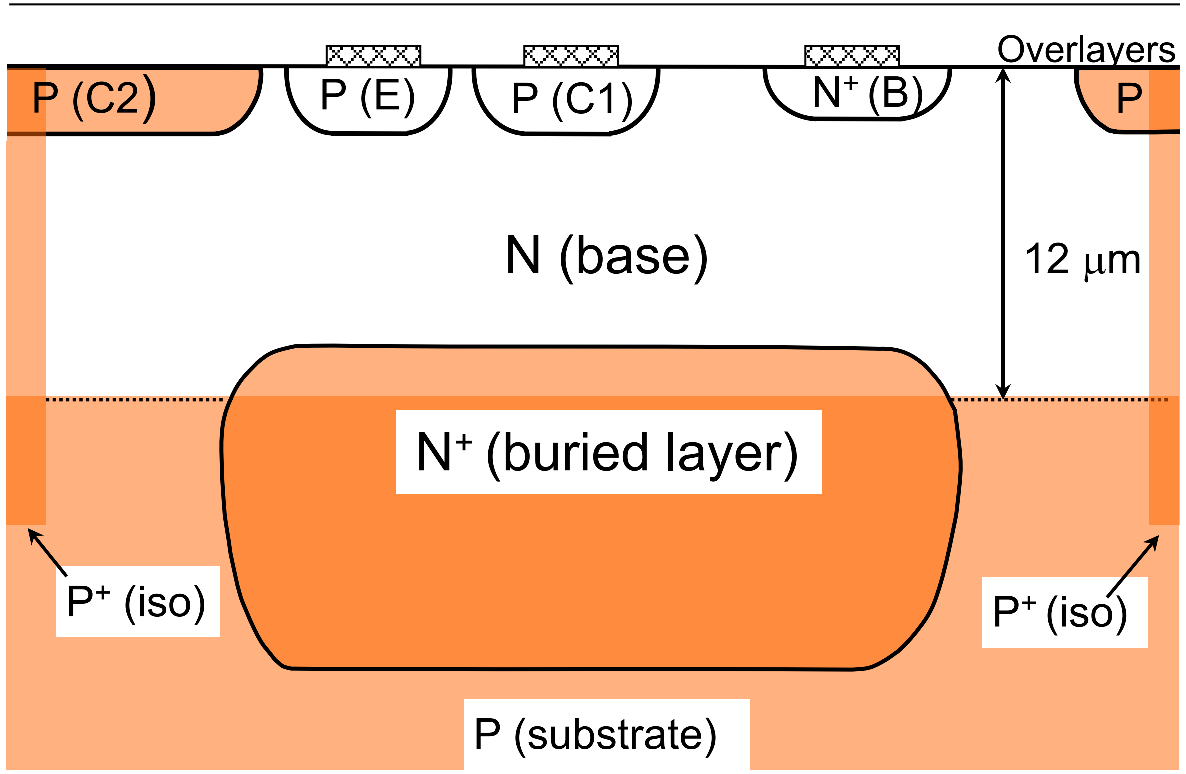
Correct aspect ratio



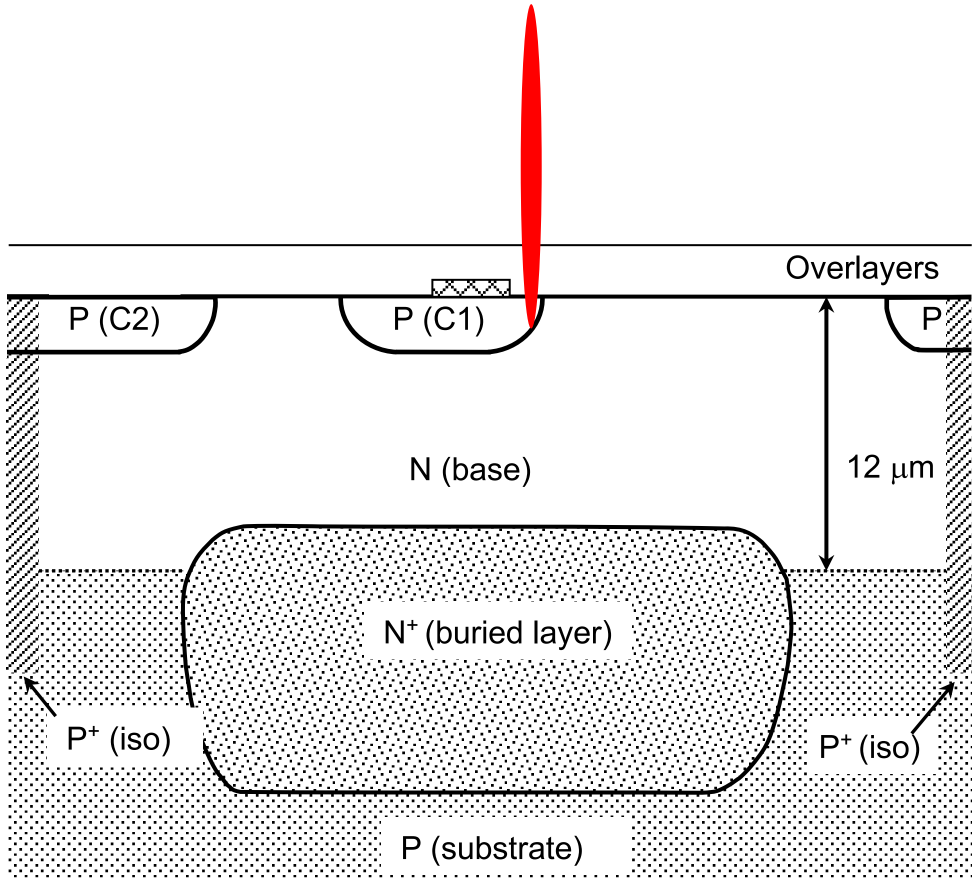


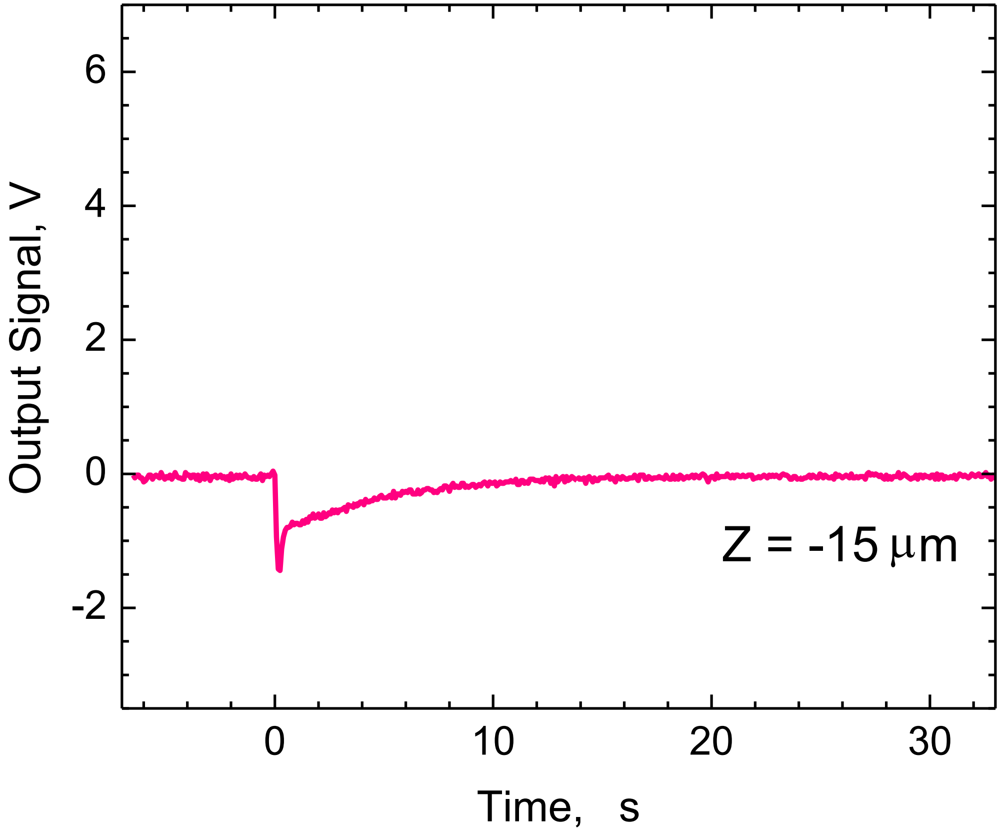
Three-Dimensional Mapping of SEE Sensitivity
(LM124 Q20: General Characteristics)





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





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

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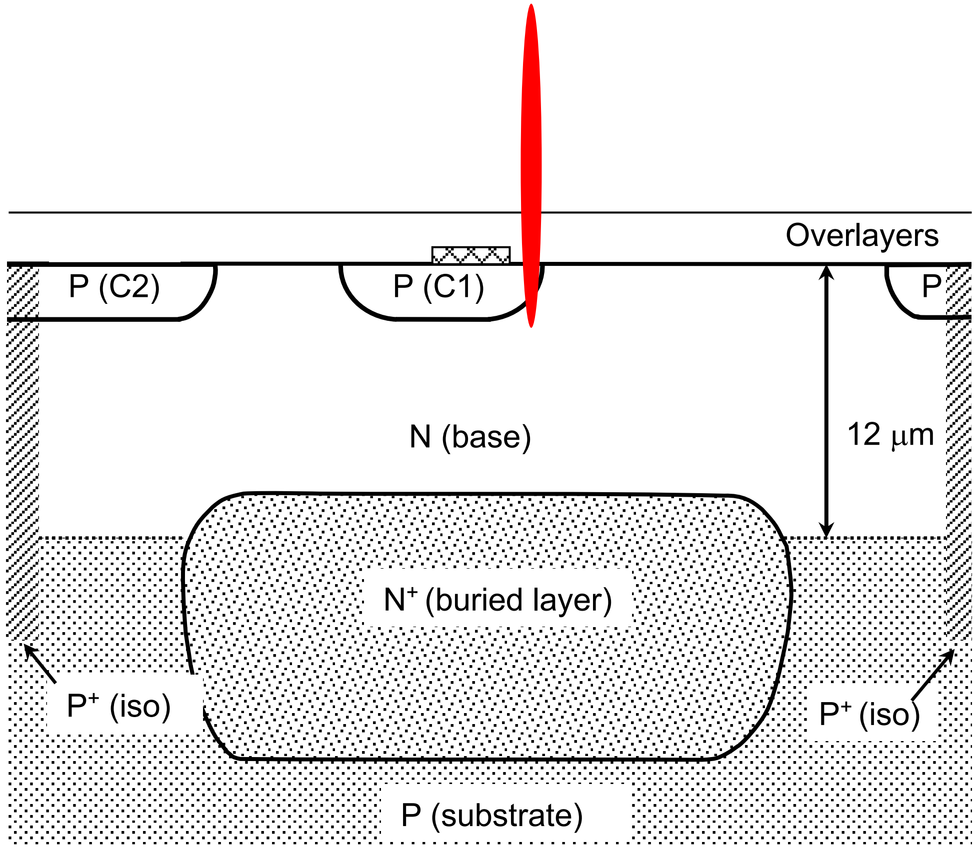

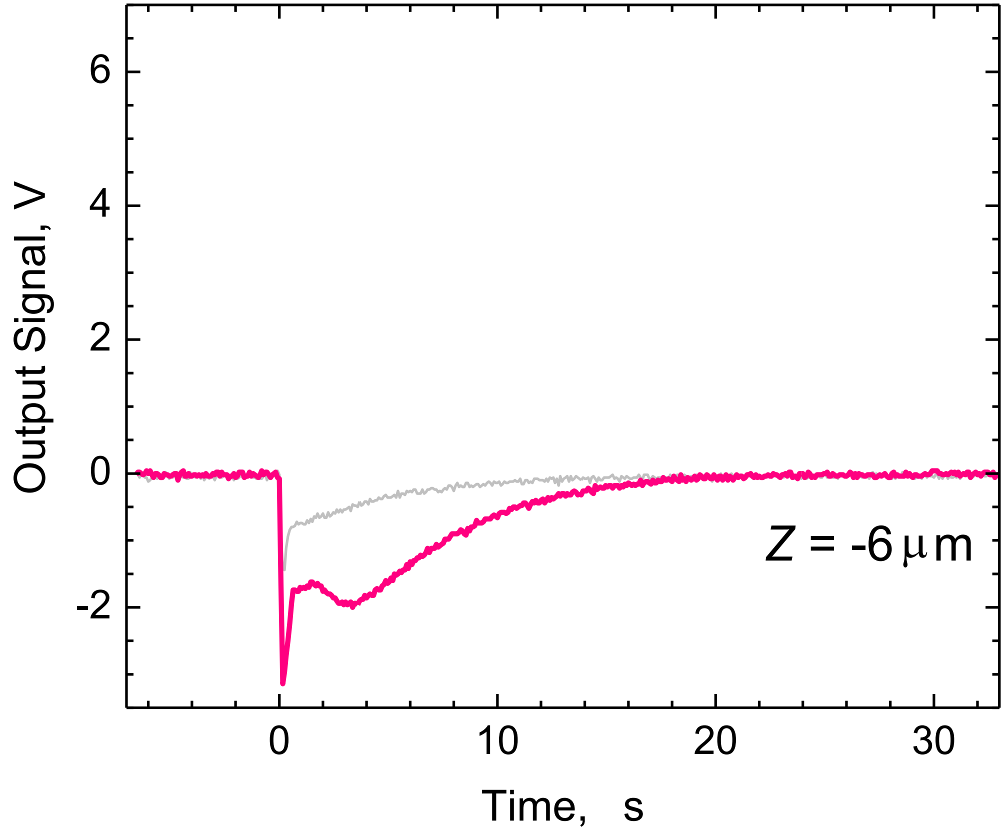

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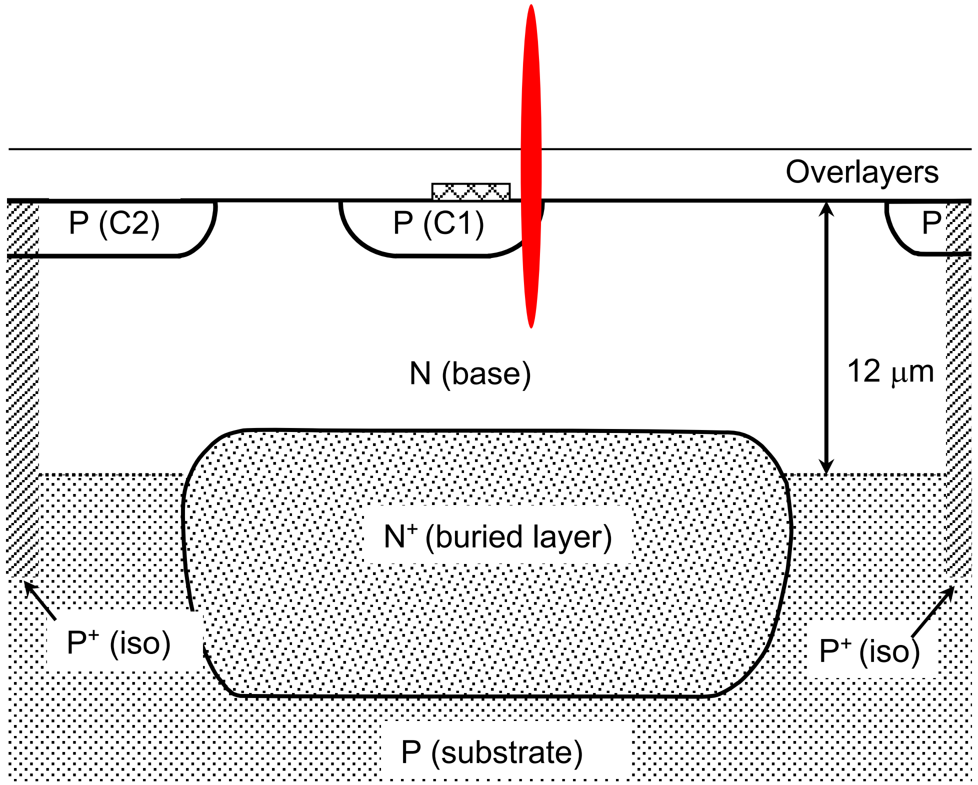

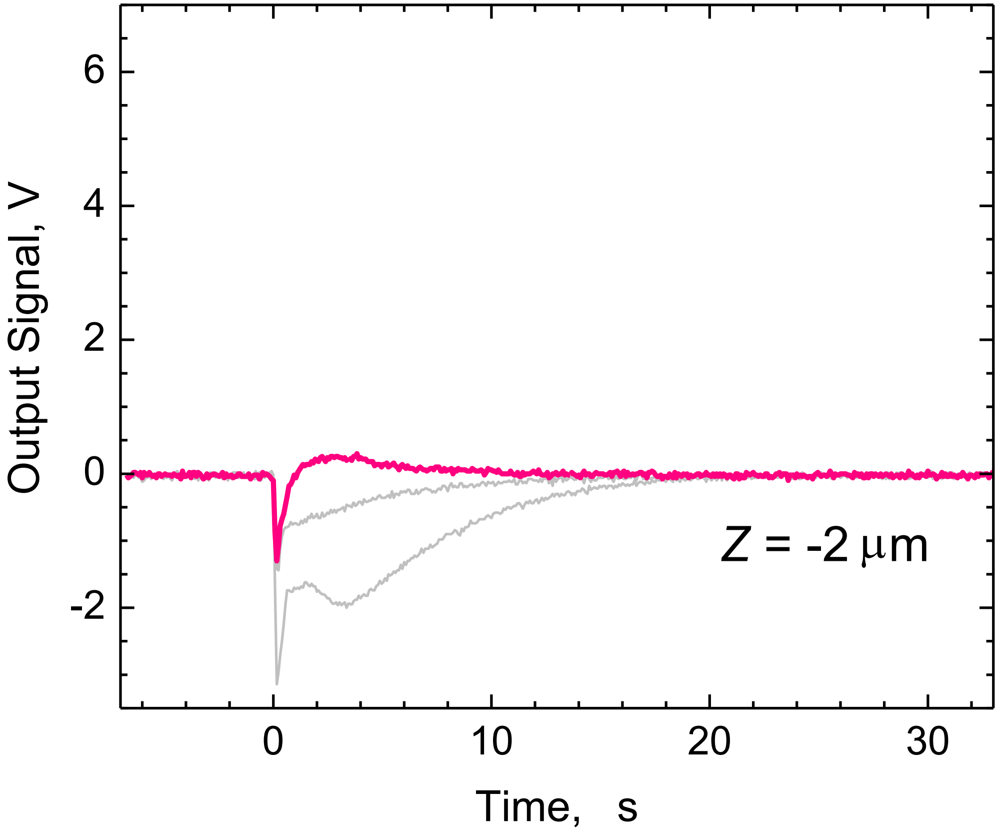

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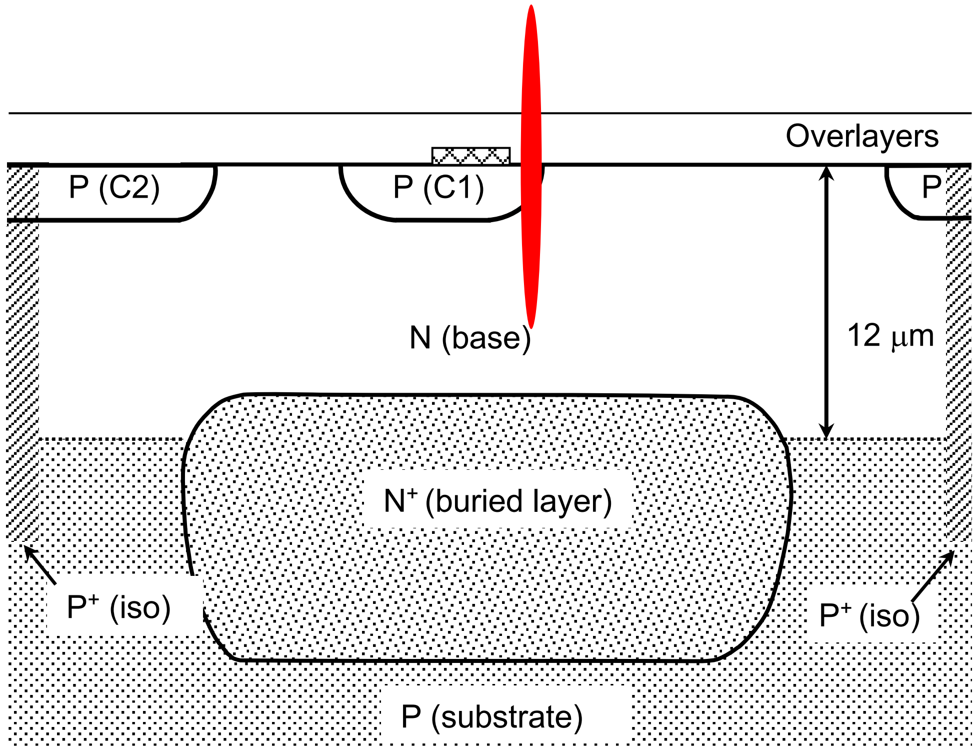

