RADLAS 2024

BASICS AND DEFINITIONS FOR LASER TESTING OF SINGLE-EVENT EFFECTS

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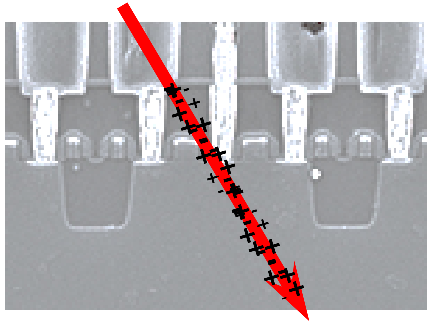
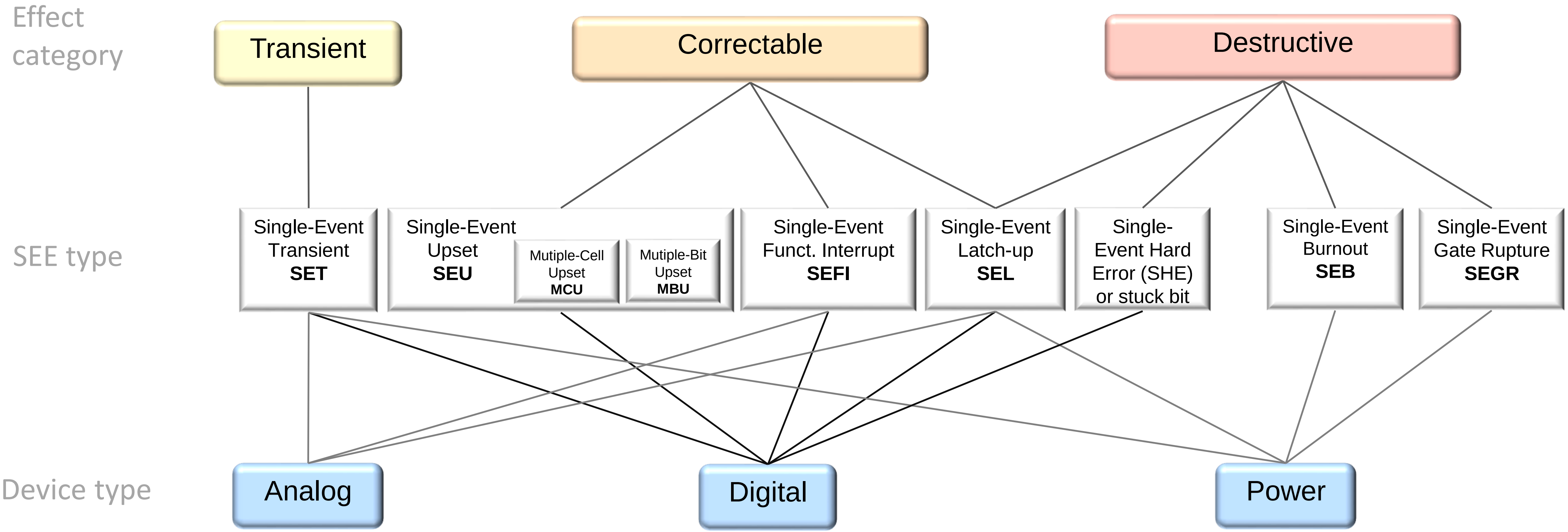
Content

- SEE reminders
- Principles of laser testing
- Experimental parameters
- Laser-ion correlation
- Summary

Single-Event Effects

- Effects induced by the interaction of a single particle with the materials of a device





Effect category

Transient

Correctable

Destructive

SEE type

Single-Event Transient **SET**

Single-Event Upset **SEU**

Mutiple-Cell Upset **MCU**

Mutiple-Bit Upset **MBU**

Single-Event Funct. Interrupt **SEFI**

Single-Event Latch-up **SEL**

Single-Event Hard Error (SHE) or stuck bit

Single-Event Burnout **SEB**

Single-Event Gate Rupture **SEGR**

Device type

Analog

Digital

Power

Linear Energy Transfer (LET)

- The LET quantifies the transfer of energy from a particle to the target material

  LET = Energy transfered per unit of length

- For the particles and energies of interest:

