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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
• **Above-band gap** (*conventional, single-photon*) pulsed laser 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
• **Sub-bandgap** (*two-photon*) pulsed laser can inject charge:
  • in a well-defined **x-y-z location**
  • at a well-defined time
  • and can propagate through silicon wafers
  • but is difficult to quantify
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

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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

- **Conventional:**
  - $\lambda < 1.1 \, \mu\text{m}$
  - Above band gap
  - Single-photon absorption

- **Two Photon:**
  - $\lambda > 1.1 \, \mu\text{m}$
  - Sub-bandgap
  - Two-photon or multiphoton absorption

Band Edge (around 1.1 $\mu\text{m}$ in Silicon)
Optical Excitation of Carriers in Silicon

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

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

$E_g = 1.1\text{eV}$
Optical Excitation of Carriers in Silicon

1-Photon

\[ E_c \] 630 nm

\[ E_g = 1.1 \text{eV} \]

2-Photon

\[ E_c \] 1260 nm

\[ E_g = 1.1 \text{eV} \]

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

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**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)
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:

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

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

\[ I(r, z) = I_0 e^{-\alpha z}; \quad N(r,z) \propto I(r,z) \]
What is meant by:

• “Penetration Depth”?
• “Skin Depth”?

⇒ 1/e depth

\[ I_{1/e} = 0.368I_0 \]

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

\[ I(r, z) = I_0 e^{-\alpha z} \]

\( \lambda = 800 \text{ nm} \)

\( \frac{I}{I_0} \)

63% of Charge Deposited in 1/e depth

\( I_{1/e} = 0.368 I_0 \)
Carrier Density Distribution

1/e Optical Penetration Depth

\[ I(r, z) = I_0 e^{-\alpha z} \]

\[ N(r,z) \propto I(r,z) \]

\[ \lambda = 800 \text{ nm} \]
Nonlinear (Two-Photon) Optical Absorption

Absorption Coefficient, cm\(^{-1}\)

Penetration Depth, \(\mu m\)

- 600 nm
- 800 nm
- 1.06 \(\mu m\)
- 1.26 \(\mu m\)

Wavelength, nm
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:

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

Nonlinear Absorption (Two-Photon)
Nonlinear (Two-Photon) Optical Absorption

Carrier generation equation:

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

- 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
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 3-D mapping and backside illumination.

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

800 nm

Depth in Material, µm
Distance, µm

N \alpha l^2

Depth in Material, µm
Position, µm

1.26 µm

1/e Contour

w(z)

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Pulsed Laser-Induced SEE Experiment

Above-Bandgap Single-Photon

Nd:YAG  ps DL  
1 ps 590 nm  
PD1  
ccd  
DUT  
xyz

Sub-Bandgap Two-Photon

Ti:Al₂O₃  OPA  
120 fs 1.26 μm  
PD1  
NIR FPA  
PD2

Sub-Bandgap Pulsed Laser-Induced SEE Experiment
Two-Photon Absorption

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:

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

- \( \beta_1 \) is proportional to the real part of the nonlinear susceptibility \( (\chi^{(3)}) \)
- \( \gamma_1 \) describes the refraction due to free carriers
- Nonlinear refractive index changes

**Net conclusion**: results described here represent a convenient 0th 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

Surface elements opaque to optical excitation

Substrate transparent to single photon sub-bandgap excitation

Tightly focused two-photon excitation source

Region of 2 Photon Carrier Generation

Recent Developments:
Quantitative Characterization of TPA SEE

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Region of 2 Photon Carrier Generation

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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 other effects
- NRL has been initiated a program to address this problem
- The current status of this effort is presented here

\[ N \propto I^2 \]

\[ w(z) \]

\[ 1/e \text{ Contour} \]

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), $\beta$

Nonlinear refraction (NLR), $n_2$

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

$\text{Re}\{\chi_{NL}\}$:
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)
Controlling the Focused Laser Spot Size

**Underfilled Objective: Gaussian Beam**

**Overfilled Objective: Non-Gaussian (Truncated) Beam**
1.6 nJ Truncated Beam

Markedly non-Gaussian
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?

\[
dN(r, z) \frac{dt}{\Delta t^2} = \alpha l(r, z) + \beta_2 I^2(r, z)
\]