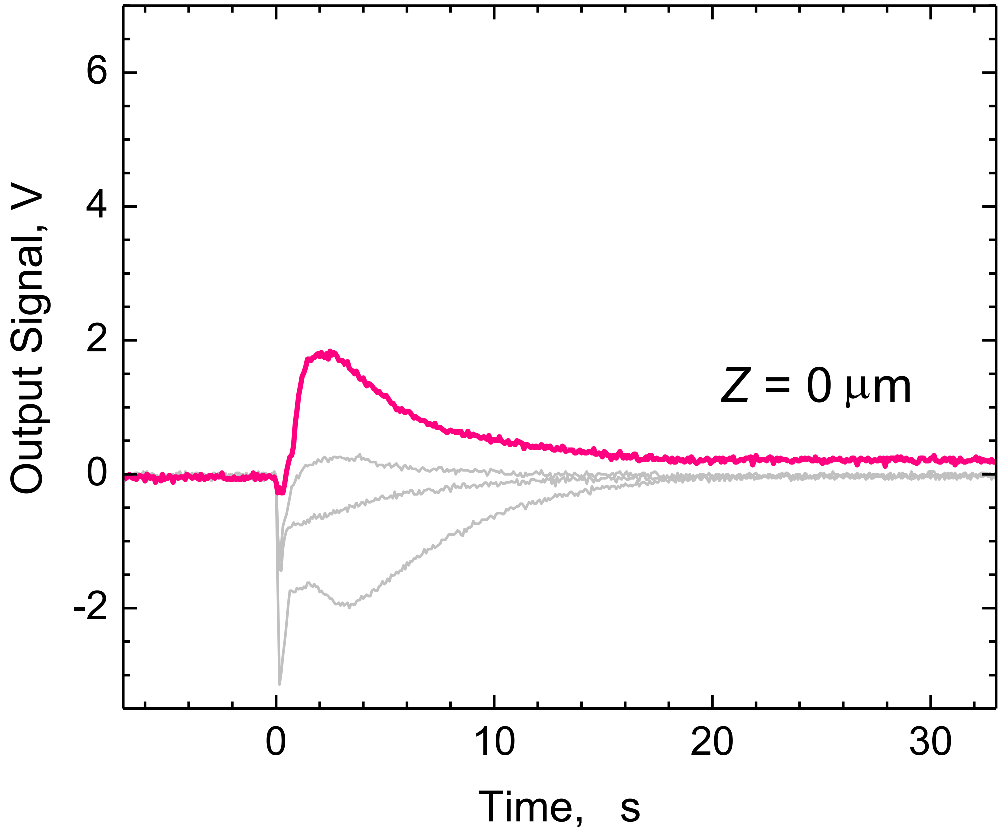

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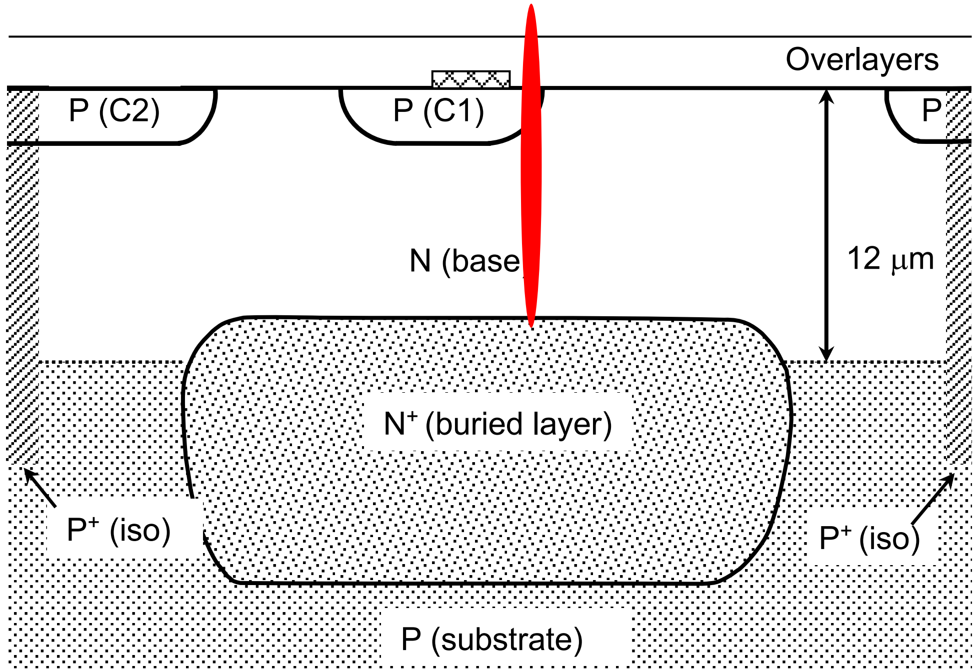

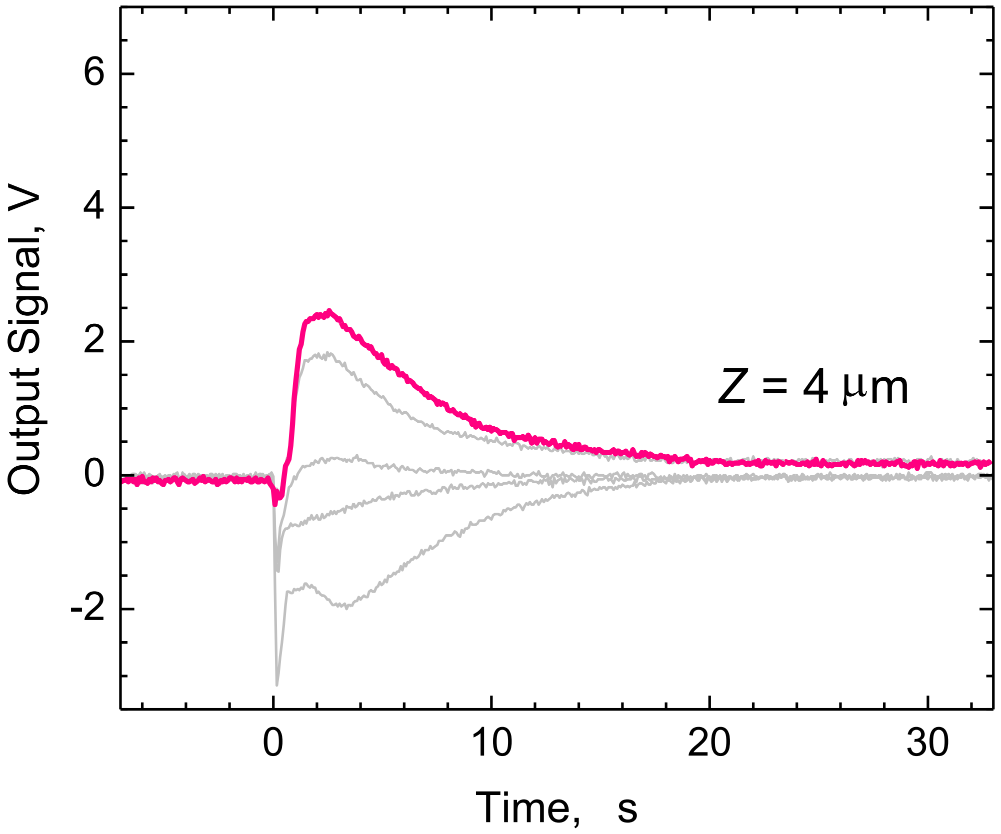

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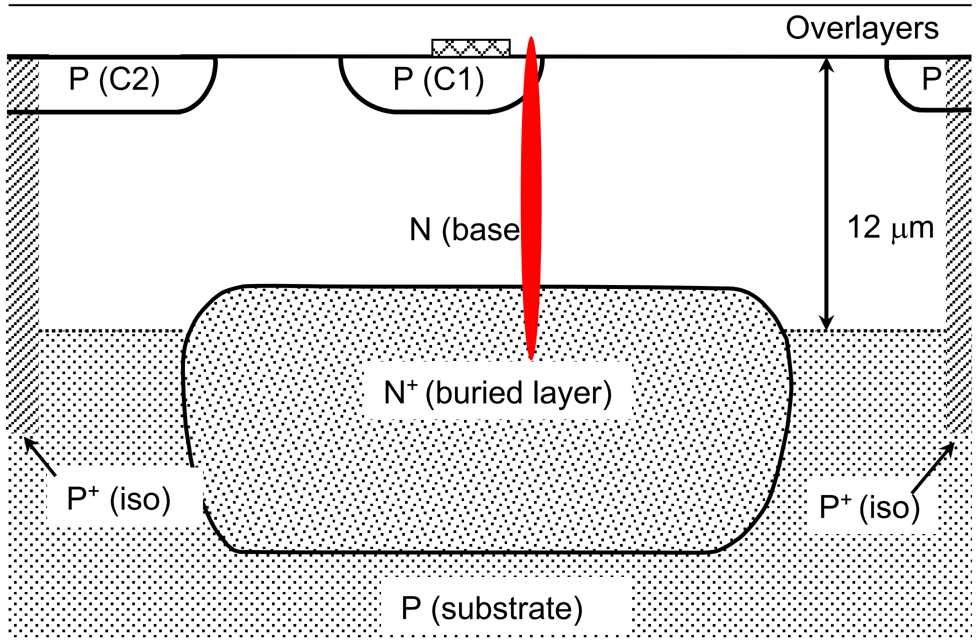

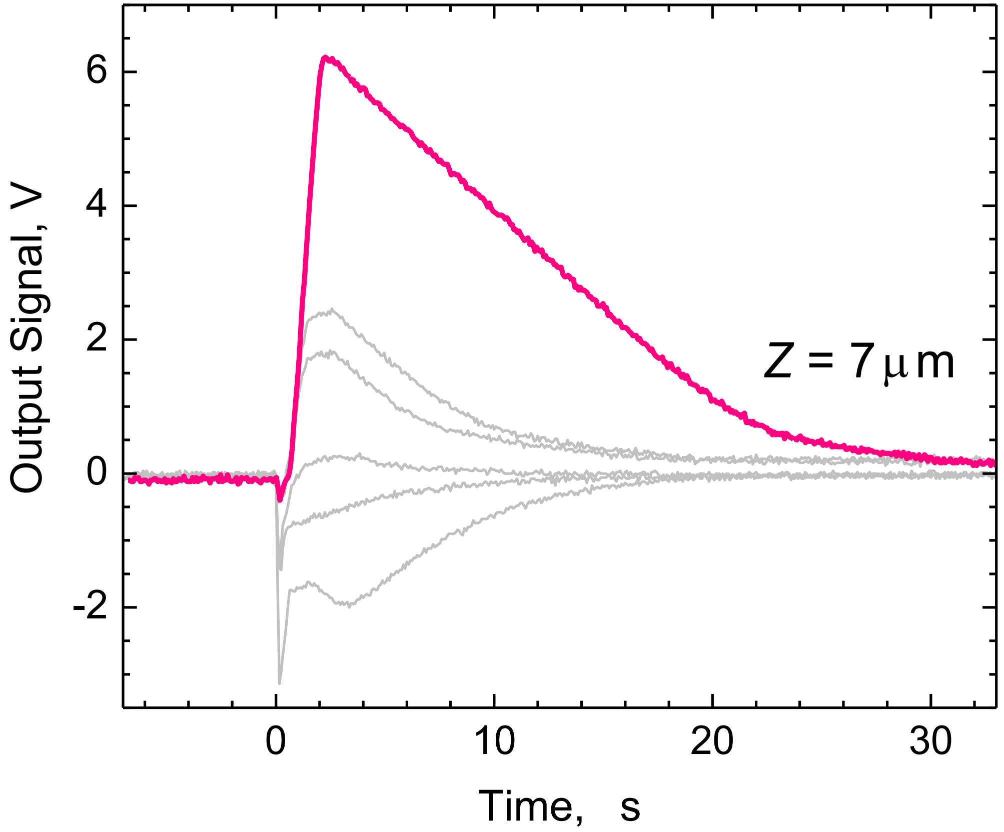

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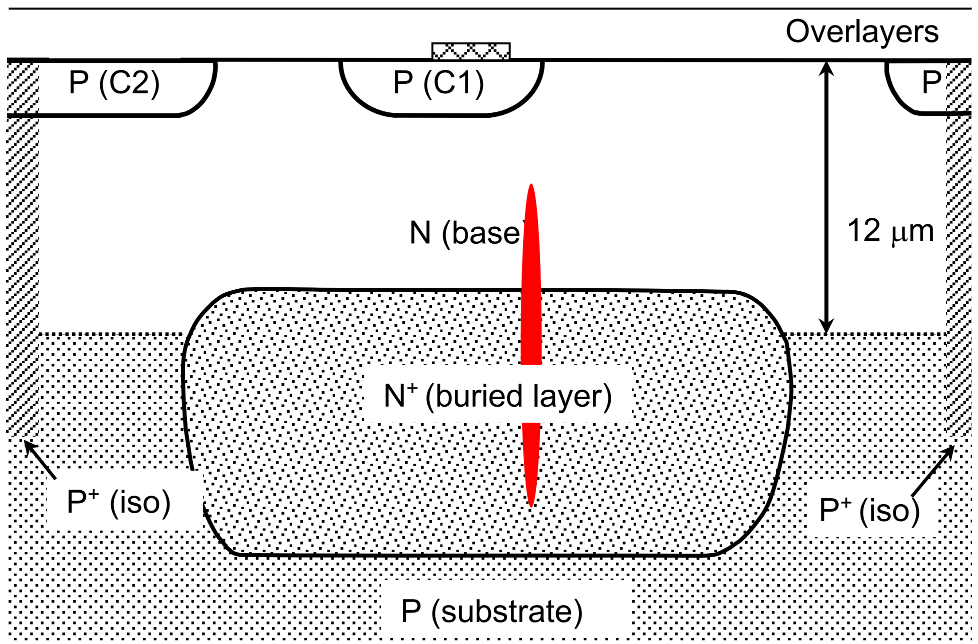

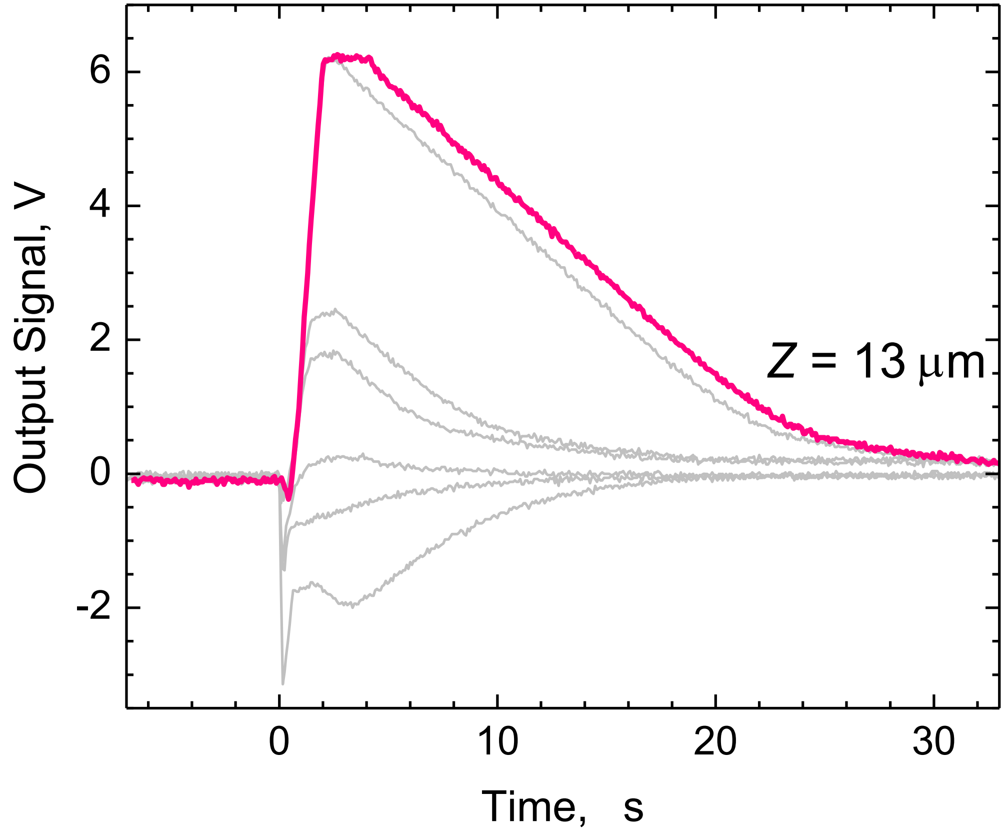

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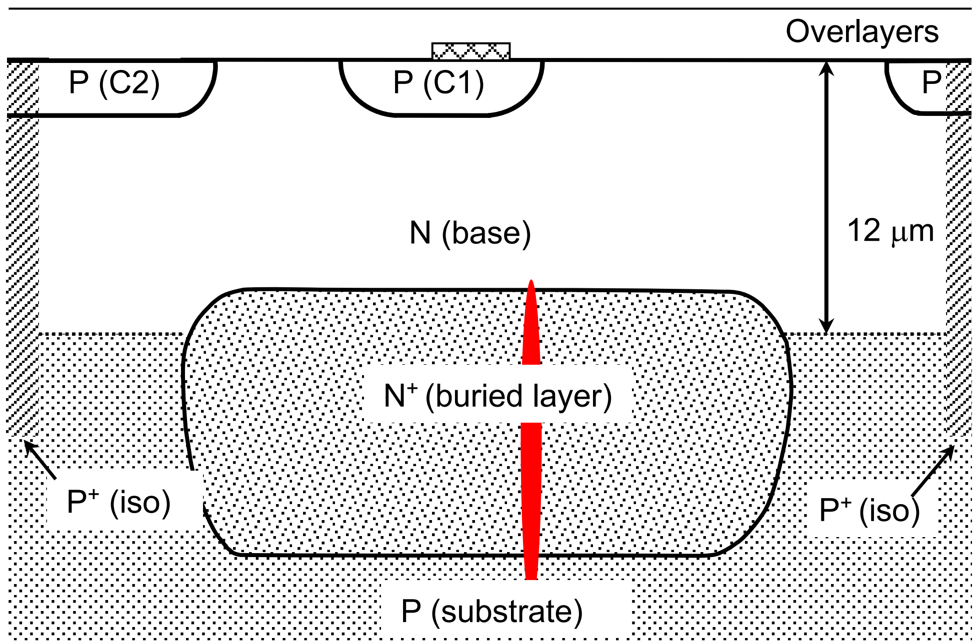

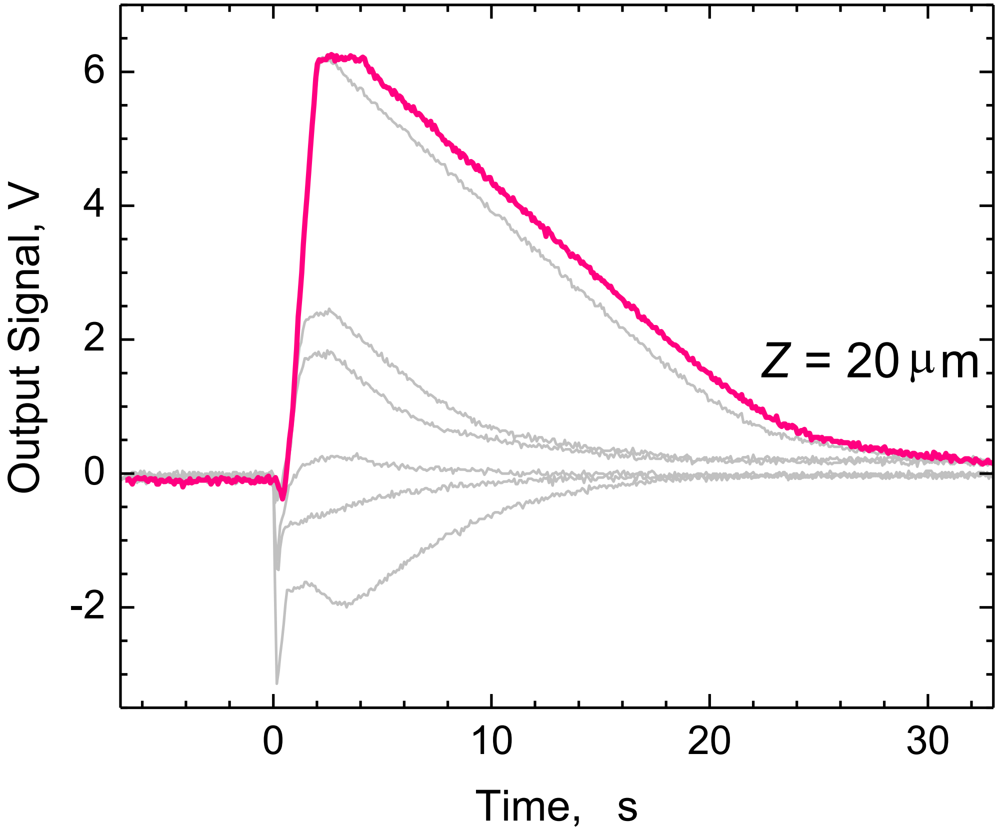

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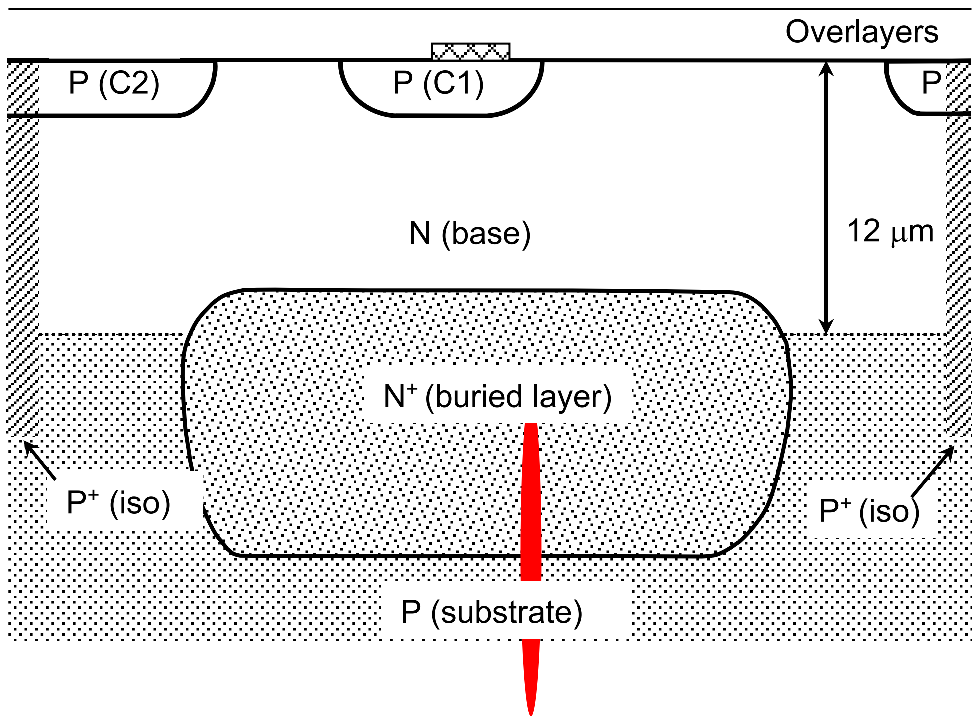