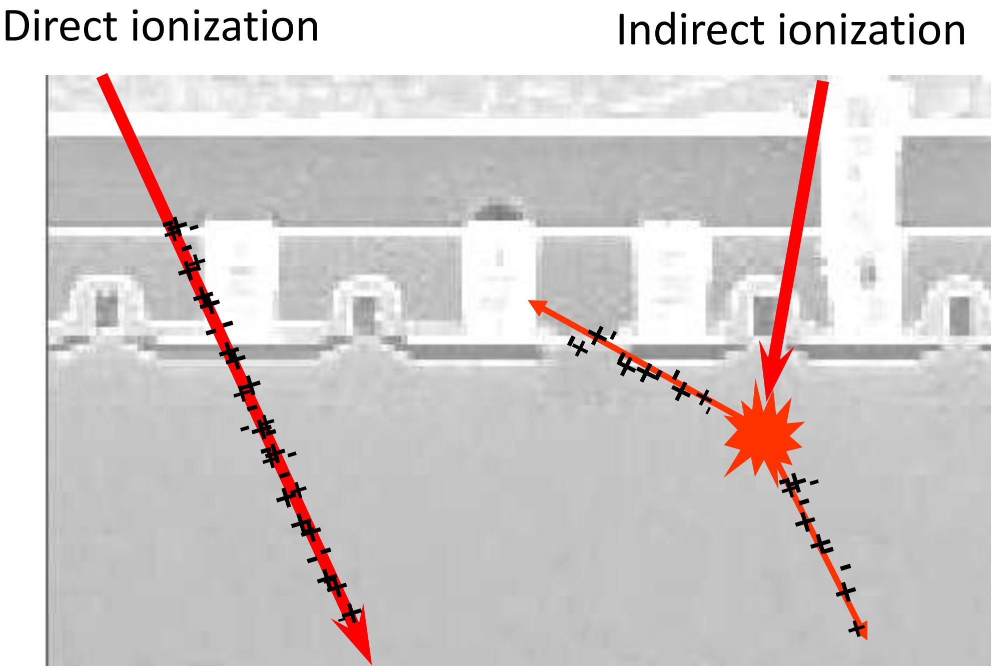
  LET ≈ electronic stopping power

- For a given target material, LET is normalized with respect to the material density:

  LET_{Si} expressed in $\text{MeV.cm}^2\text{.mg}^{-1}$

- In device physics, the interaction is modeled by the electron-hole pair generation rate