Experimental Observable:

\[
Q_{dep} \sim \frac{(PE)^2}{r^4 \Delta t^2}
\]

Calibrated InGaAs Photodiode:

\[
V(t) \sim PE
\]
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

- NIR camera
- DUT
- BS2
- BS3
- AC
- NLPD
- L2
- P1 λ/2
- 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

Microscope objective
Sensitive volume
Laser beam

Backside

Microscope objective
Sensitive volume
Laser beam

$2w_0$
$n_{Si} \approx 3.5$
Relevant Experimental Parameters: Laser-induced electron-hole generation rate

\[ G(r, z, t) = \eta \alpha \left( \frac{2TE_0}{w_0^2} \right)^{3/2} \left( E_\gamma \pi^2 w_0^2 \tau \frac{w_{Si}(z)^2}{w_0} \right) e^{-\alpha z} e^{-\frac{t^2}{\tau^2}} \]
Laser Parameter Summary

• **Wavelength**
  – Determines absorption in silicon
  – The longer the deeper (but lower resolution)

• **Pulse duration**
  – The shorter the closer from particles

• **Spot size**
  – Limited by diffraction
  – Minimum value = maximum fidelity

• **Energy**
  – Main experimental variable
  – Difficult link with LET

Fixed by laser source technology & cost

Often fixed by optical setup, but can be adjusted
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

1. Define Grid
2. Choose Laser Energy
3. Select Position
4. Laser Strike
5. Logic State control

If SEU?
- Yes: Reinitialization
- No: Proceed to next step

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

Laser Pulse Energy

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From SEU mappings to X Section analysis
CASE STUDY 2

Single-Event Upset Mapping in a commercial SRAM
Case study 1: HM6504 SRAM

- \( V_{DD} = 5V \)
- \( I_{DD\text{max}} = 50mA \)
- Wavelength : 800nm
- Pulse length : 1ps
- Spot 1/e \( \Phi \) : 1.1\( \mu \)m
- Scanning step : 1\( \mu \)m
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 addresses 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

All to 0

All to 1

4 pJ

20µm
SEU mapping

7.2 pJ

All to 0

All to 1
SEU mapping

10.4 pJ

All to 0  All to 1

20µm
SEU mapping

20 pJ

1 to 0

0 to 1

20µm

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SEU Laser cross-section

Laser pulse incident energy (pJ)

Laser SEU cross-section (cm²)

Data
- ▲ All-to-0
- ▼ All-to-1
- • Average

Corrected for
- ○ Beam
- ◇ Beam & Metal
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 operational 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

Heavy ion (Br)

Laser (800nm)
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

- 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.

DDC RDC19220
1-Photon

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

\[ I(r, z) = I_o e^{-\alpha z} \]
Latch-Up Screening of COTS Parts for Space Missions

DDC RDC19220
Latch-Up Screening of COTS Parts for Space Missions

- 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.

SEL sensitive areas in COTS RDC

(DDC RDC19220)

Latch-Up Screening of COTS Parts for Space Missions

• 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

SEL sensitive areas in COTS RDC

(DDC RDC19220)


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CASE STUDY 5b
Laser-Induced Latchup Screening and Mitigation in CMOS Devices
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

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

Broad beam ions, 40MeVcm²/mg or focused pulsed Laser

“1”

“0”

Buffer

Single-shot oscilloscope

High-Z probe

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

4 rows of 200 inverters

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

Laser strike positions
Ø 1.2 µm
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.

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.

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).

Propagagation 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

SET Propagation: Summary and Conclusions

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

CASE STUDY 7

Two-Photon-Induced Single-Event Effects:

3-D Mapping of SET
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)

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

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


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

LM124 Q20 TPA SET: “Z” Dependence

Overlayers

P (C2)  P(C1)  P

N (base)  N+ (buried layer)  P+ (iso)  P+ (iso)  P (substrate)

“C1” Transient

C1-Sub “Shunt”

“C2” Transient

Dependence
CASE STUDY 8

Backside, Through-Wafer, Two-Photon-Induced Single-Event Effects
Backside “Through-Wafer” TPA Illumination

![Graph showing absorption coefficient and penetration depth vs. wavelength.](image)