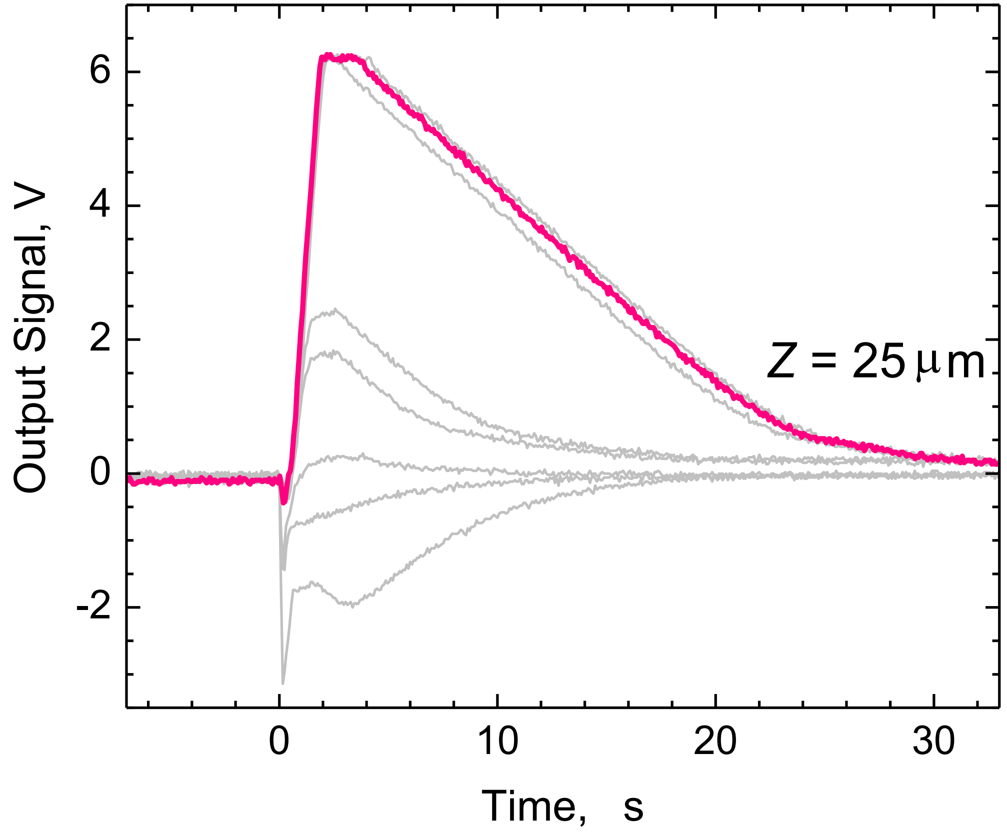

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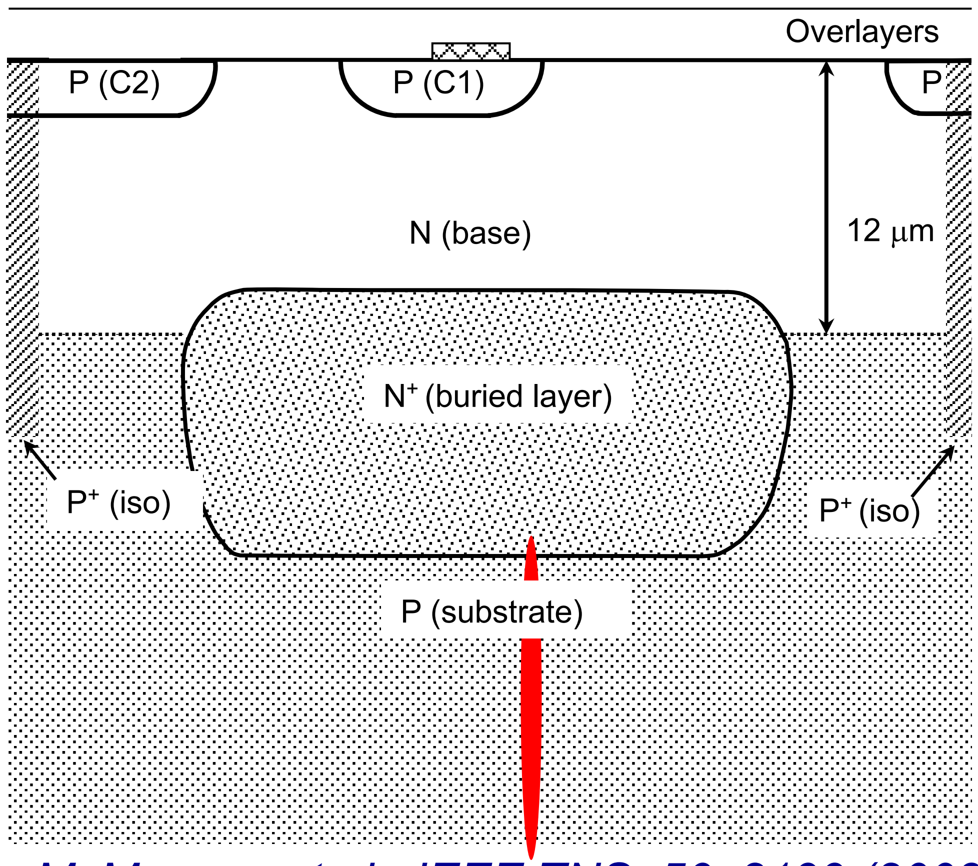

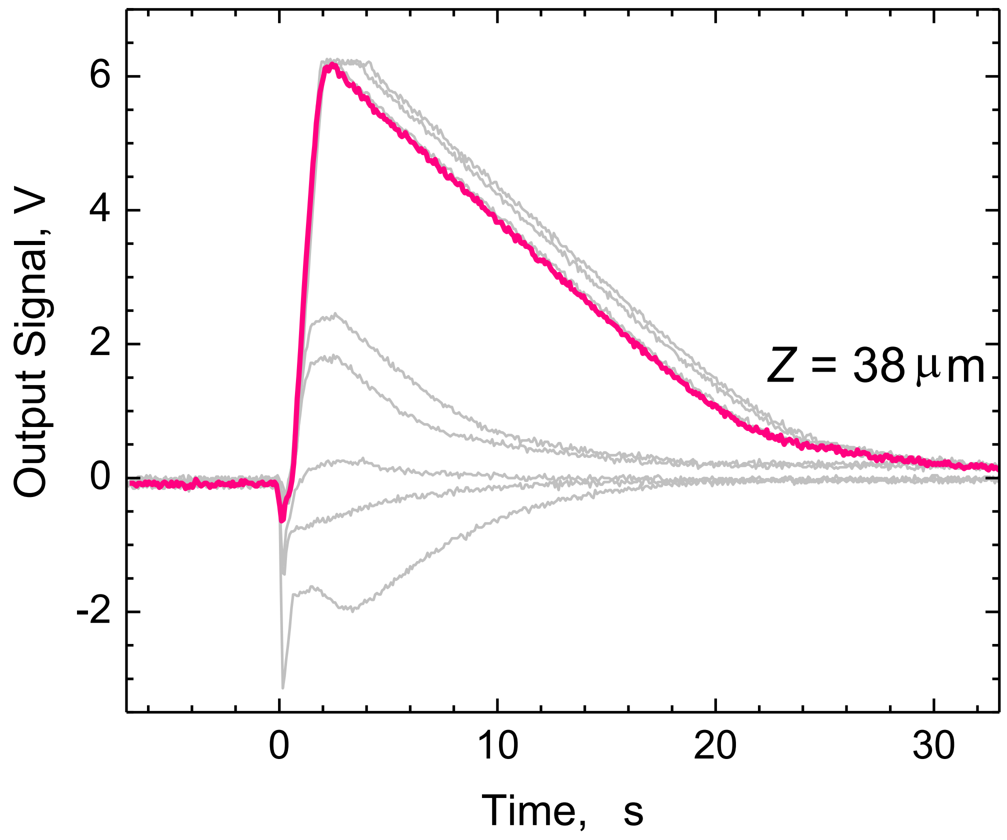

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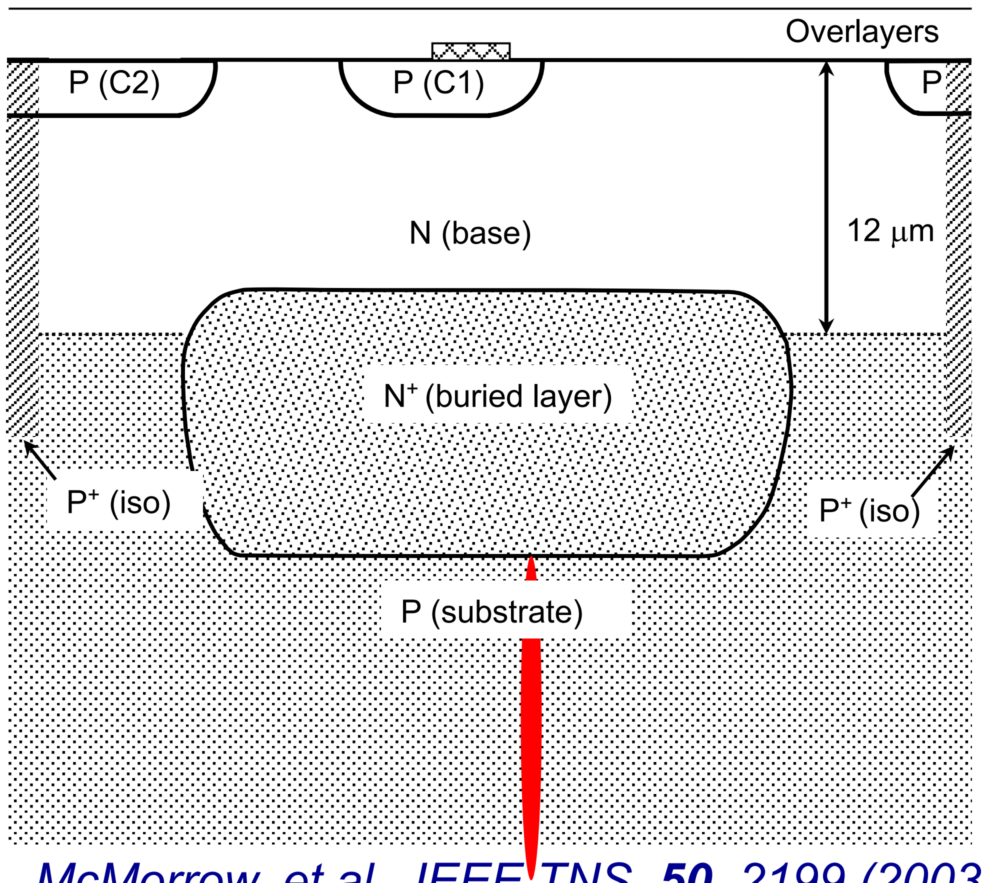

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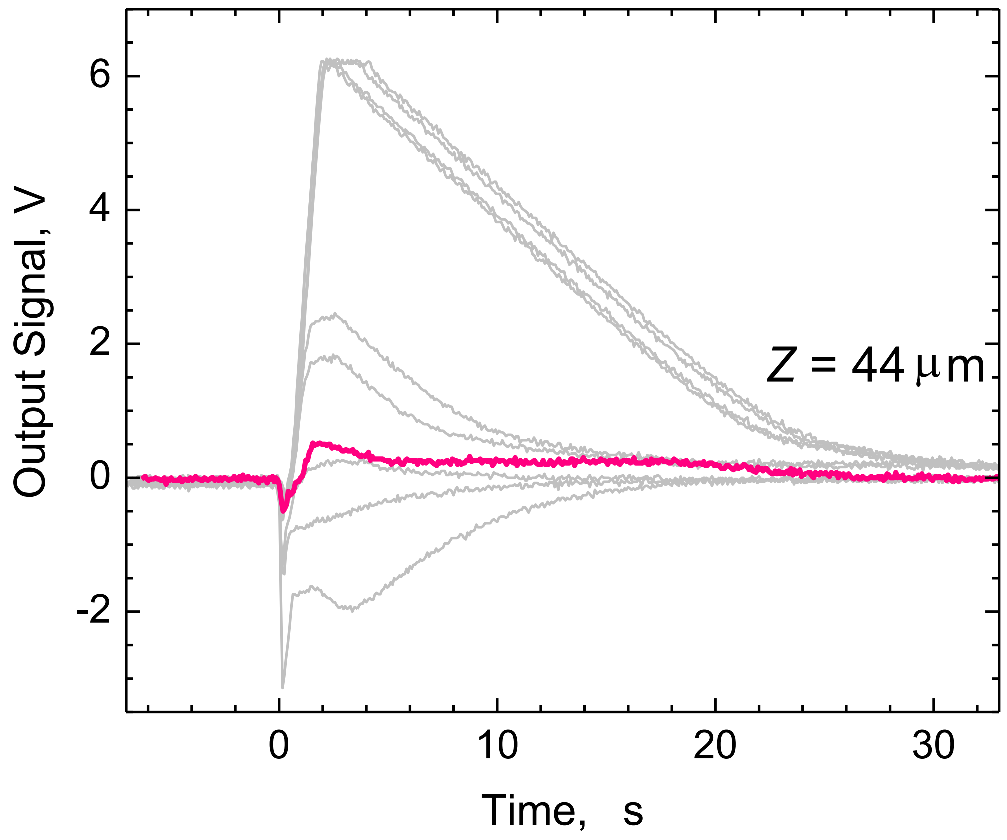
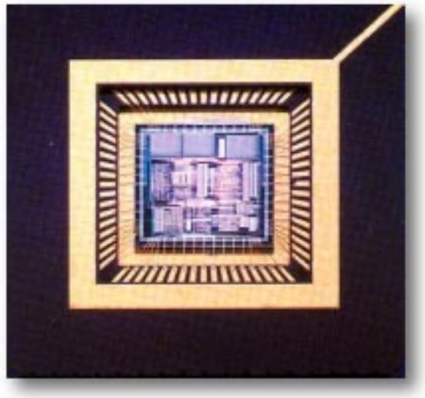
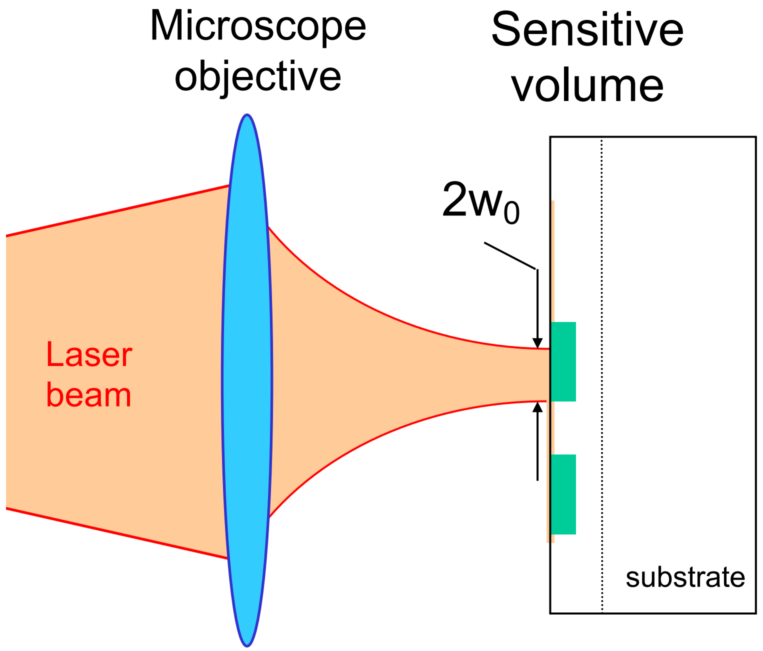
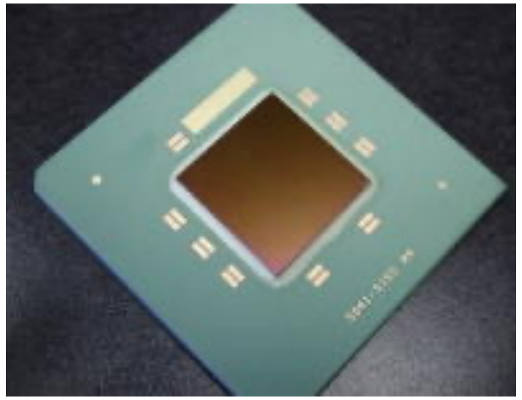


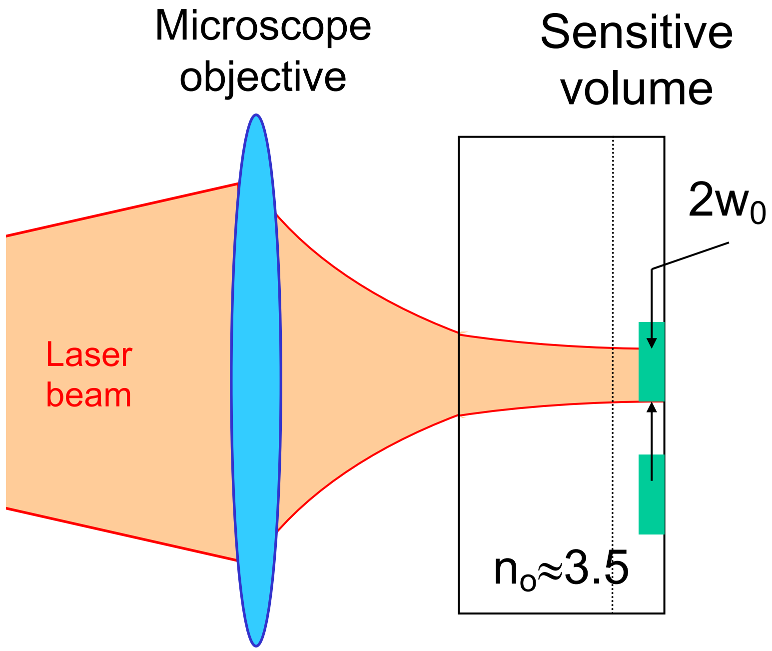
Front Side vs. Backside Illumination





Front side



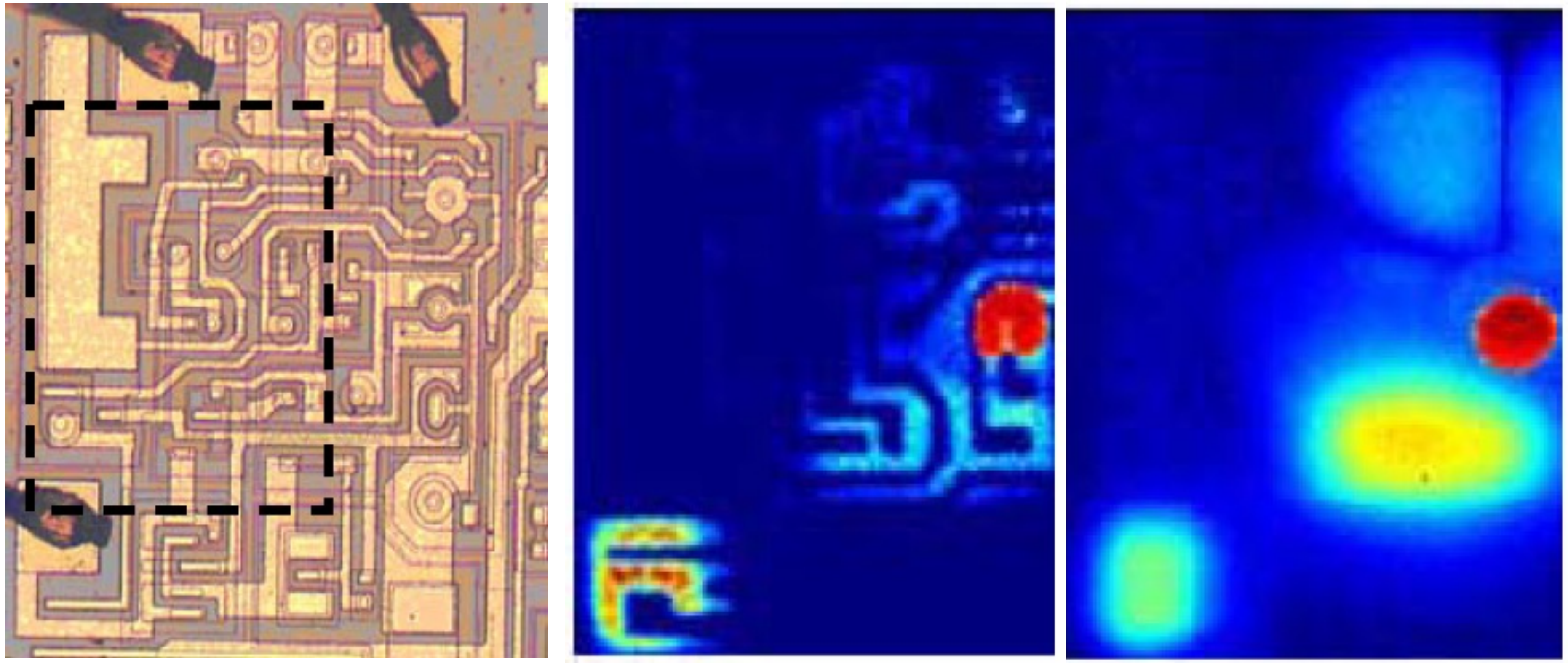


Backside

Lewis, et al., IEEE TNS 48, 2193 (2001)

Front Side vs. Backside Illumination SPA ASET Mapping – LM124

LM124 | Front side 1064 nm | Backside 1064 nm



- Plots illustrate the spatial distribution of the SET amplitude
- Sensitive areas clearly identified
- Effects of metalization evident

Lewis, et al., IEEE TNS 48, 2193 (2001)

Laser SEE Testing, Technology and Packaging

Primary experimental constraint:

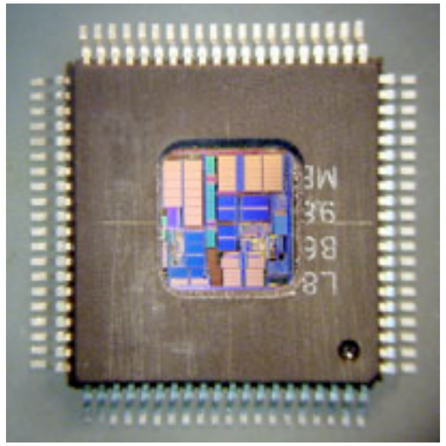
- *Optical access to silicon required*

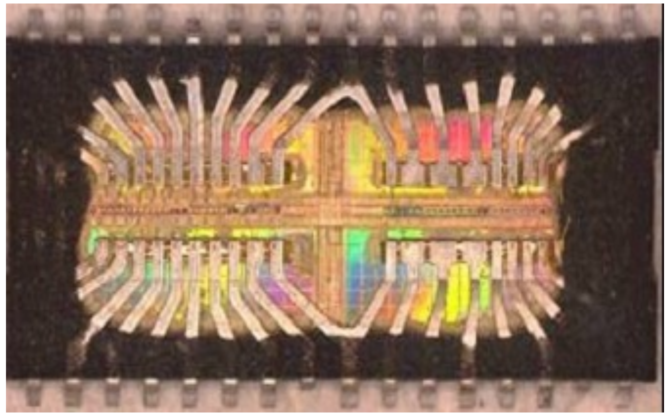
Modern process technologies

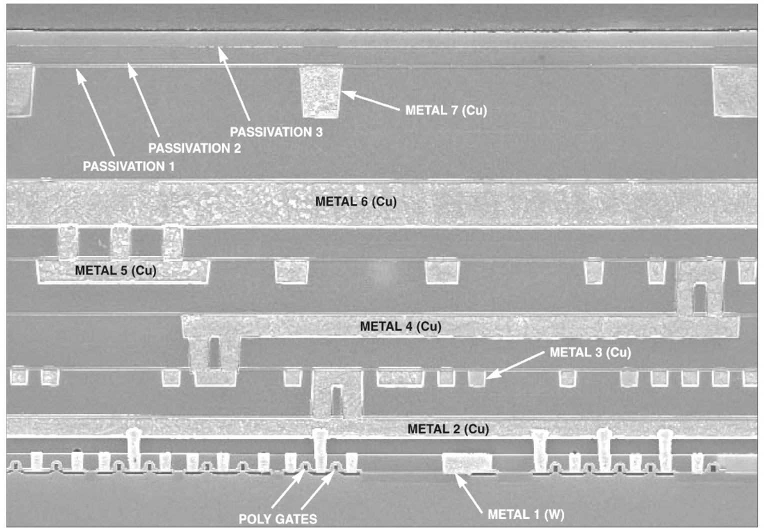
- Many interconnections layers
- Metal lines totally absorb light
- Dummy cells: metal fill for process planarization

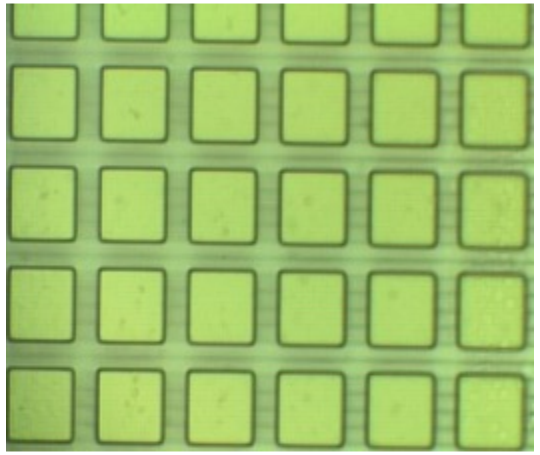
Packaging

- Ceramic or plastic opening
- Lead frame masking => repackaging
- Flip-chip
- 2.5-D, 3-D