$$G_{ion} \propto LET$$



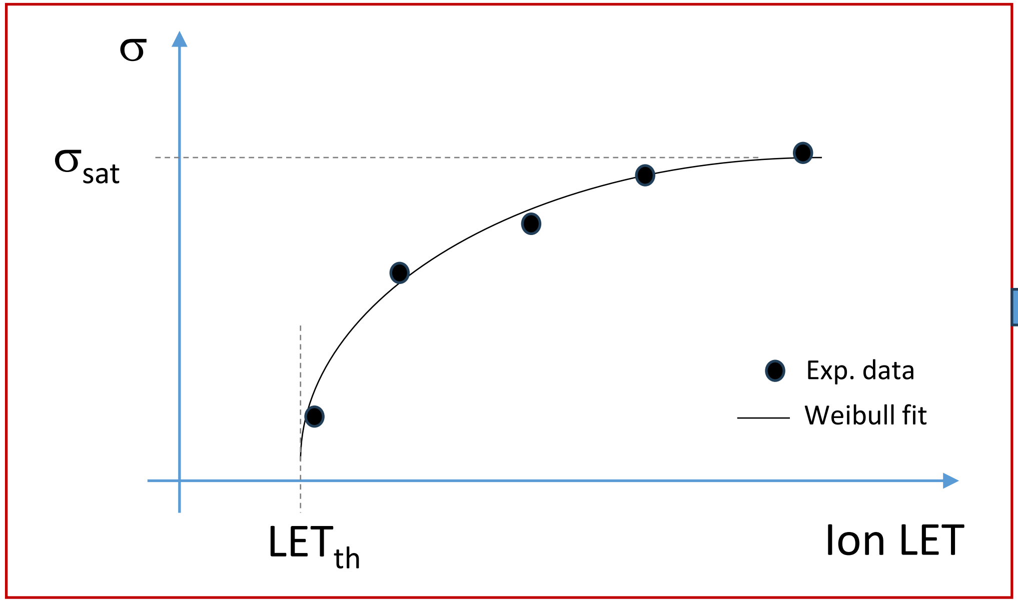
Testing for Single-Event Effects

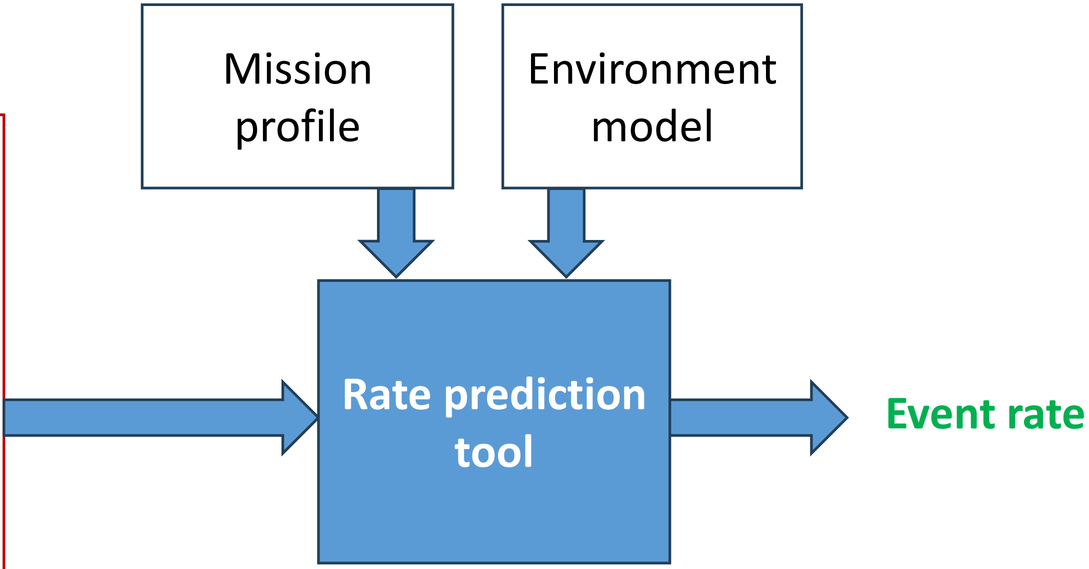
- Expose the device to a fluence $\boldsymbol{\Phi}$ of particles (mono-species and mono-energetic beam in most cases)

- Count the number $\boldsymbol{N}$ of (non-destructive) events of interest

- Derive the event cross-section $\boldsymbol{\sigma} = \frac{\boldsymbol{N}}{\boldsymbol{\Phi}}$