- Absorption Coefficient, cm$^{-1}$ vs. Wavelength, nm
- Penetration Depth, µm

Key points:
- 600 nm
- 800 nm
- 1.06 µm
- 1.26 µm
Cross Section of Modern Device

Metal

Tungston plugs

Circuit Layer

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Backside “Through-Wafer” TPA Illumination

- Circuit Layer(s)
- Substrate transparent to single photon sub-bandgap excitation
- Surface elements opaque to optical excitation
- Tightly focused two-photon excitation source
- Region of 2 Photon Carrier Generation

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

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

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
Evaluation of RHBD Approaches

Phase-Locked Loop

Evaluation of RHBD Approaches
SEE Hardened Phase-Locked Loop

7.0 nJ

Loveless, et al., IEEE TNS

VANDERBILT UNIVERSITY
School of Engineering

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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 \(\rightarrow\) 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
New Approach:

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

  ![Diagram of Single-Event Effects in Substrate-Etched SOI Devices]

- Initial demonstration: application to a 90 nm Freescale SRAM
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.
Cut a hole in the package 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 in package

Silicon thickness = 700 A

Silicon Dioxide thickness = 1450 A

Overlayers = 5 microns


SERESSA 2015 – Puebla, Mexico
Single-Event Effects in Substrate-Etched SOI/CMOS Devices

Backside View

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
Initial Concerns:

- Device functionality
- Heat dissipation
- SEU performance
Optical Excitation of Carriers

- Single photon absorbed
- By the material (silicon)
- Creates a single e-h pair
Optical Excitation of Carriers

90 nm SRAM
SEU Threshold
590 nm
$\text{SPA}_{th} = 0.77 \text{ pJ}$

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

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

Silicon thickness = 700 Å
Silicon Dioxide thickness = 1450 Å

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

Freescale 90 nm SRAM


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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

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

Error Map for
Bits 1, 2, and 3


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

4-bit errors are common

Maps for Individual Bit Errors near Threshold

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

2D Mapping with 293 nm Laser Pulse

Near threshold

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

Pulsed Laser Single-Event Effects

CASE STUDY 10

Two-Photon-Induced Single-Event Effects:

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

Subcollector-Substrate Junction
p-type substrate: 8-10 Ω•cm

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

MODEL VALIDATION AND CALIBRATION

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

Subcollector-Substrate Junction
p-type substrate: 8-10 Ω•cm

Collector: Case 2
V_C = +3 V

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

$E_g = 3.4 \text{ eV}$

$E_g = 4.2 \text{ eV}$
Basic Mechanisms: Single-Event-Induced Charge Collection in GaN HEMTs

Investigation into the SET mechanisms of GaN HEMTs:

• The first demonstration of laser-induced SEE in $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N/GaN}$ 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

- 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+)

- 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.

\[ V_g = 0 \text{ V; biased } \text{“on”} \]

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

- Cross section vs. LET
  - $L_0$
  - $\sigma_S$

Pulsed laser

- Laser cross section vs. Energy
  - $E_0$
  - $\sigma_{LS}$

Rate prediction

- Designs comparison
  - Parametric evaluation
  - Screening

Complex case studies

- Rare events analysis
- Rad-hard design
What should I use for:

<table>
<thead>
<tr>
<th></th>
<th>Heavy ions</th>
<th>Laser</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Single</td>
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<tr>
<td>Screening devices with different designs in the same technology node for SEU-MBU</td>
<td>++</td>
<td>+++</td>
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<tr>
<td>Accurate SEU cross section vs LET measurement for a memory device</td>
<td>+++</td>
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<tr>
<td>Testing fault-tolerant system level solutions</td>
<td>+</td>
<td>+++</td>
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<tr>
<td>Analyzing deep charge collection mechanisms</td>
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<td>+</td>
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<tr>
<td>Mapping SEL sensitive area of a flip-chip device</td>
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<tr>
<td>Validating an SEL-free design</td>
<td>++</td>
<td>+</td>
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<tr>
<td>Studying rare SEFI events in a recent digital device</td>
<td>++</td>
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<tr>
<td>Defining design margins for analog SET in linear devices</td>
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<tr>
<td>Validating the radiation hardening efficiency of a design update</td>
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<tr>
<td>Obtain a 3D view of charge collection volumes</td>
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