Solution:
Backside, through-wafer testing

Additional Experimental Considerations for Laser SEE Testing

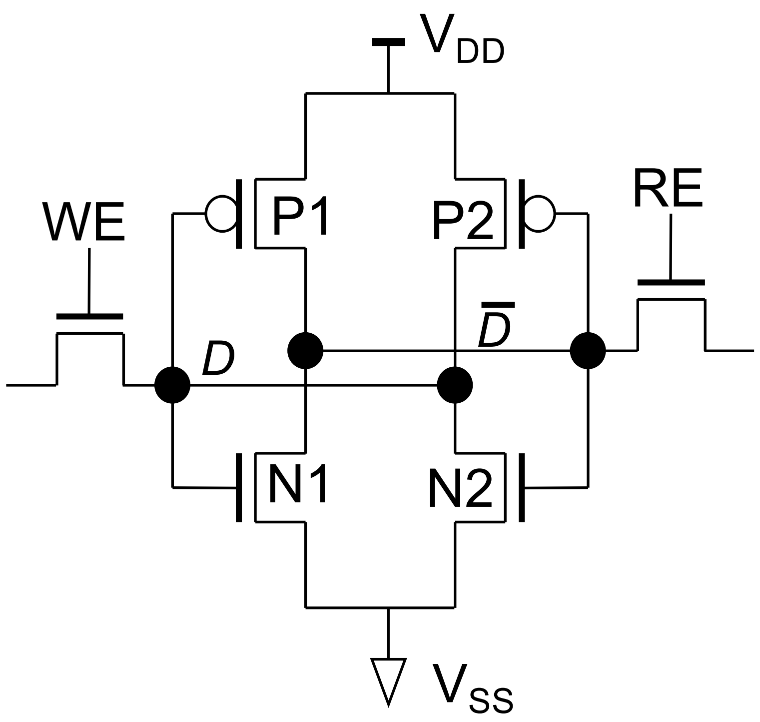
- Test setup requires considerations different from heavy ion tests
  - SEU tests: real time error feedback advantageous
  - Scanning: synchronization to xyz stage and oscilloscope
- Sample preparation:
  - Optical access to silicon
    - Top: package delidded
    - Back: backside polished; thinned if necessary
    - Board: no major obstructions (capacitors, etc.)
- Angle of incidence typically (almost always) set at zero degrees
  - Pulse energy adjusted to tune effective LET
  - Pulse energy (LET) can be varied continuously
  - Angular effect limited by high index of refraction (Snells's Law)
  - Spot size effects
- Mechanical stability essential
- Optical calibration and validation essential for many studies

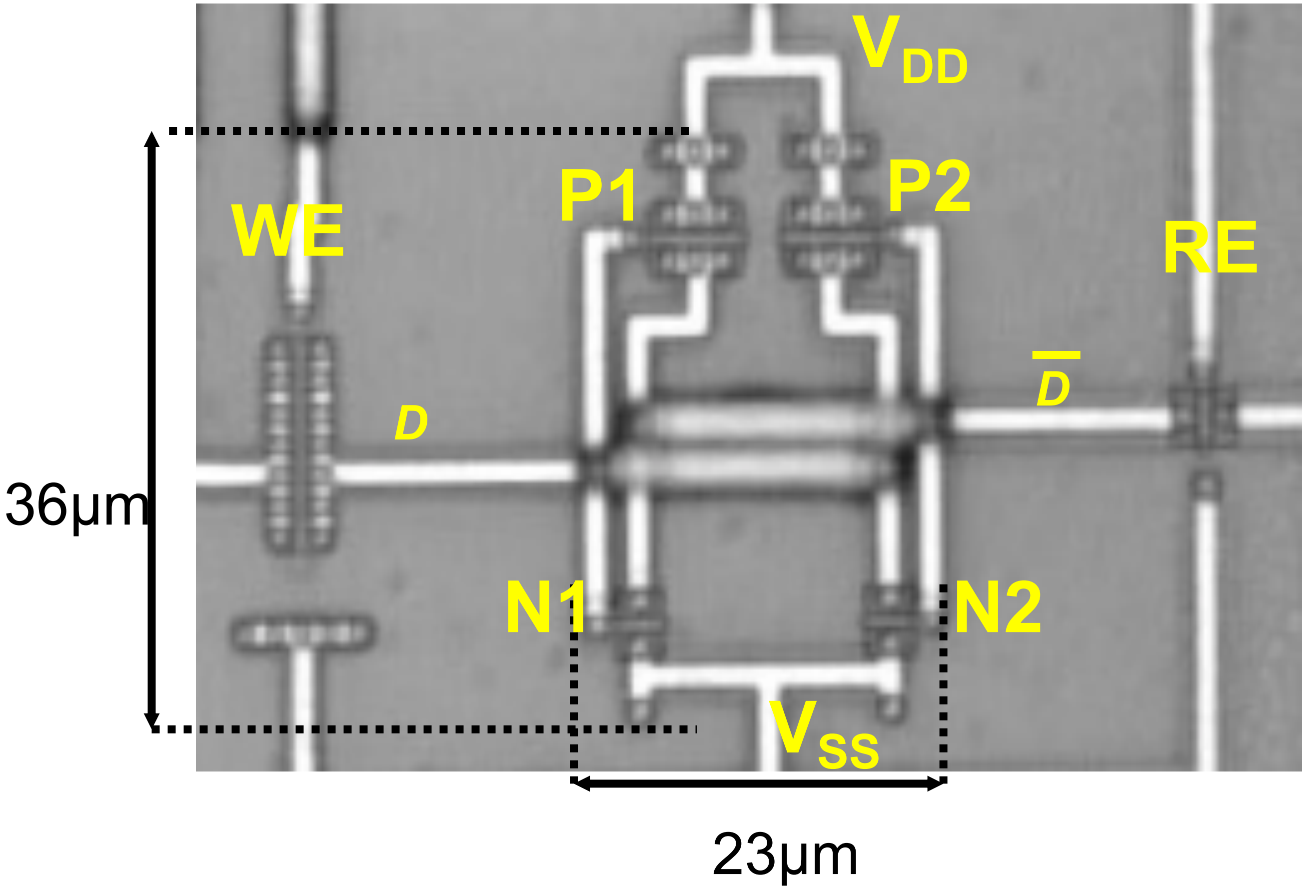
Single-Event Upset Mapping in an SRAM Cell

Single-Event Upset Mapping in an SRAM Cell

<u>Custom 6T SRAM cell</u>

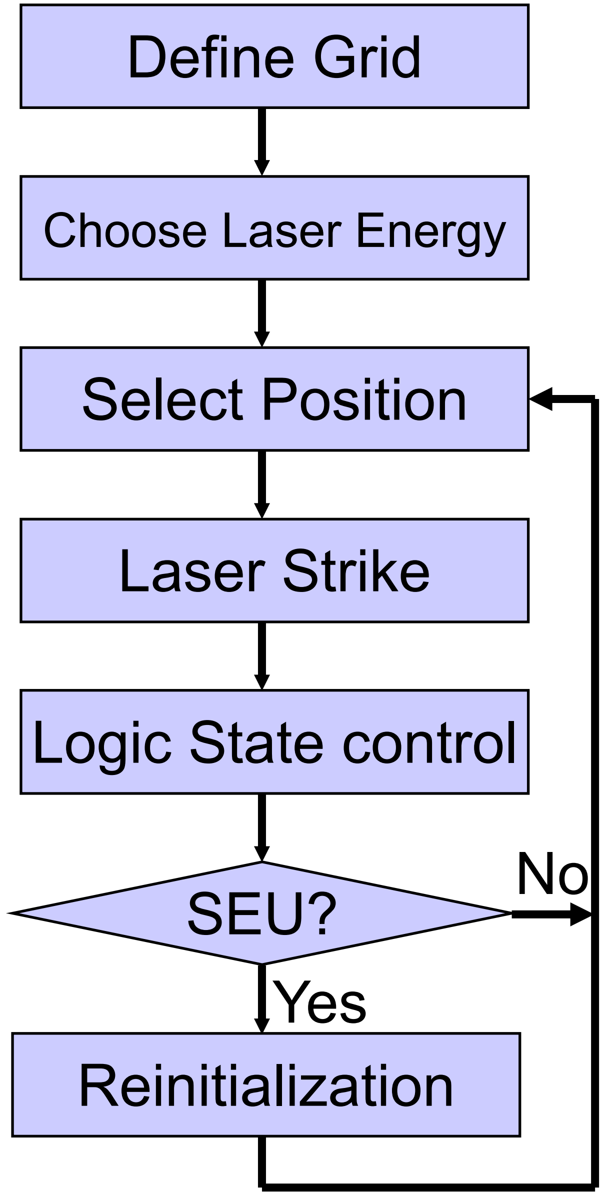
- 0.8 µm AMS BiCMOS technology
- low density of metal tracks (SPA technique and frontside testing)

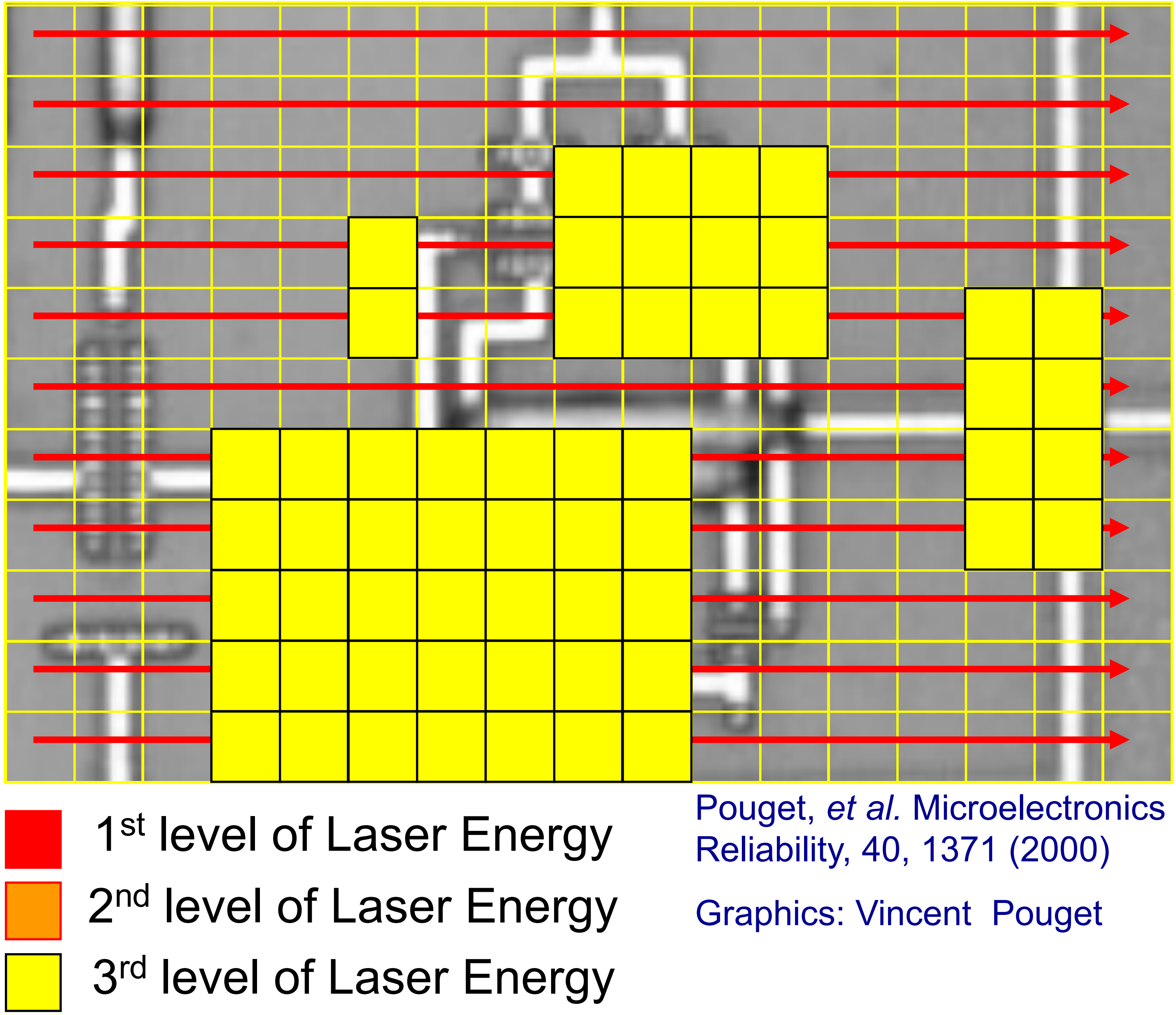




Pouget, *et al.* Microelectronics Reliability, 40, 1371 (2000)

Scanning Automation : Basic Principle





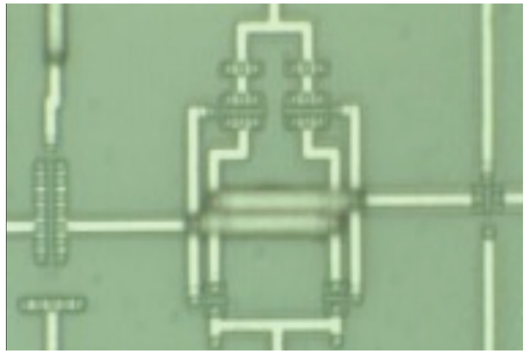
Pouget, *et al.* Microelectronics Reliability, 40, 1371 (2000)

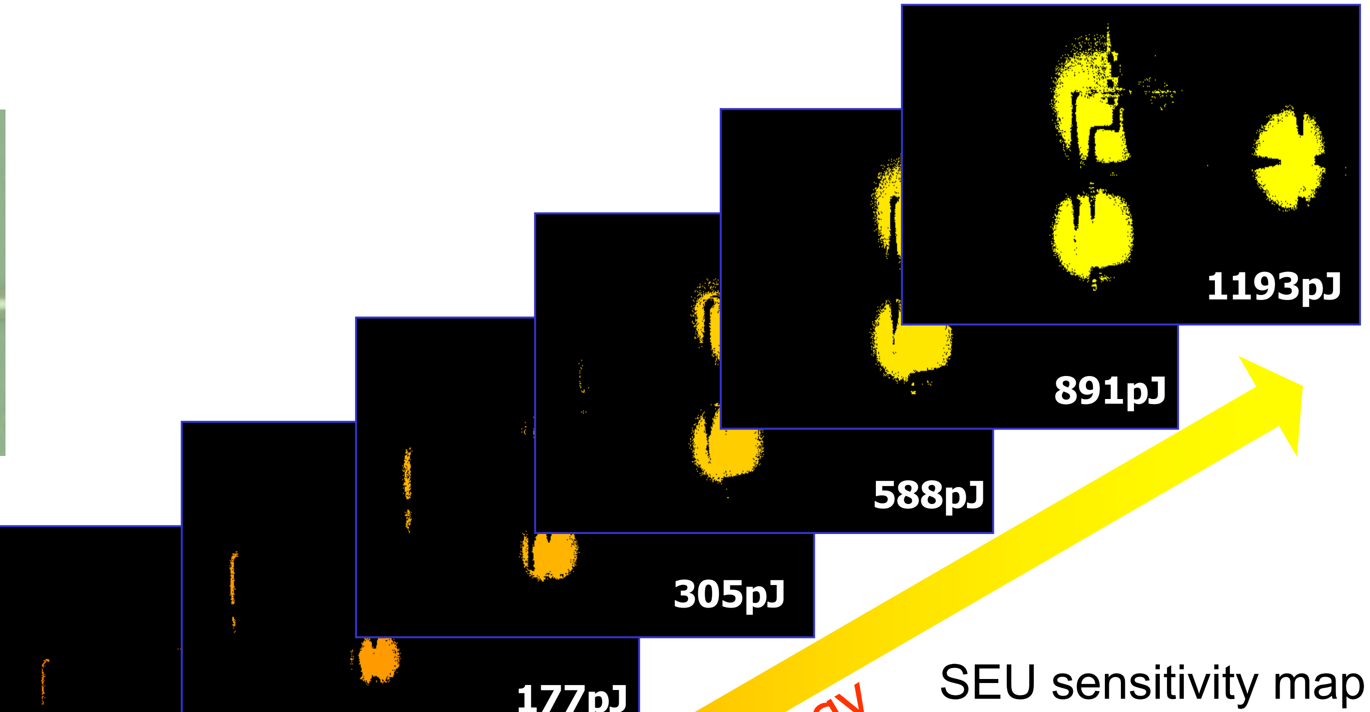
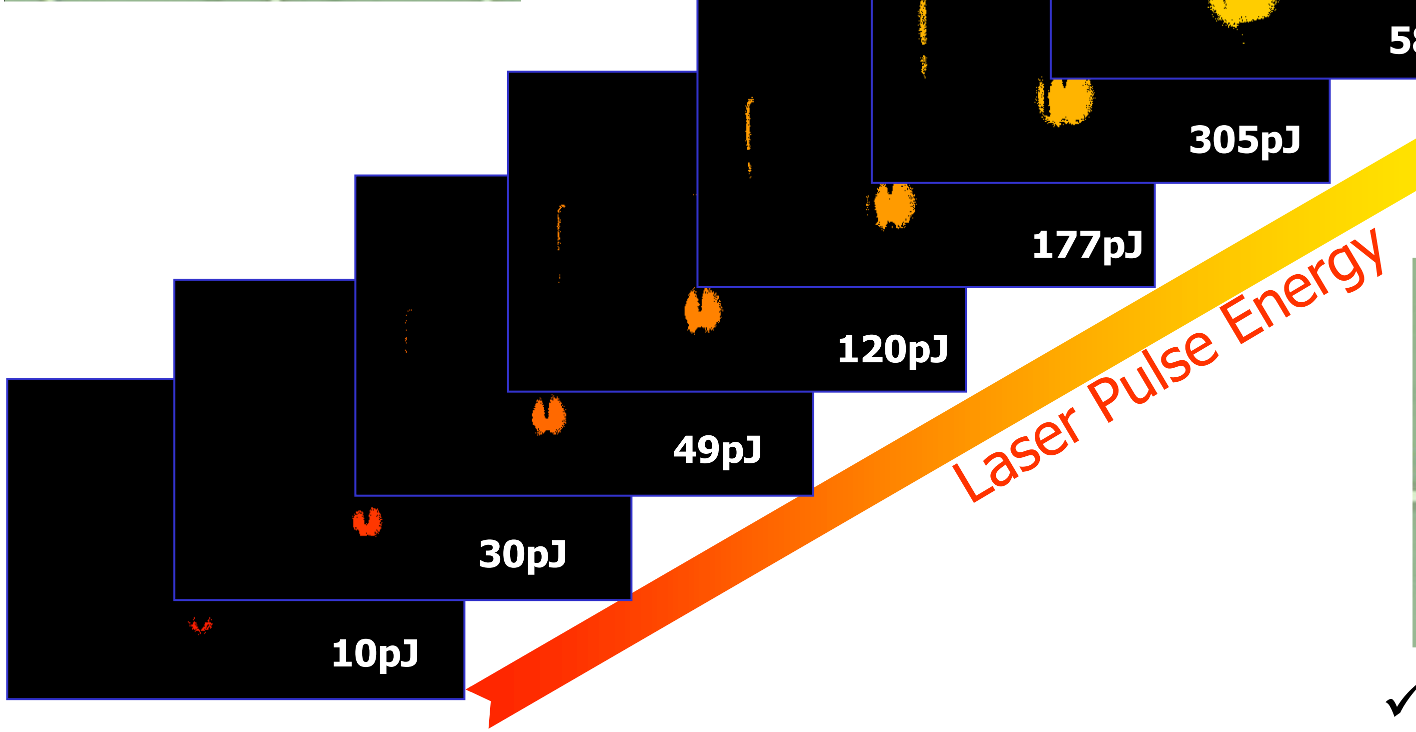
Graphics: Vincent Pouget

SEU Mapping

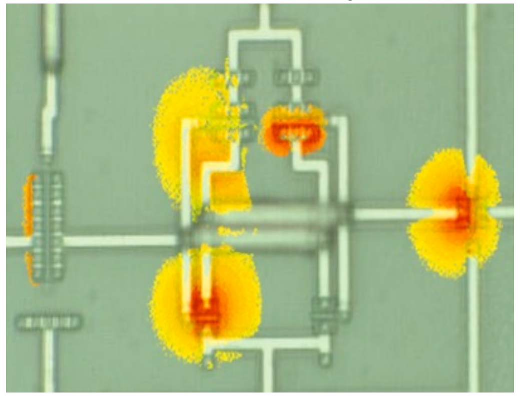
Pouget, et al. Microelectronics Reliability, 40, 1371 (2000)

6T SRAM Test Vehicle



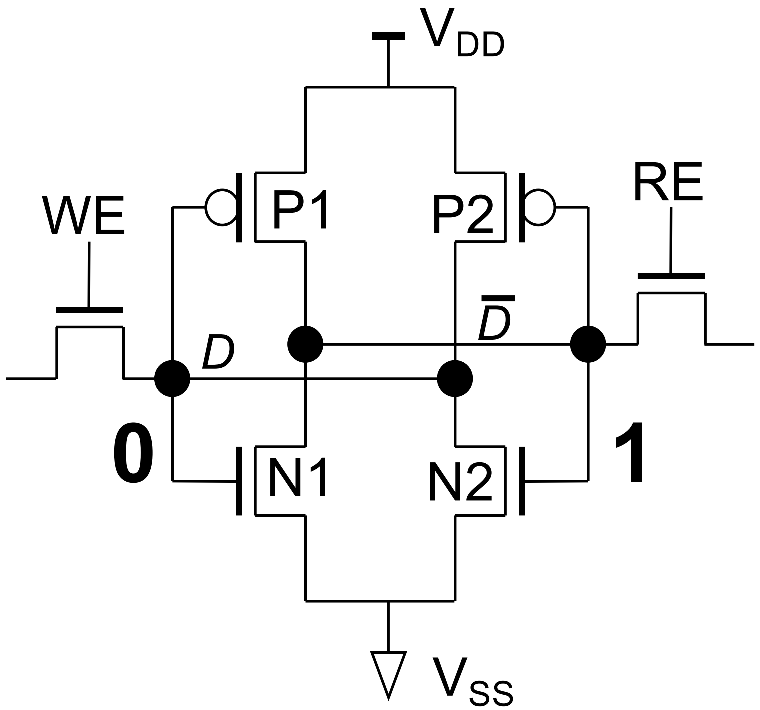
SEU sensitivity map

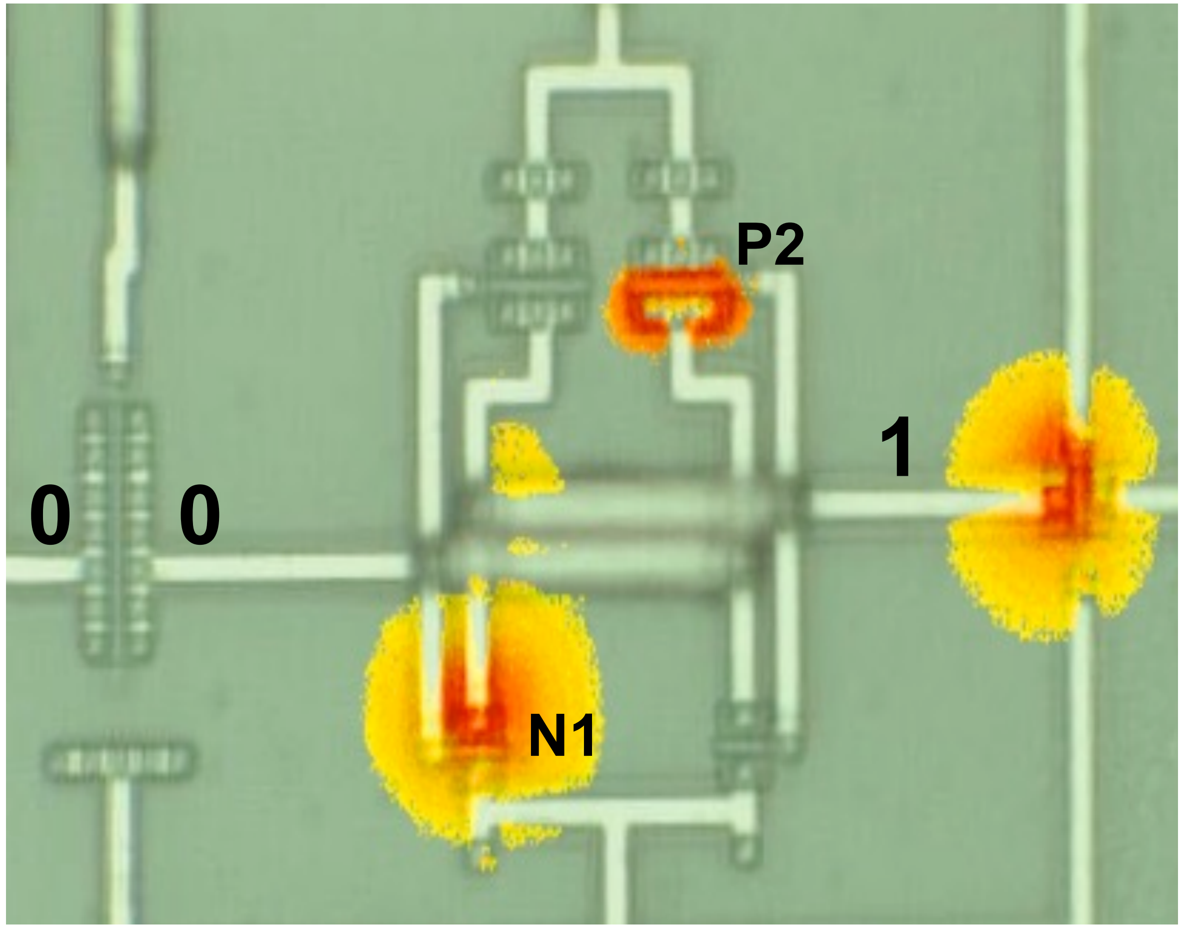


✓SEU mechanisms

✓Design optimization

SEU Mapping : Sensitivity of the NMOS Drain

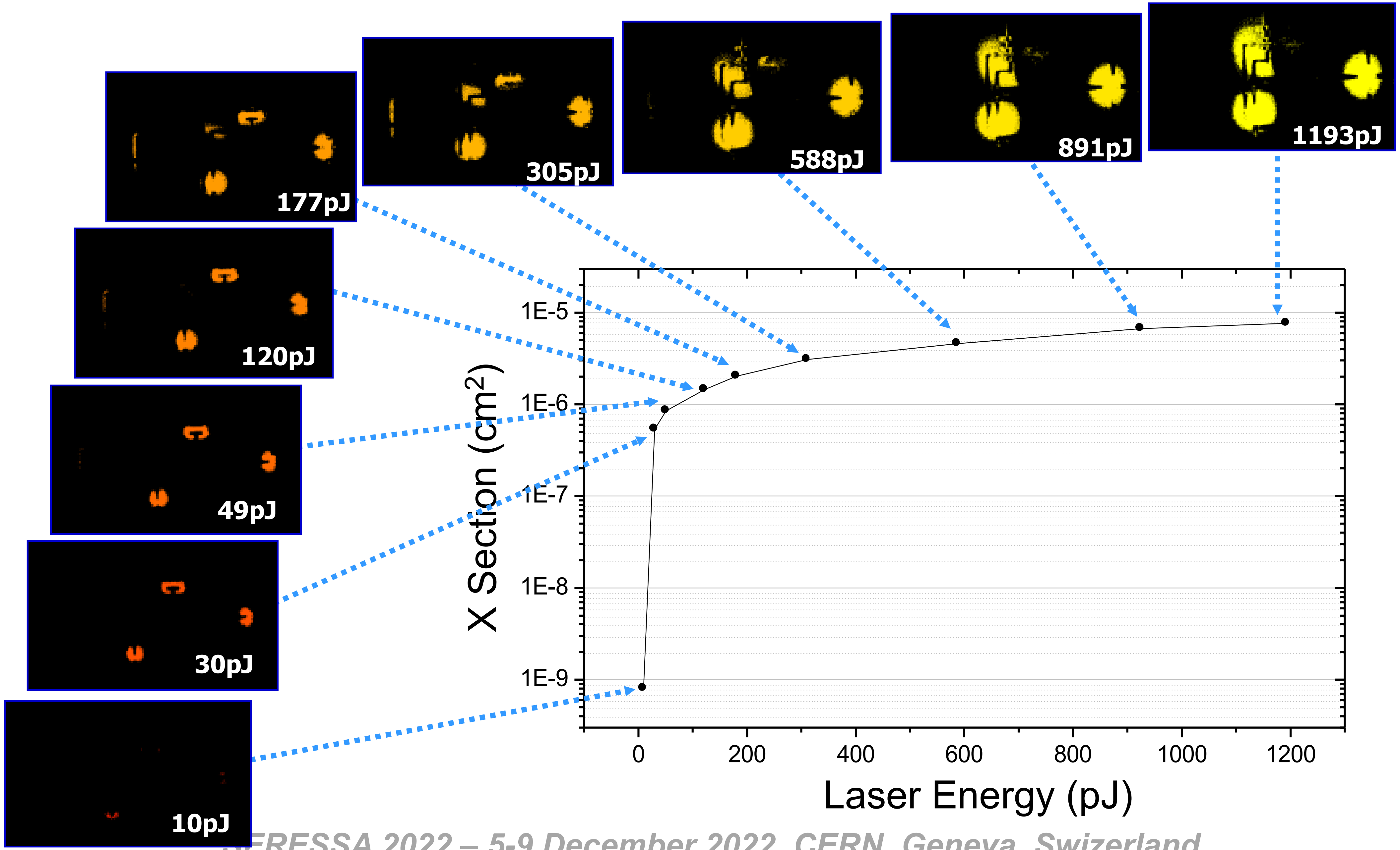




Pouget, *et al.* Microelectronics Reliability, 40, 1371 (2000)

From SEU Mapping to Cross-Section analysis

Pouget, et al. Microelectronics Reliability, 40, 1371 (2000)



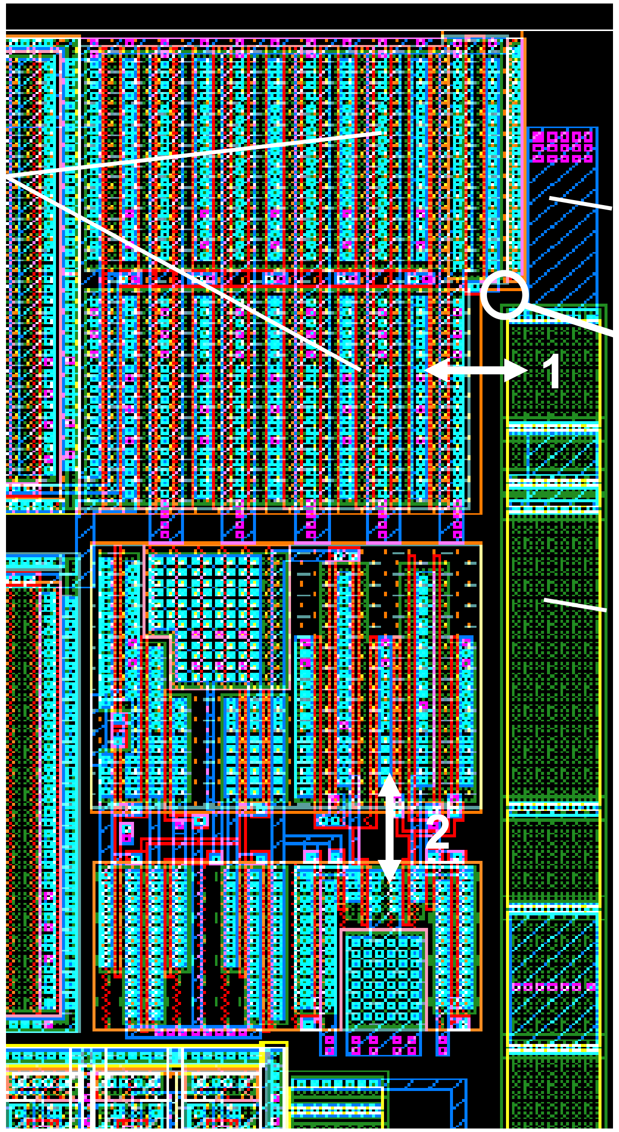
Spatial Selectivity *Example*:

Laser-Induced Latchup Evaluation and Mitigation in CMOS Devices

Latch-Up Mitigation of RH Parts for Space Missions

- LVDS Quad differential line driver (DS90C031) designed into (~2000) GPS II upgrade program
- Unanticipated latchup sensitivity observed in HI testing (*NASA*)
- Unacceptable for mission requirements; threatened to delay launch date (big $$$)
- Pulsed laser SPA SEL evaluation (*NRL*) revealed sensitivity localized to a small region → redesign possible
- Redesigned (*Boeing*) → refabricated (*NS*) → retested (*NASA*)
- <u>*No Latchup observed in redesigned part*</u>
- Launch on schedule

National Semiconductor DS90C031 LVDS Original Design



Drive Transistor

Ground

Latchup Location Identified by Laser

Resistor

Design: Boeing

Fab: National Semi

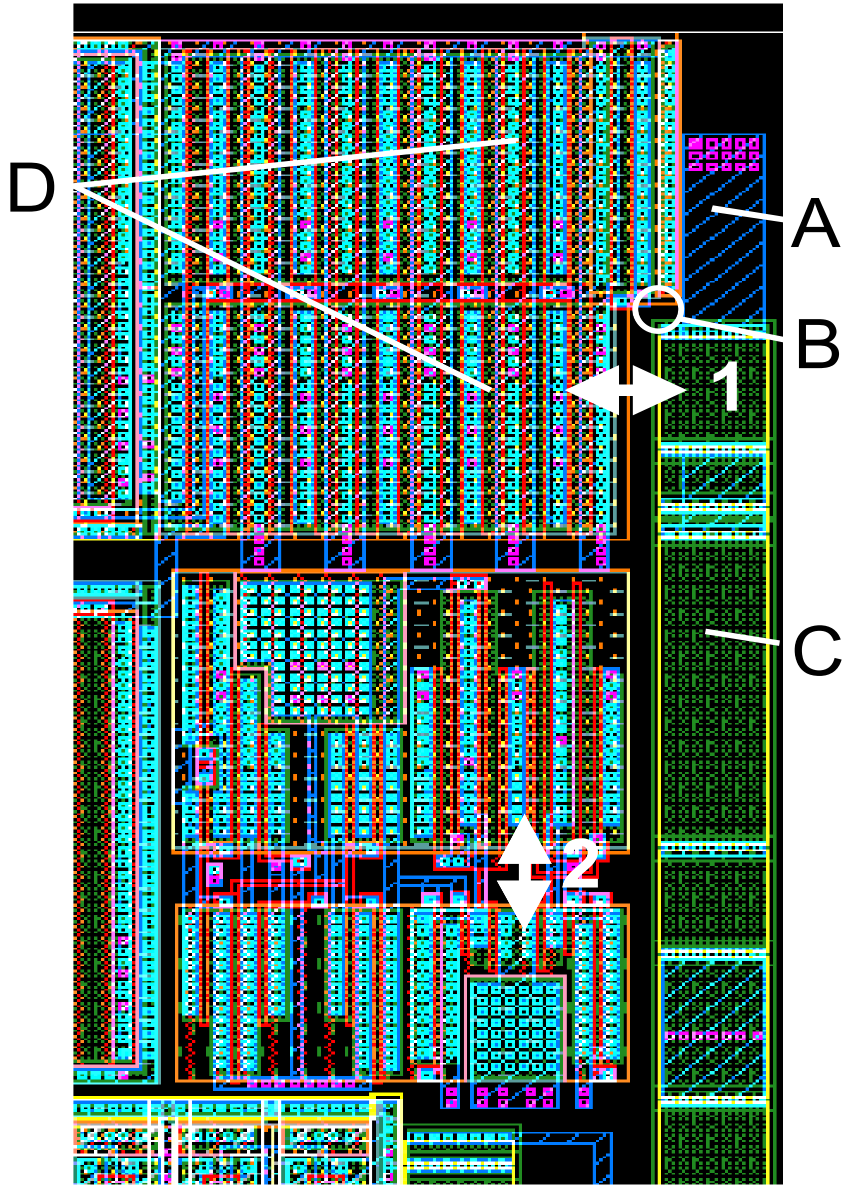
Rad test: NASA Goddard

Also involved: Sandia

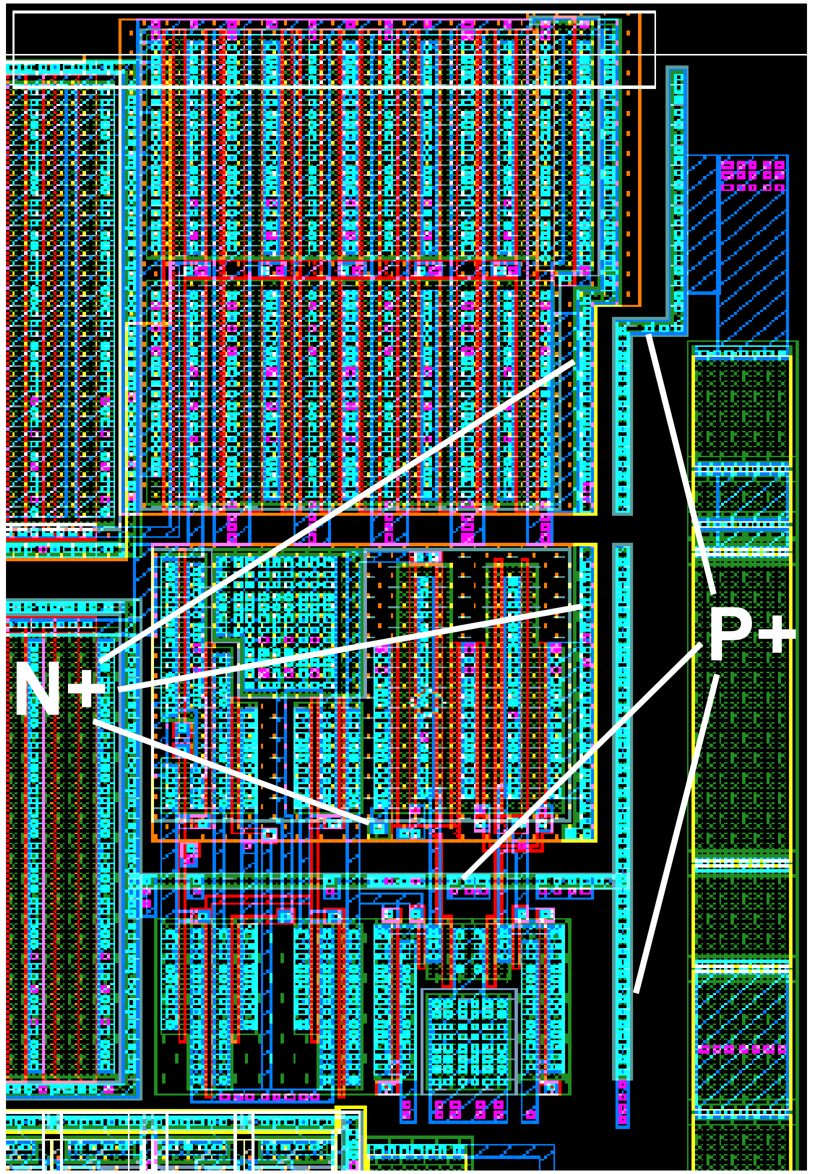
*McMorrow, et al., IEEE TNS **53**, 1819 (2006).*

National Semiconductor DS90C031 LVDS
Comparison of Two Designs

Original Design



Redesigned Part



Design: Boeing

Fab: National Semi

Rad test: NASA Goddard

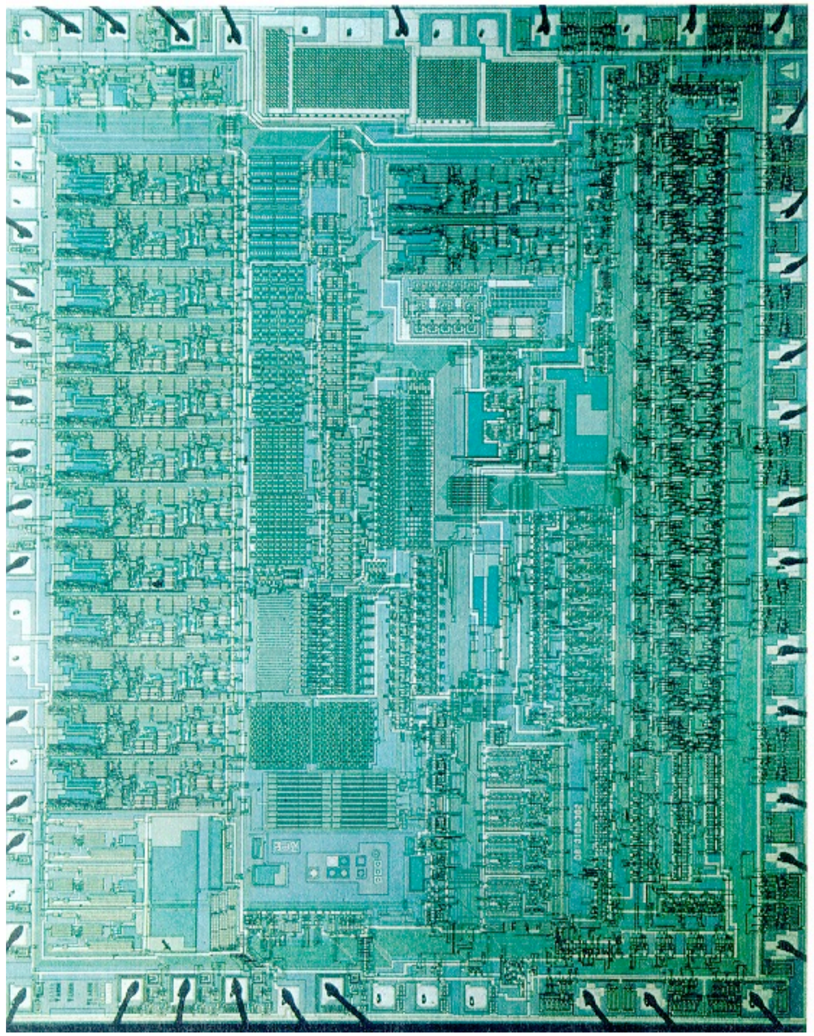
Also involved: Sandia

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

Part Screening Using PL SEE

- Screening to reject
- Screening to accept

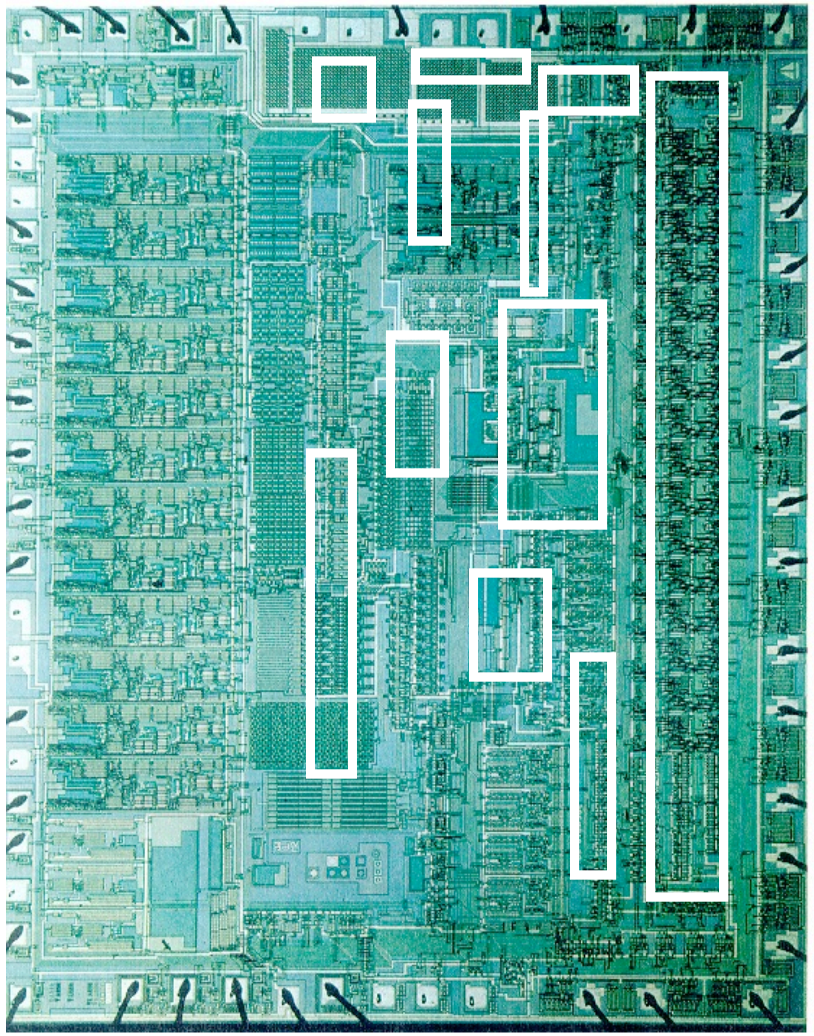
Latch-Up Screening of COTS Parts for Space Missions



DDC RDC19220

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

Latch-Up Screening of COTS Parts for Space Missions



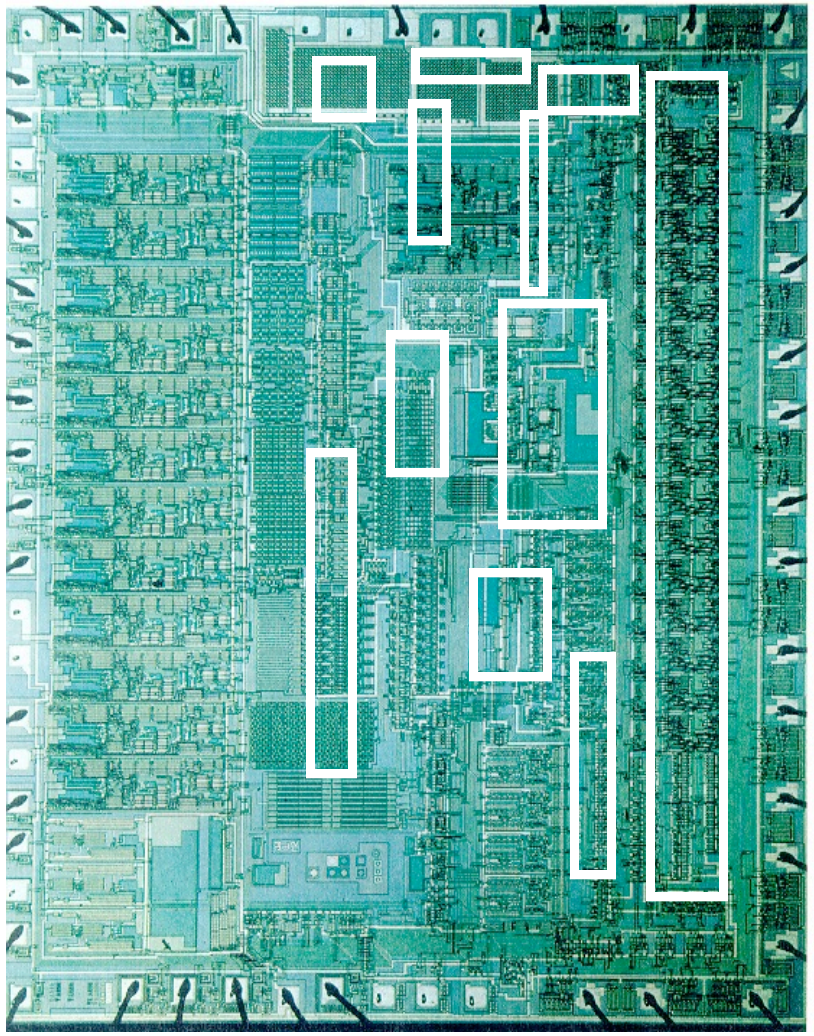
SEL sensitive areas in COTS RDC

(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

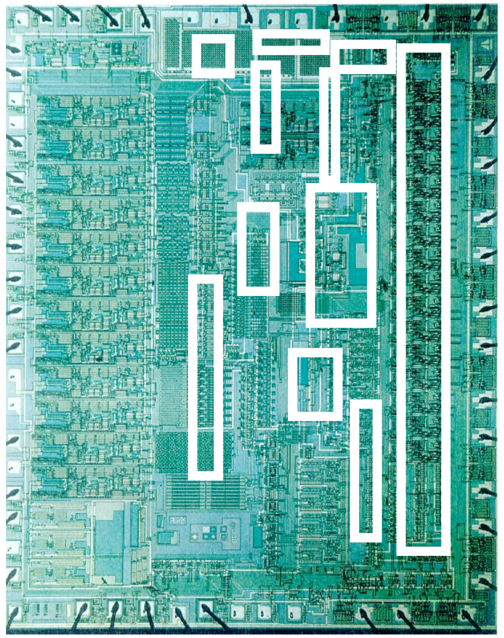
(DDC RDC19220)

- 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 was latch-up free and, following heavy-ion testing, was deemed acceptable for the mission in question

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

Latch-Up Screening of COTS Parts for Space Missions

Can SEL screening be quantitative?



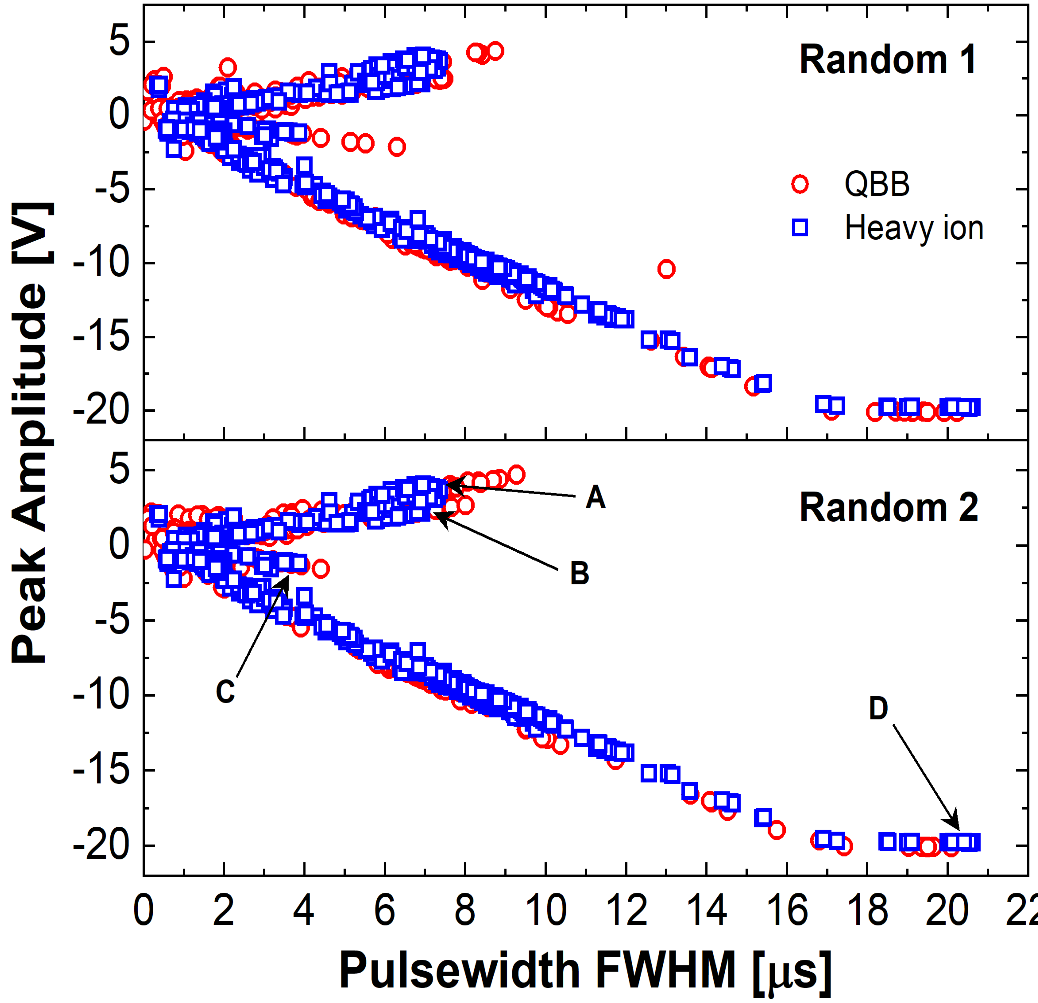
- This example:
  - 2.8 pJ latchup threshold (590 nm)
  - 1.4 pC deposited charge
  - LET_{th}: 8 MeV·cm^2/mg
- HI LET threshold: 5-15 MeV·cm^2/mg
- 0.8 μm bulk technology node

Single-Event Latchup Screening

- Topic of considerable current interest
  - *Can we use laser SEL screening to relieve stress on accelerators?*
- SEL screening is ***routinely used*** in different laboratories ***to eliminate parts*** from consideration for space missions and to minimize the amount of heavy-ion testing required
- However, SEL screening is ***rarely used for part acceptance***, but that may change as the landscape moves towards constellations of lower-cost, smaller satellites, and ***as quantitative methods mature***

Analog Single-Event Transient (ASAT) Screening

- Good agreement between laser- and ion-induced *individual SET pulse shapes* and for the *VΔt representation*
- Pulsed laser irradiation can be used to generate the *"worst case" transients* for linear devices
- Pulsed laser irradiation has proven to be an *effective and cost efficient screening method* for linear bipolar parts for space missions
- Such screening has been used in lieu of heavy-ion testing by NRL, NASA Goddard, JPL, and others



Laser SEE Screening Conclusions and Status

- Screening to eliminate parts:
  - Demonstrated for SEL and ASET
  - Commonly utilized by various laboratories
- Screening to accept parts:
  - Work in progress; some examples exist
  - Depends on criticality of the mission
  - Depends on criticality of the part
  - Depends on philosophy of program manager
  - Part by part decision

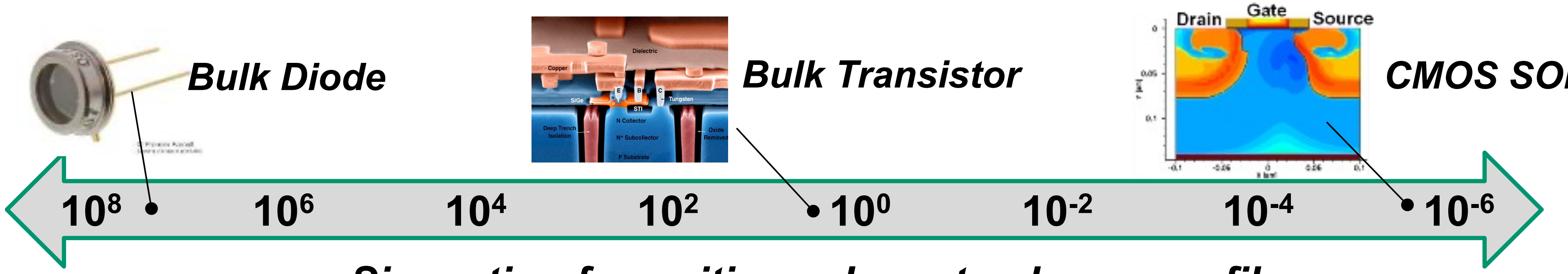
Laser-Ion Correlation

With proper dosimetry, calibration, and a validated charge-deposition model, we can now attack problems that were not possible previously. TPA laser-ion correlation is one such problem.

Laser/Ion Correlation: Description of the Challenge

Challenges:

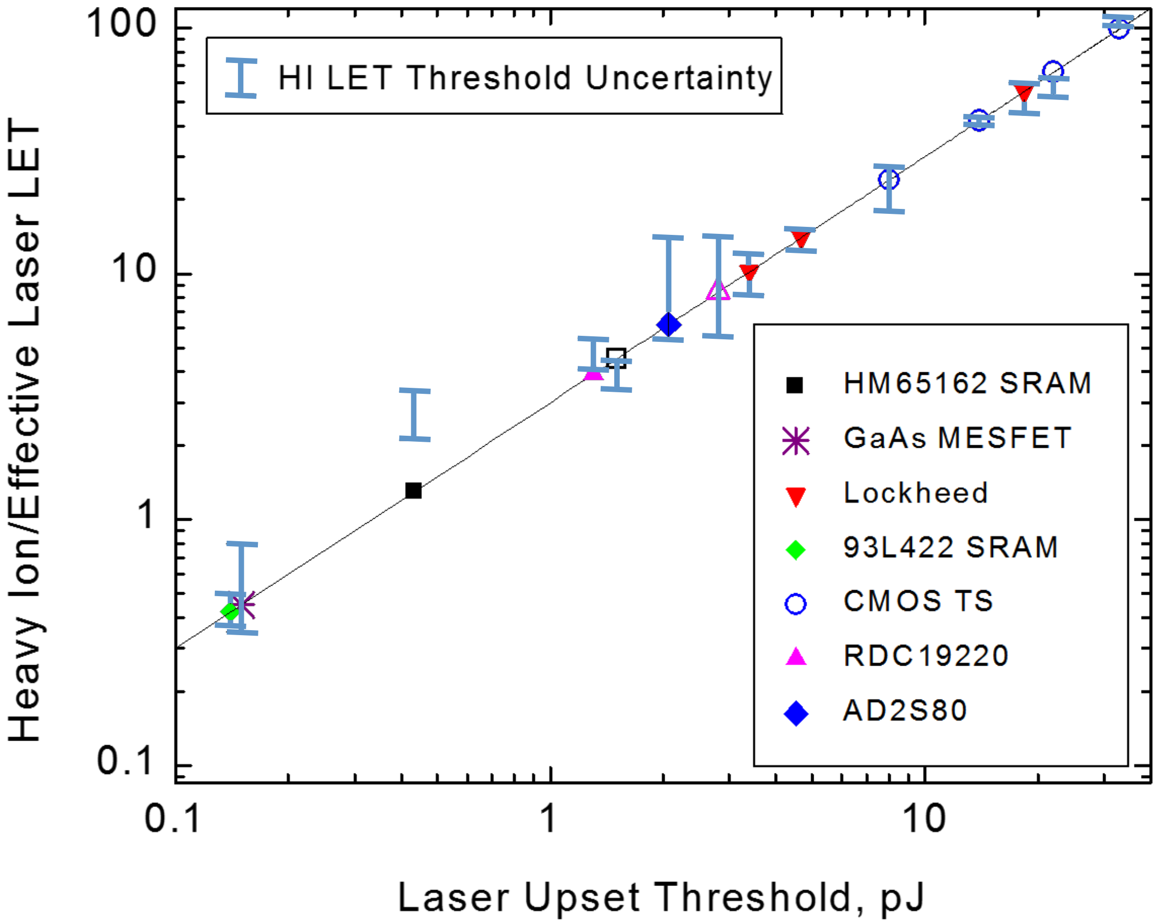
- Technology diversity
  - CMOS, HBT, Bulk, Epitaxial, SOI, III-V, Heterojunction, FinFET, etc.
- Incident (TPA) laser pulse parameters
  - Accurate beam-line characterization and calibration
  - Laser pulse energy, spot size, pulse width
- Accurate modeling of the charge deposition



Size ratio of sensitive volume to charge profile

Historical Laser/Ion Correlation
Empirical Correlation - SPA

590 nm Top-Side Single-Photon Absorption SEU and SEL



McMorrow, et al., TNS, 47, 559 (2000)

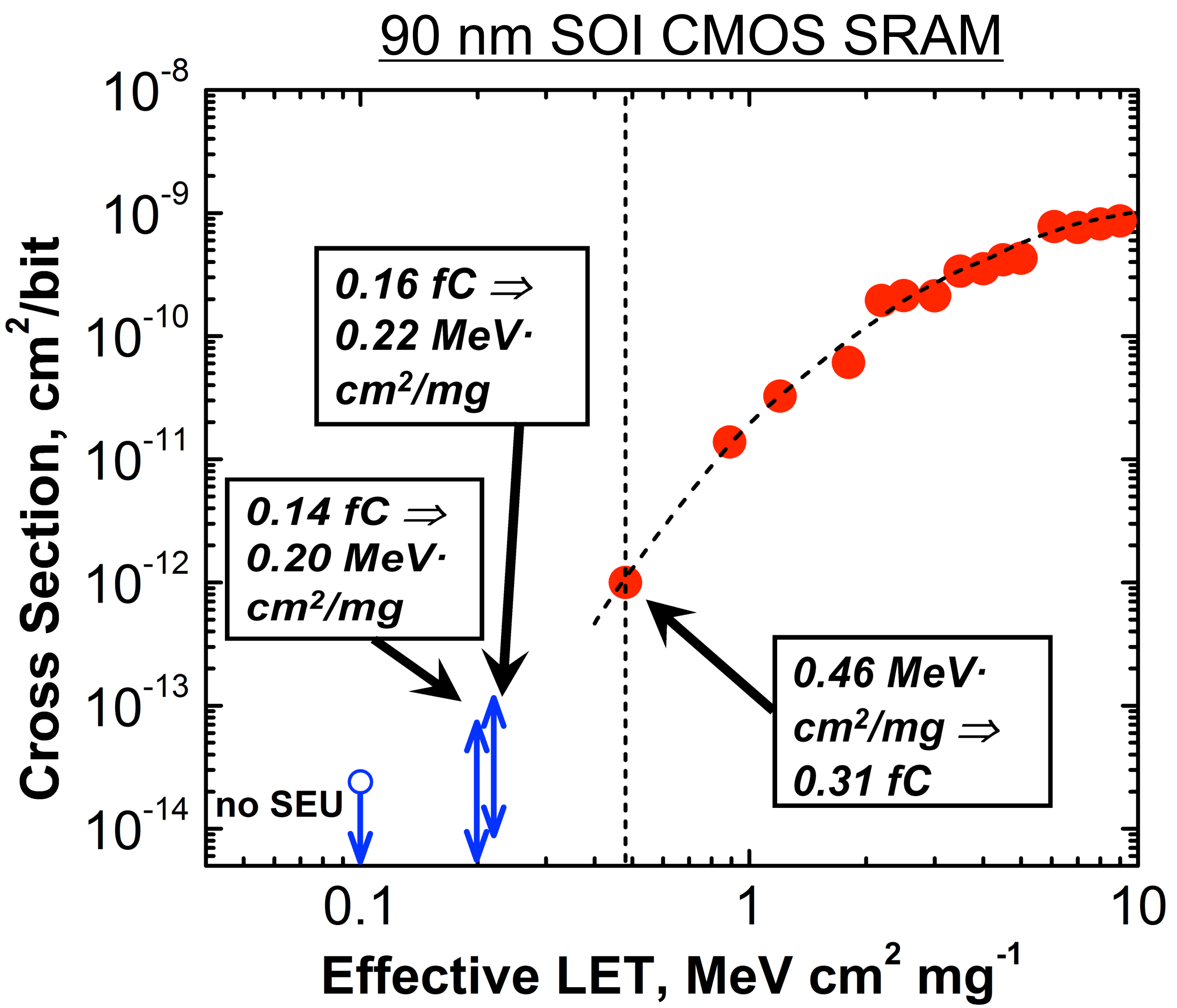
Moss, et al., TNS 42, 1948 (1995)

- Empirical correlation by identifying conditions that gave rise to an equivalent device response
- Correlation Factor:

  3 pJ ≈ 1 MeV•cm^2/mg

- Proved valid for a wide range of devices and technology nodes (*down to 0.25 μm bulk CMOS*)
- Specific to a given optical geometry (laser wavelength, pulse width, spot size)

Laser/Ion Correlation: 90 nm SOI SRAM



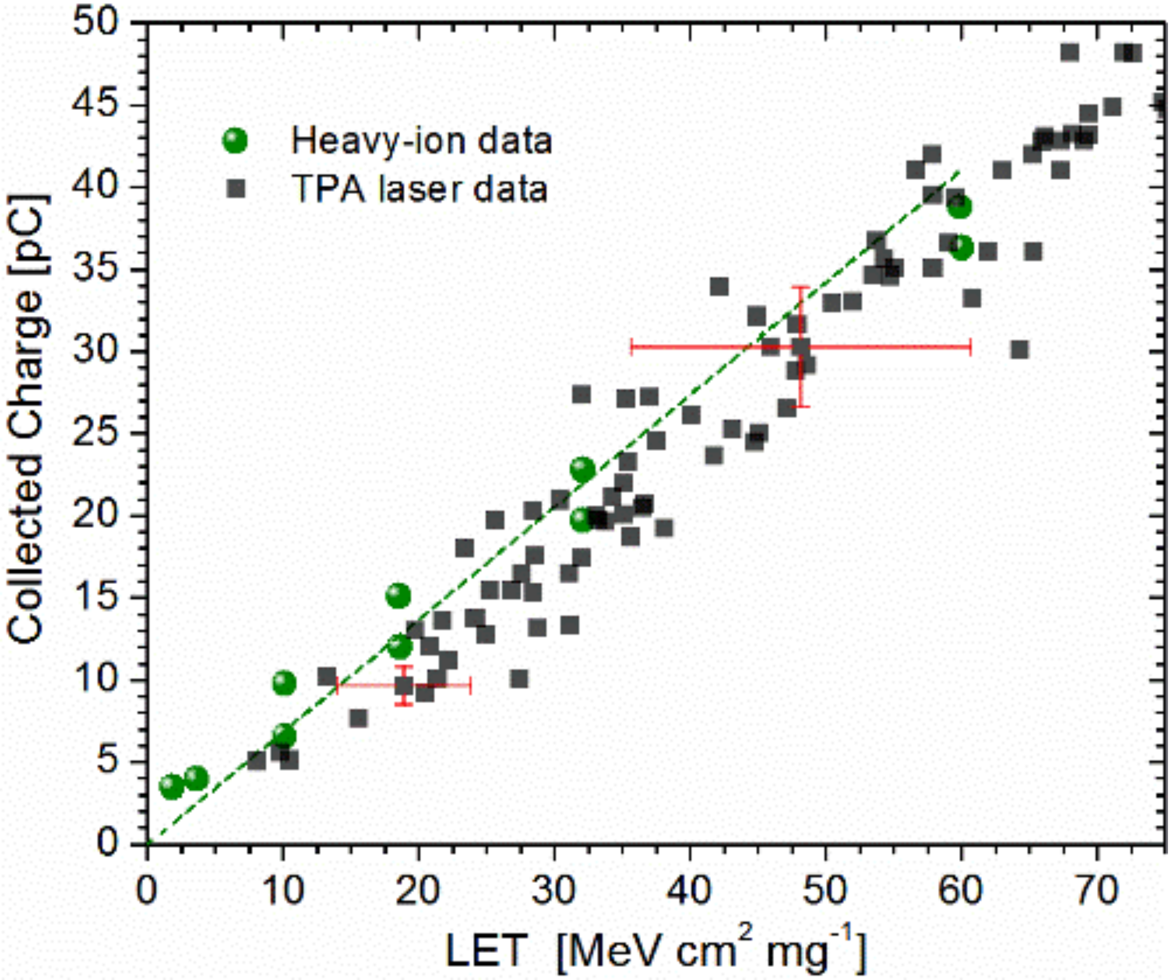
Heavy Ion: 0.1 < LETth < 0.46

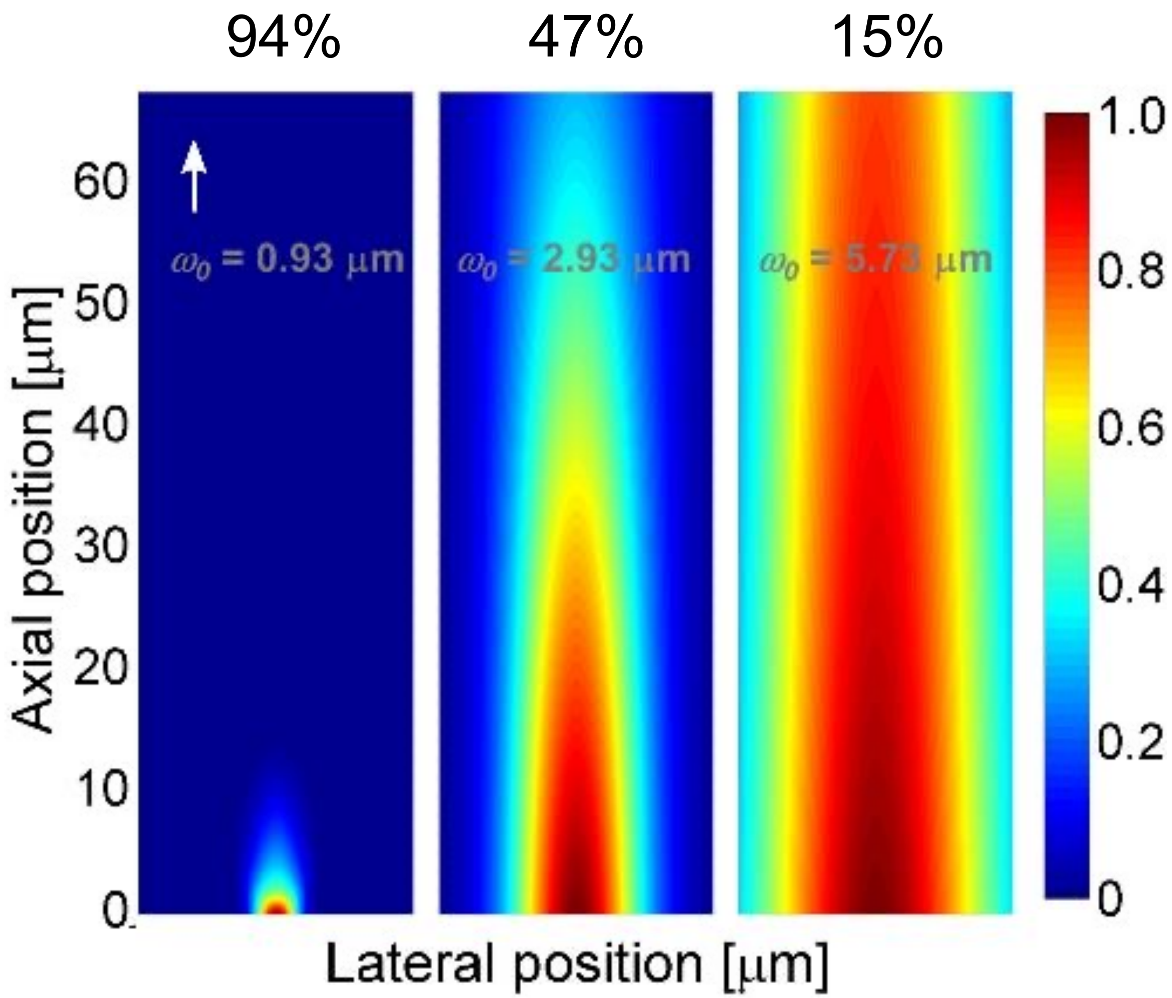
Laser: LETth ≈ 0.2 MeV·cm^2/mg

McMorrow, et al., IEEE TNS 60, 4184 (2014)

Laser/Ion Correlation: Bulk Si Diode - TPA

➢ <u>Combination of experimental measurements and accurate charge deposition modeling</u>



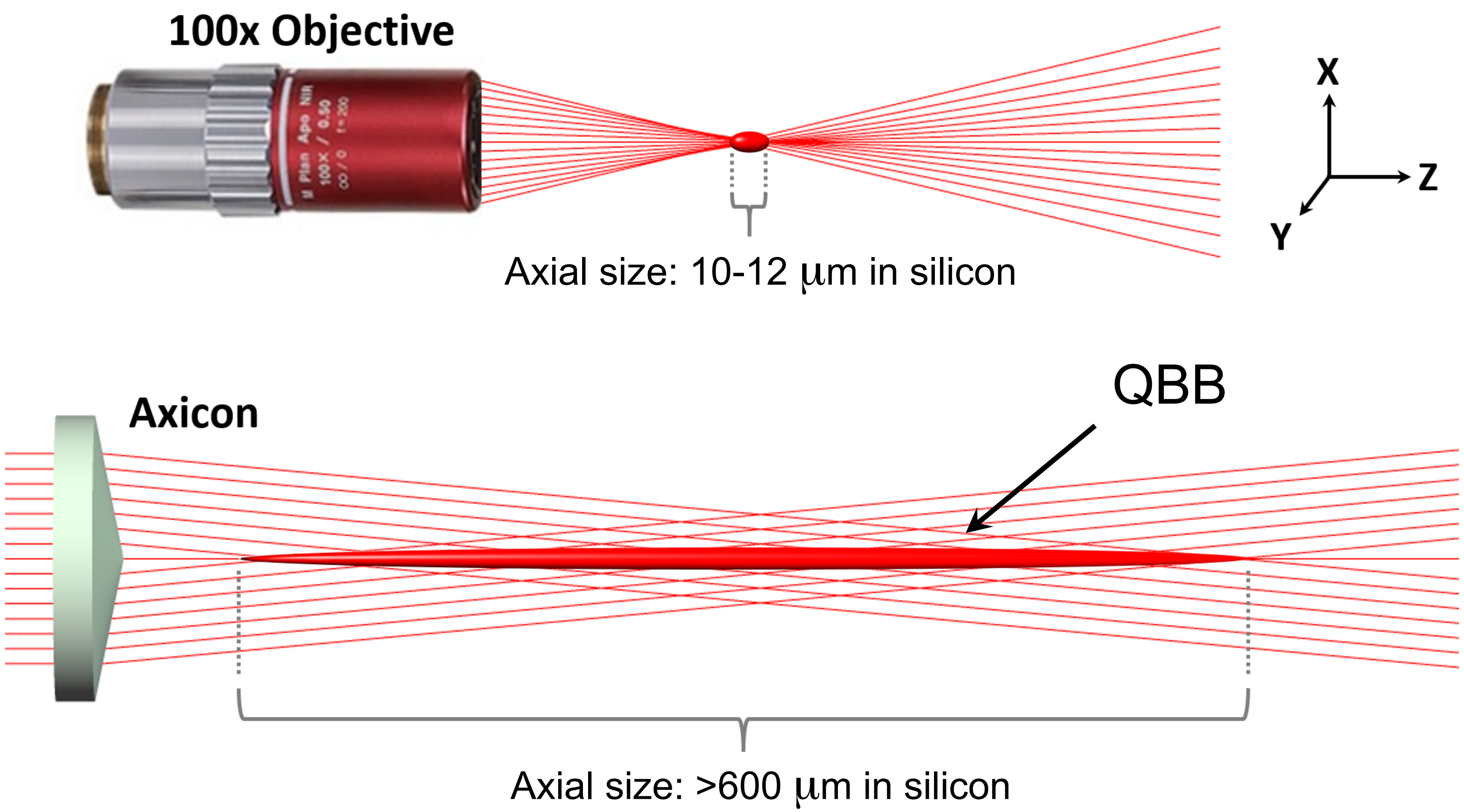


Nearly one-to-one correlation observed over entire LET range

Hales, et al., IEEE TNS 65, 1724 – 1733 (2018)

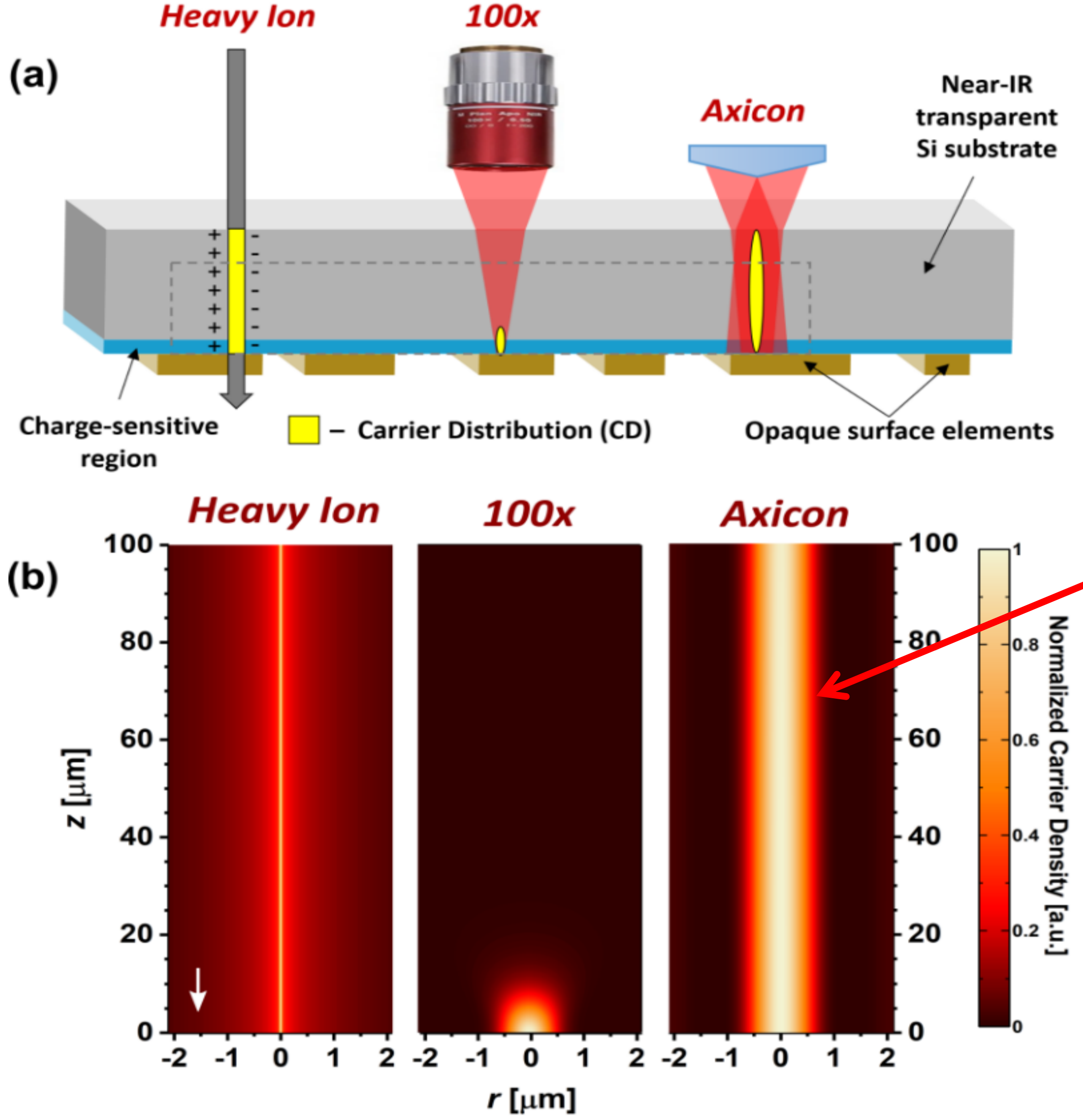
PL SEE Using Axicon -- Quasi-Bessel Beam

Spherical Lens vs. Axicon TPA Charge Generation in Silicon



Hales, et al., TNS 67, 81-90 (2020)

PL SEE Using Axicon -- Quasi-Bessel Beam

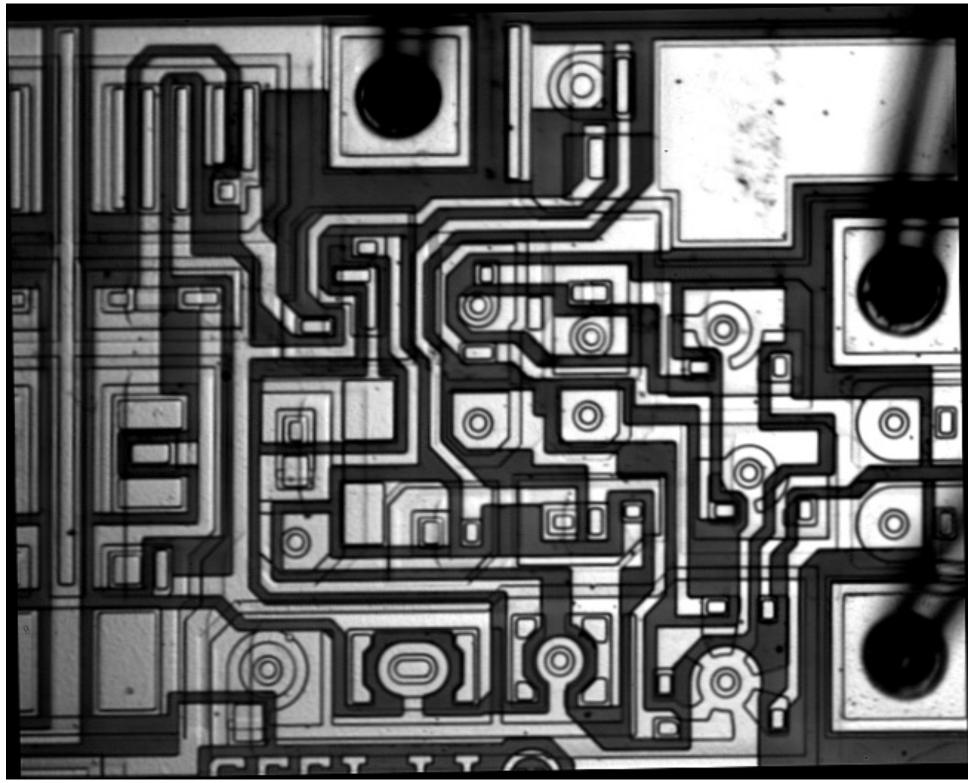


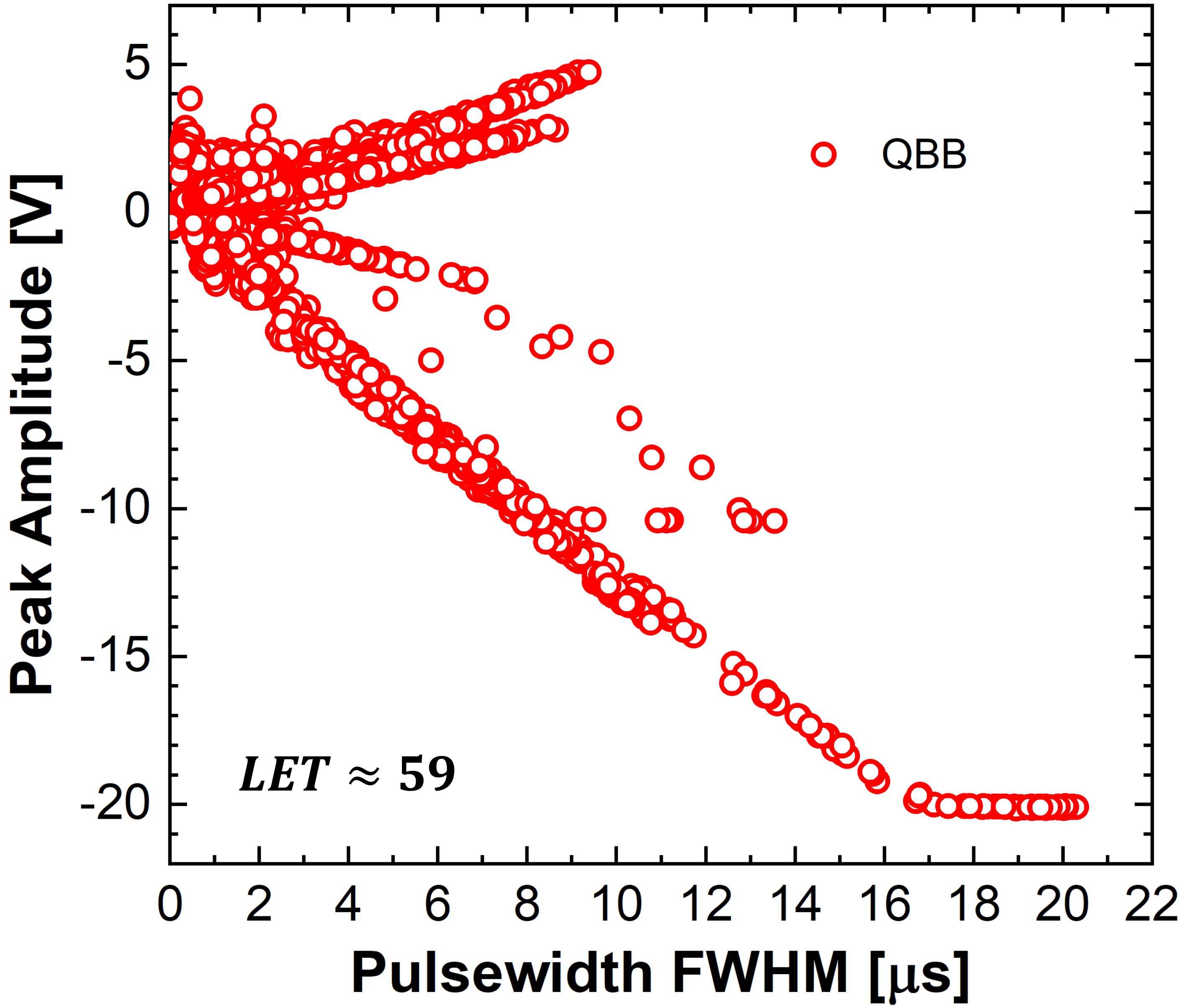
Constant LET

Hales, et al., Optics Express 2019

V-Δt Curves for Entire LM124 Chip

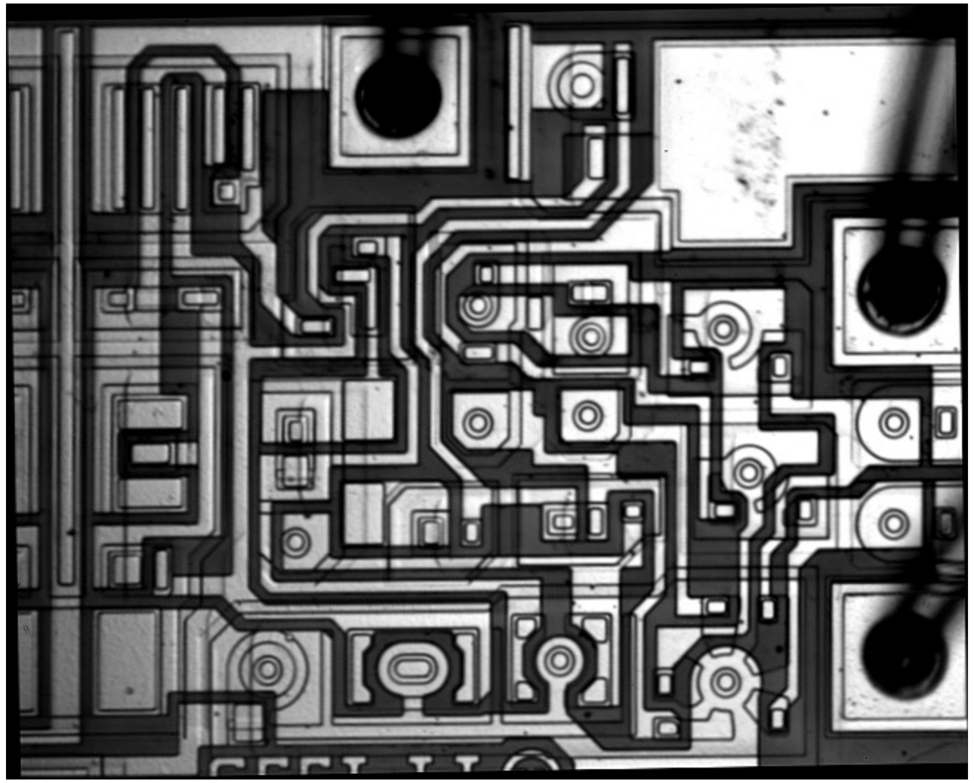
- *Acquired QBB data one month before heavy-ion testing*

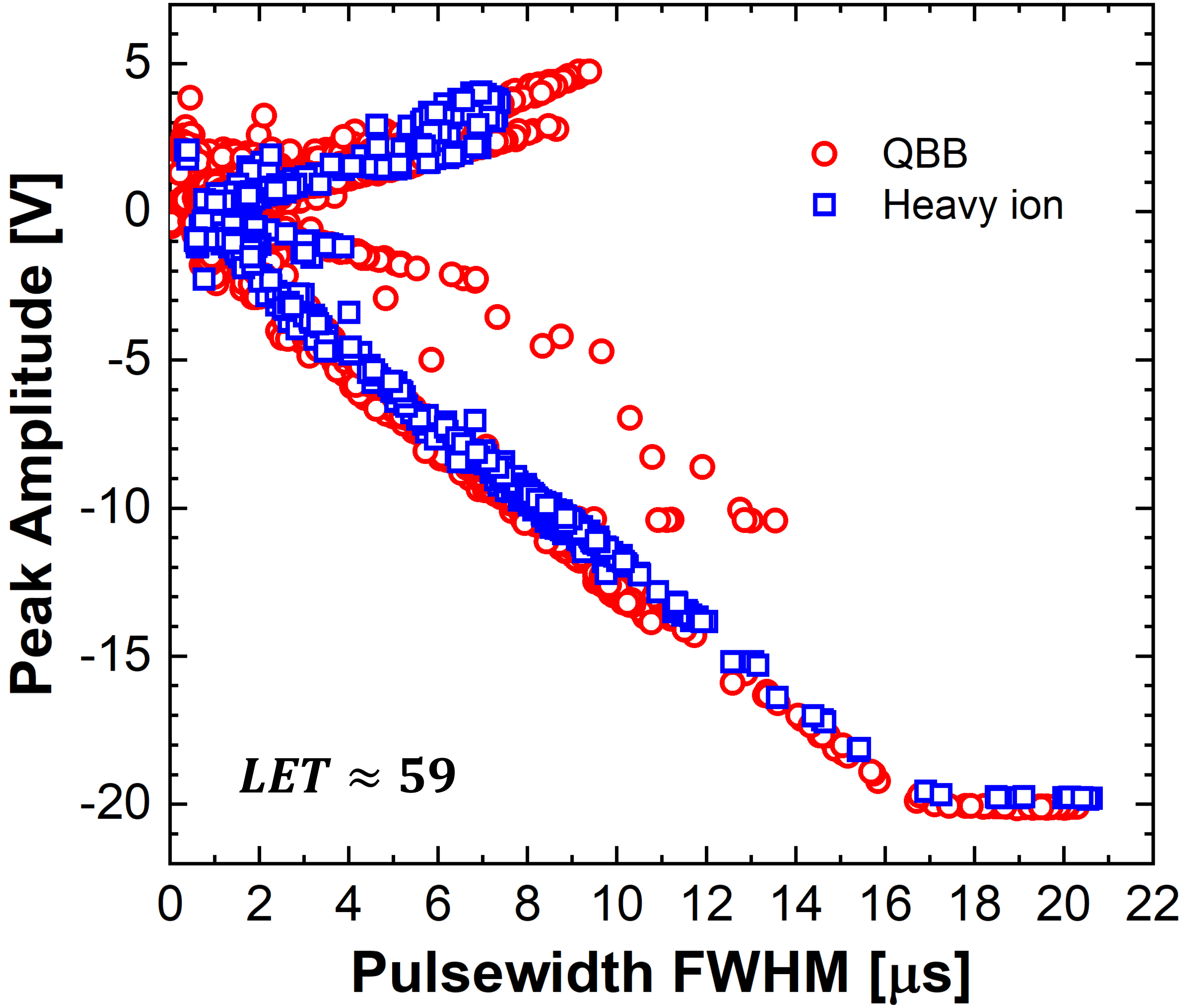




V-Δt Curves for Entire LM124 Chip

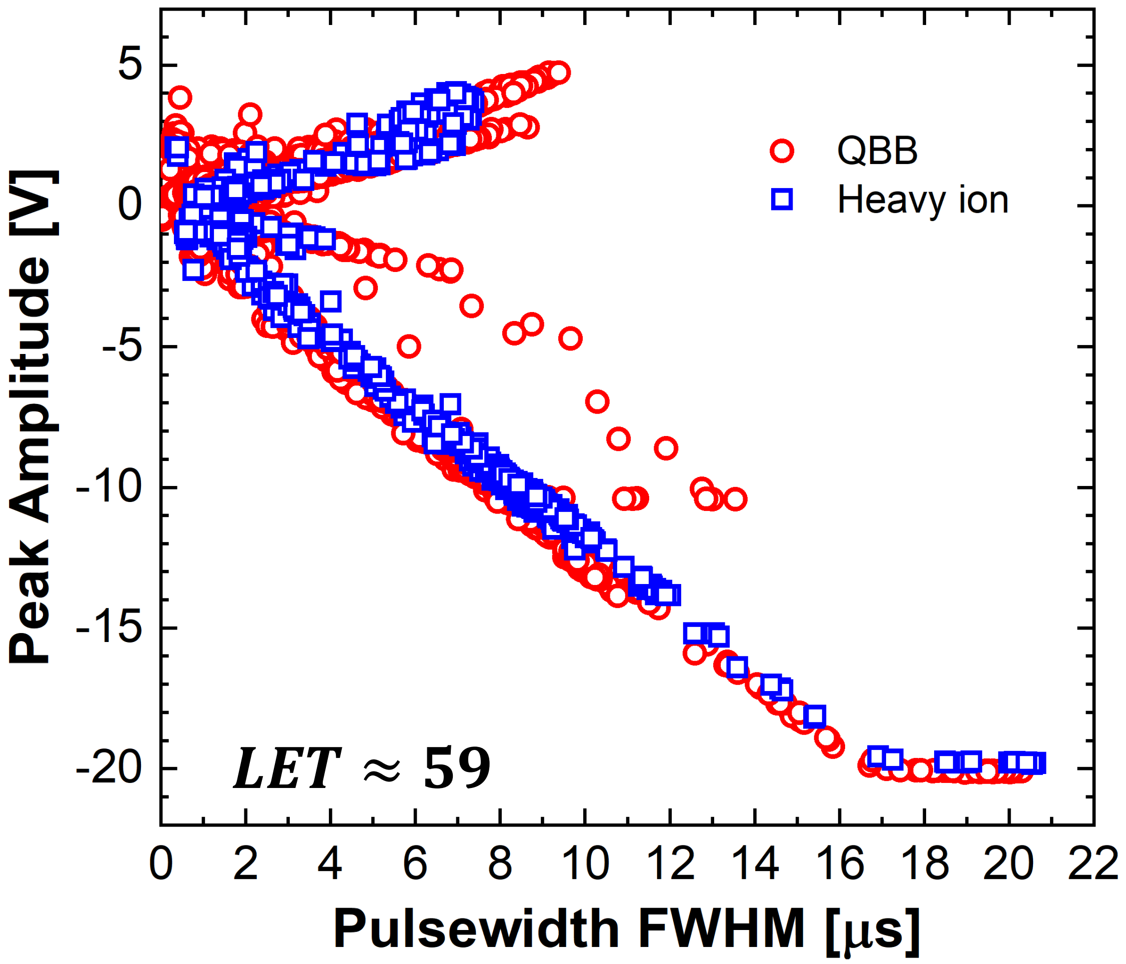
- Two data sets ***show remarkably good correlation*** across all four major branches with both the slopes and end points matching well

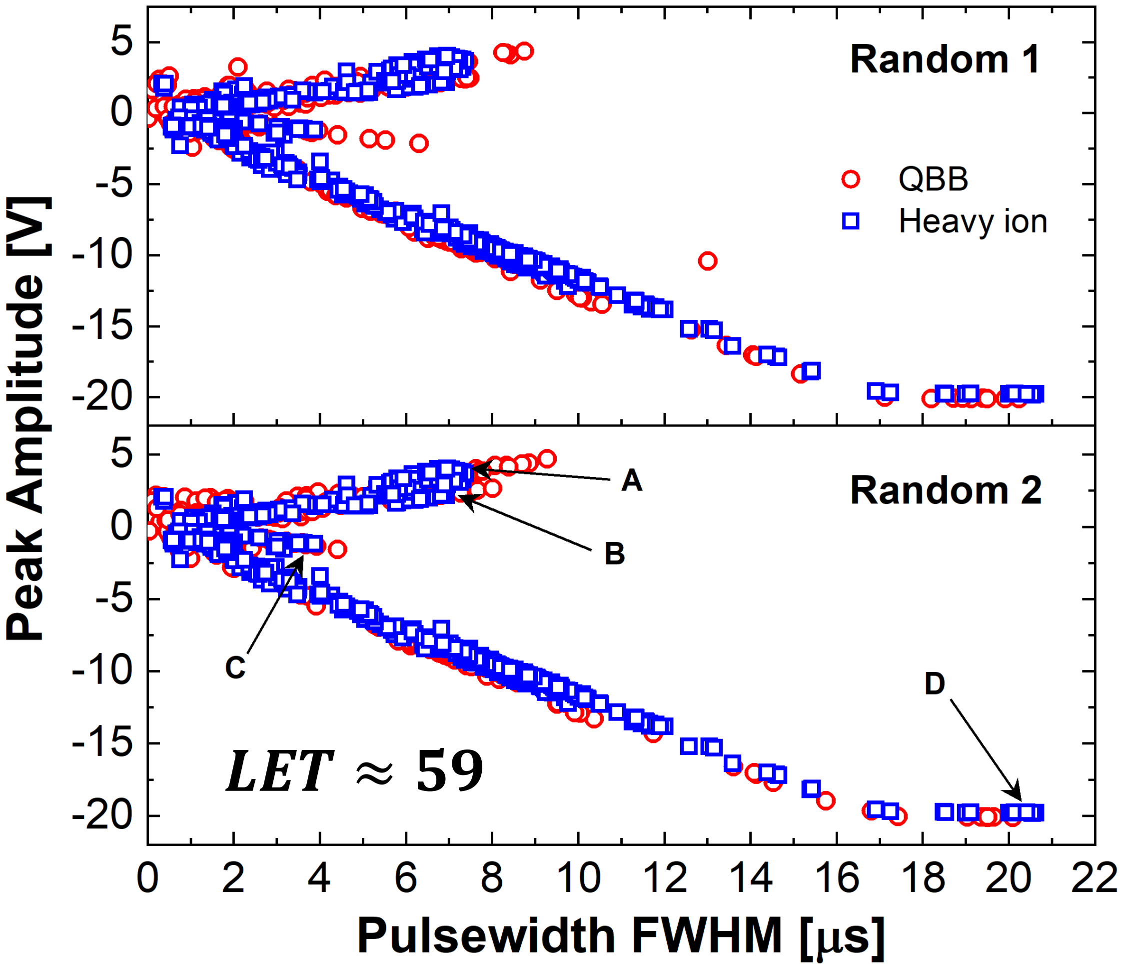




V-Δt Curves for Entire LM124 Chip

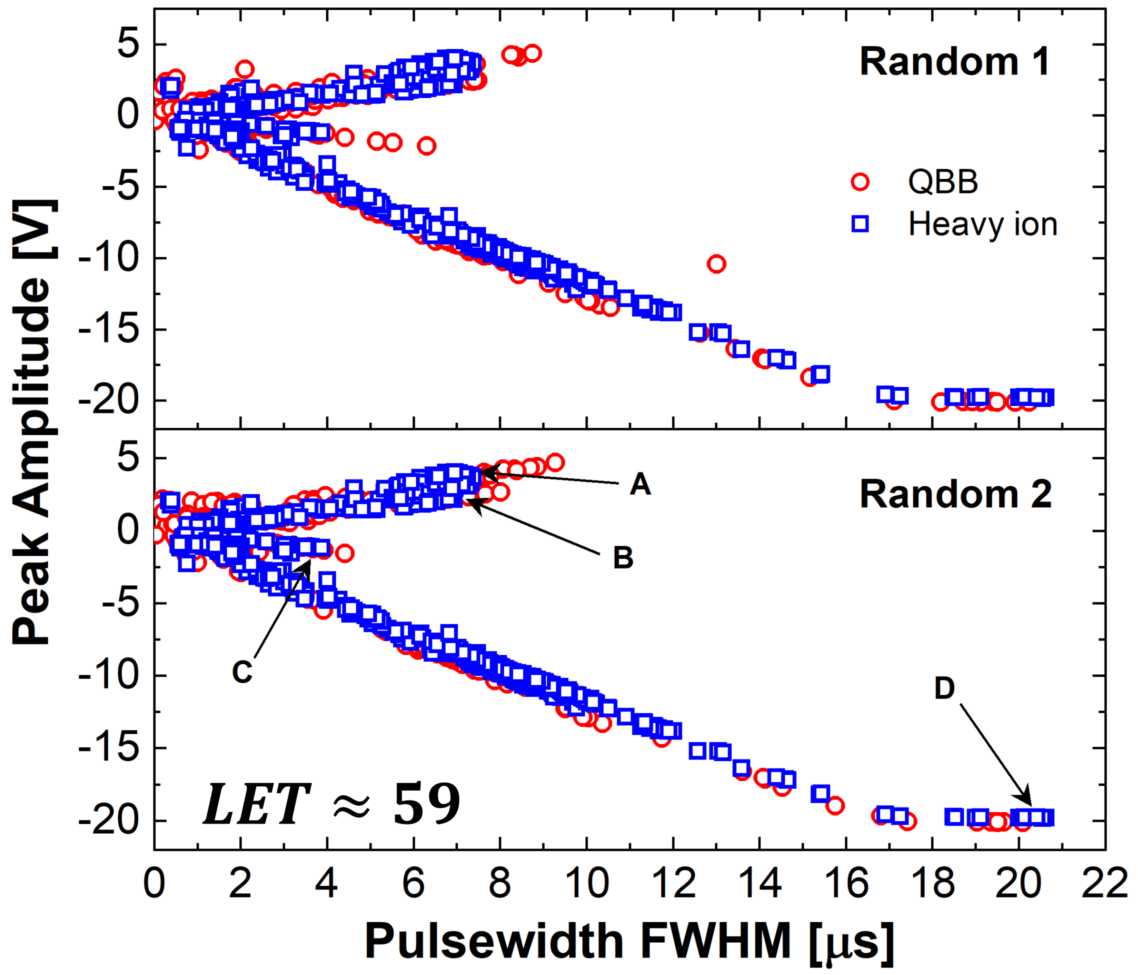
- *Randomly selected 500 SETs to reproduce sparsity of heavy-ion data; improves agreement*

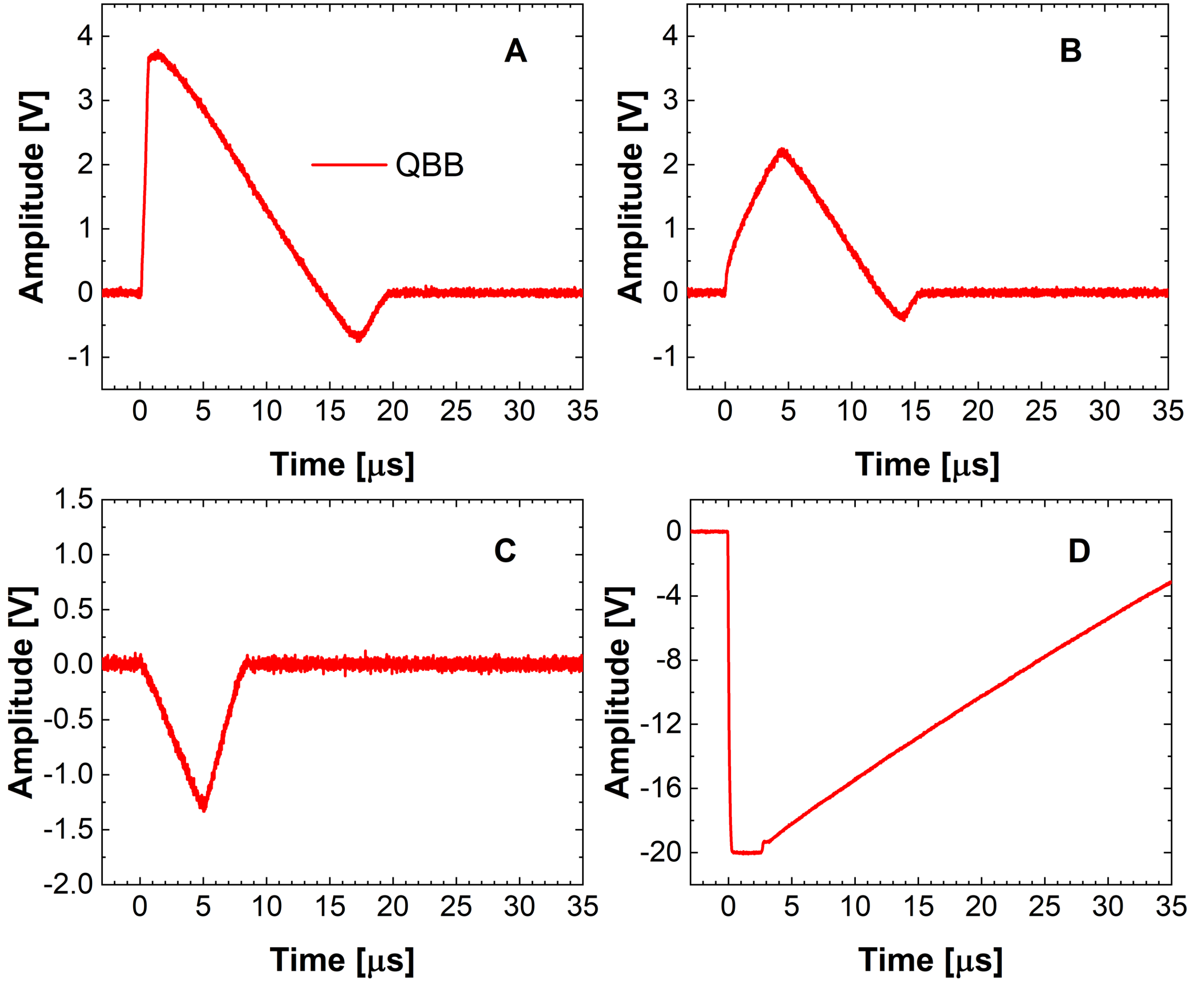




V-Δt Curves for Entire LM124 Chip

- Comparison of respective QBB and Heavy Ion SETs
- Good correlation shown for worst-case SETs





V-Δt Curves for Entire LM124 Chip

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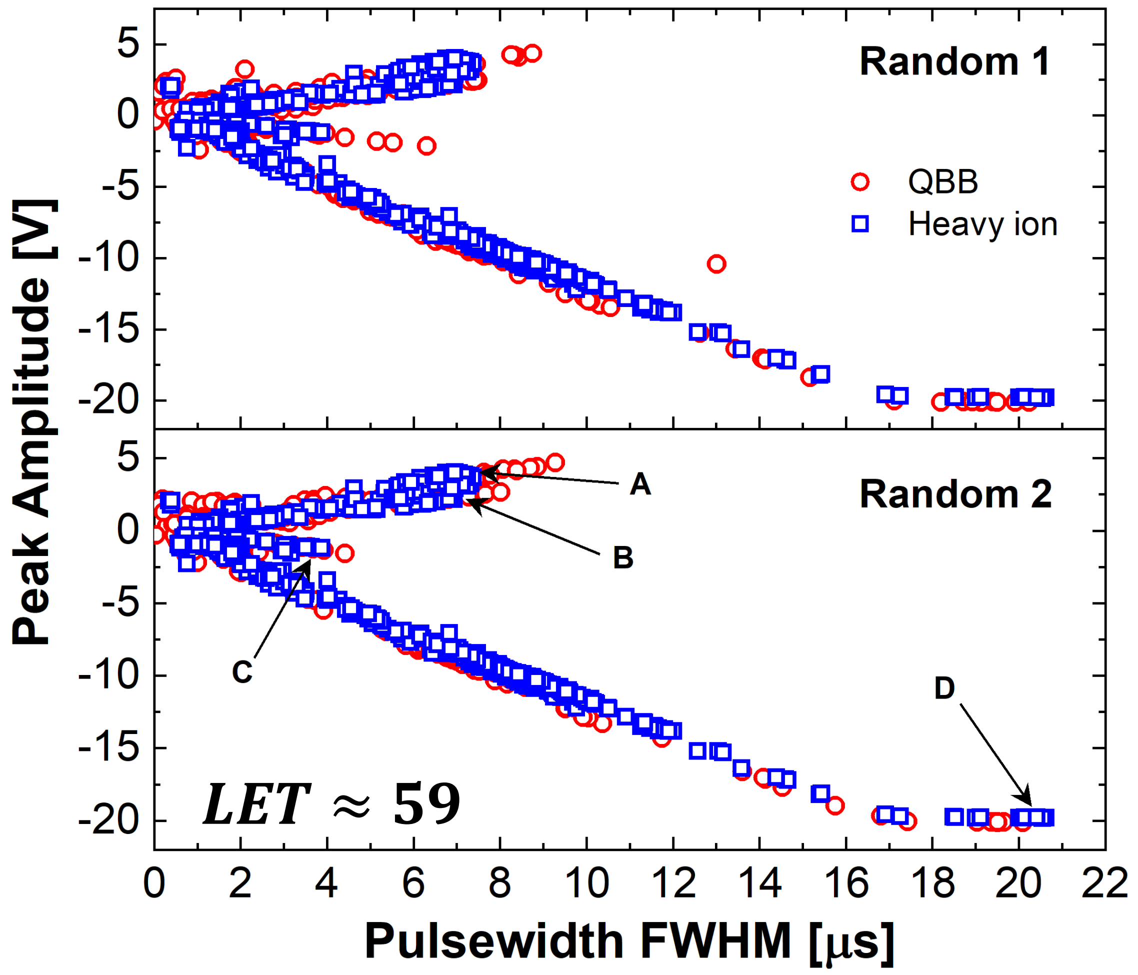
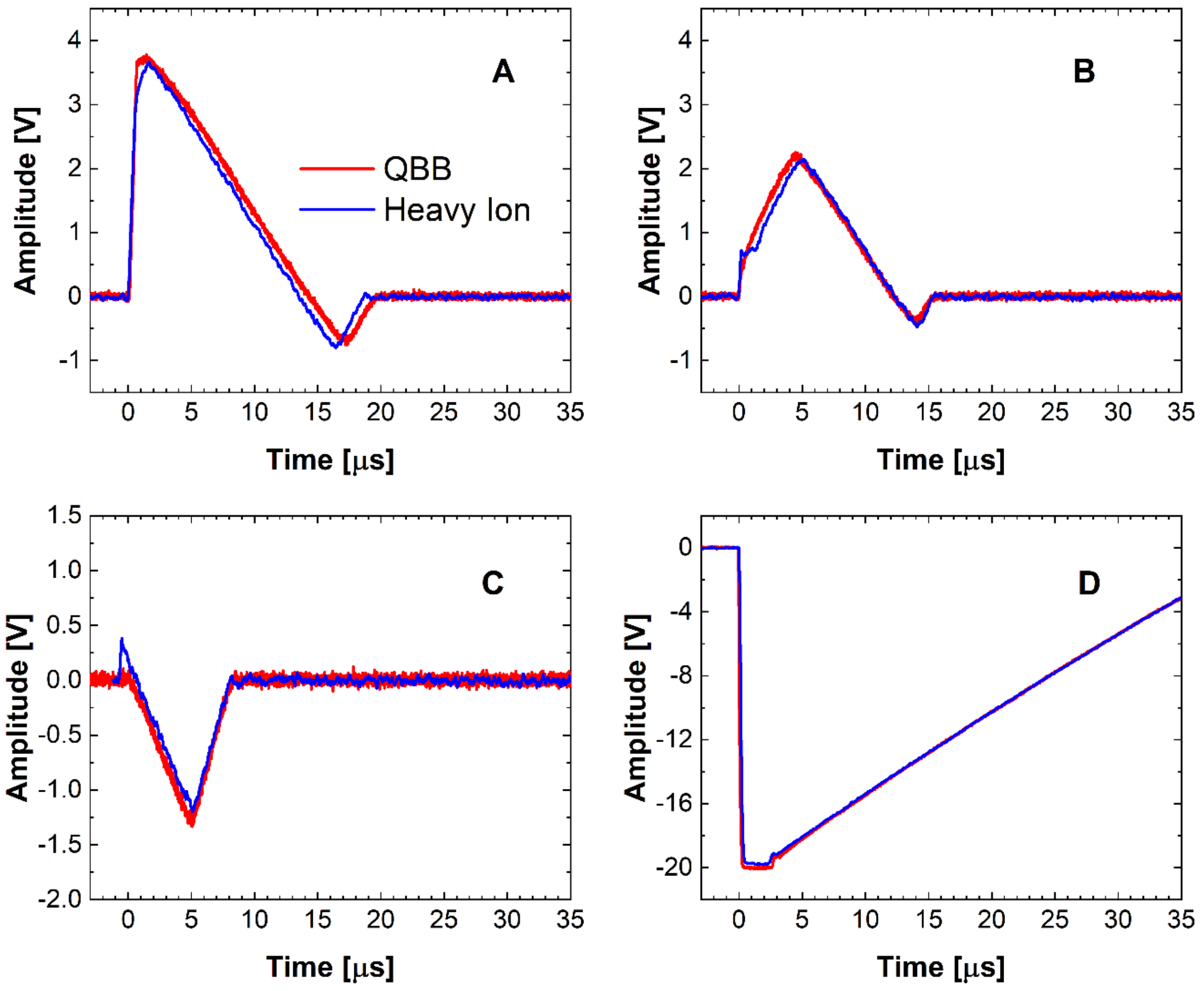
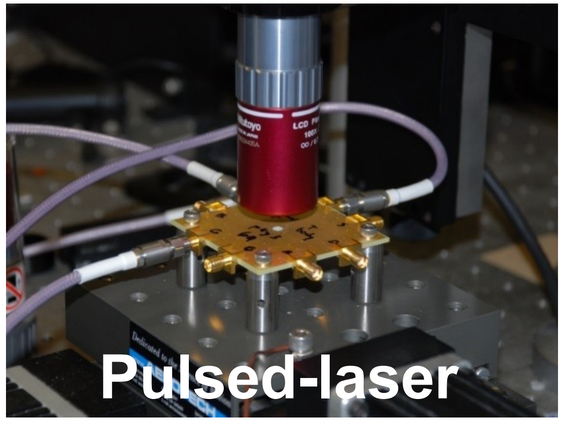
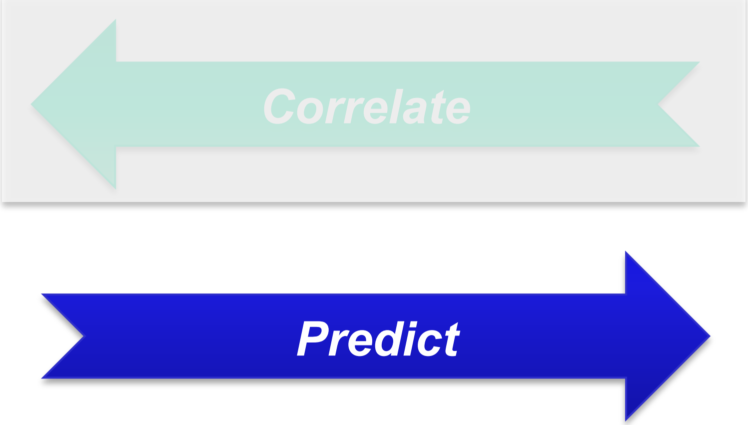


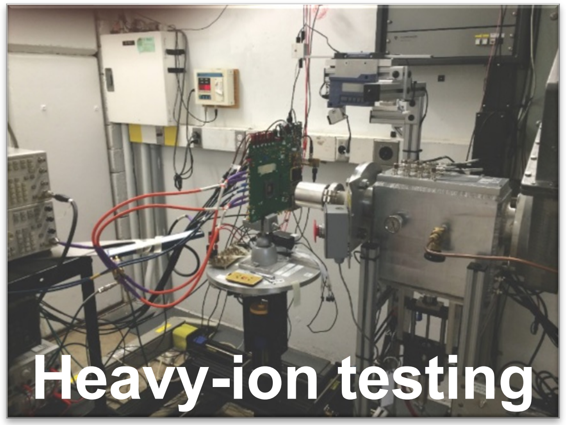


Axicon SET Summary

- **Accurate SET prediction in a complex device has been demonstrated**
  - *Laser-equivalent LET is calculated directly*, without fitting or adjustable parameters
  - Complicated SET response in LM124 demonstrated via whole chip response and worse-case transients
- QBB provides a laser testing approach with *predictive capability* that can potentially help alleviate the burden on traditional heavy-ion testing
- Investigation in wider variety of devices being targeted as well as other SEEs







Summary and Conclusions

- Brief overview of PL SEE
- Theoretical basis
- Experimental examples
  - Historical
  - Current
- Interesting things moving forward
  - Laser/ion correlation
  - PL SEE Part Screening
  - Axicon-based SEE