Experimental measurement of a device sensitivity





Mission profile

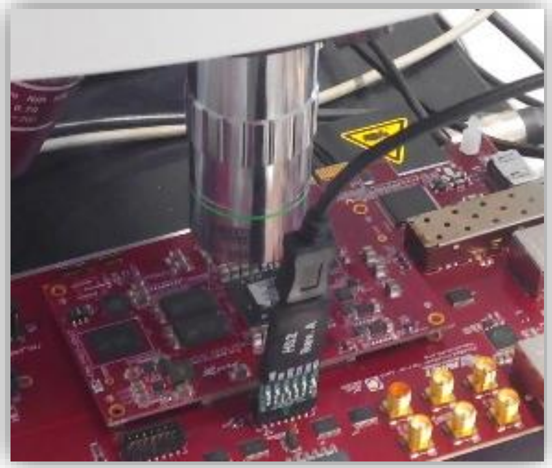
Environment model

Rate prediction tool

Event rate

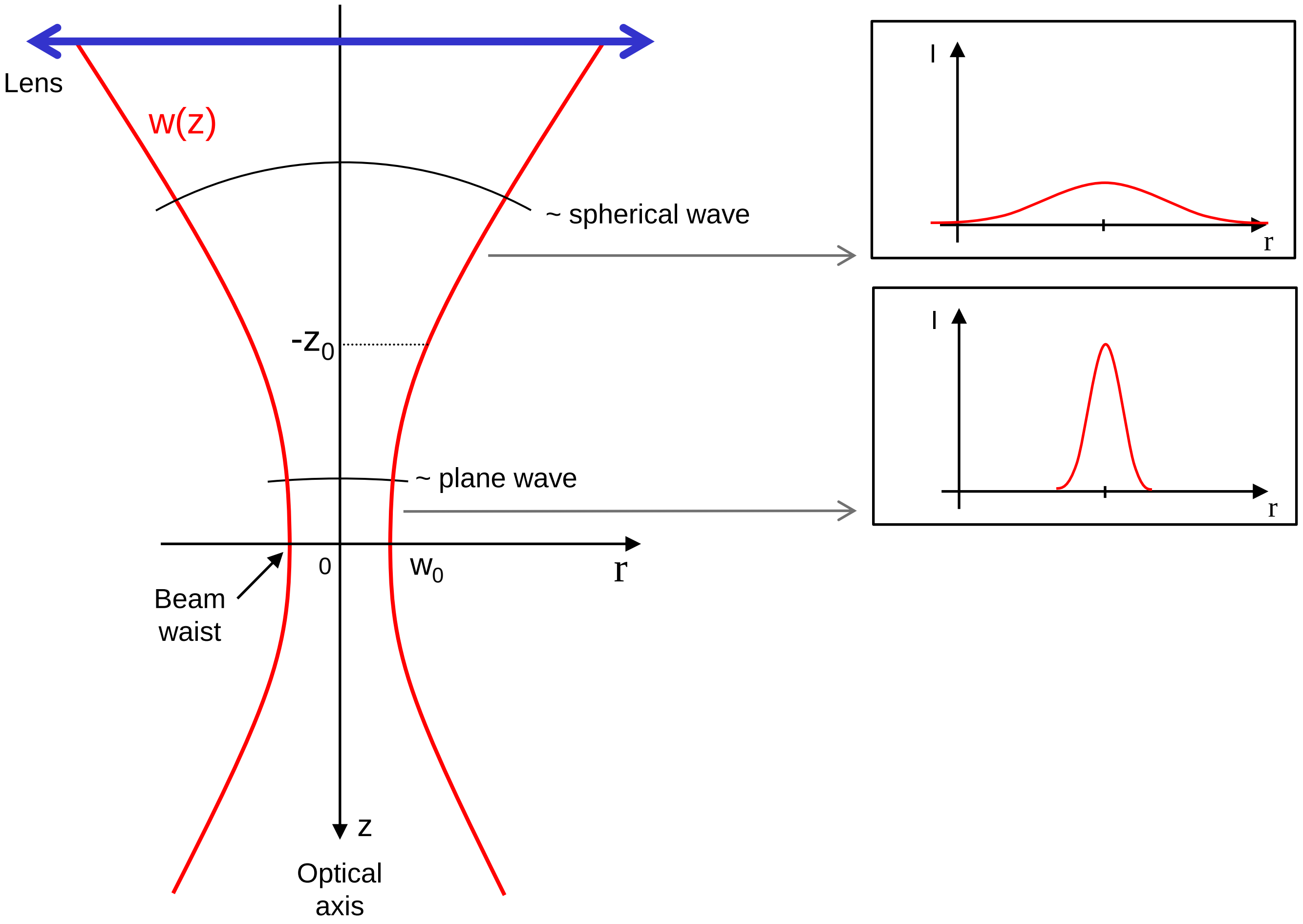
Can we measure this using a laser?

Principles of laser testing



- Using a focused beam of short laser pulses to generate electron-hole pairs in the semiconductor volume of a device
  - Short pulses to reproduce the transient nature of an ionizing radiation interaction
  - Focused beam to reproduce the local nature of the interaction
- Main advantages of laser testing
  - **Spatial resolution** of sensitive regions of a component
  - Convenient **in-lab tool** to reduce testing costs & constraints
- Main limitations
  - Requires **optical access** to the active semiconductor volume
  - **Calibration** of laser pulse energy with respect to LET has uncertainties
- No ionization of the dielectric materials ⇒ no Total Ionizing Dose
  - Good for searching rare events
  - Laser testing not suitable if dielectric ionization may contribute to the SEE (SEGR in power devices, SEU in flash memory cells…)
- No atomic or nuclear interaction ⇒ no Displacement Damage

Focusing a Gaussian laser beam…



Optical intensity

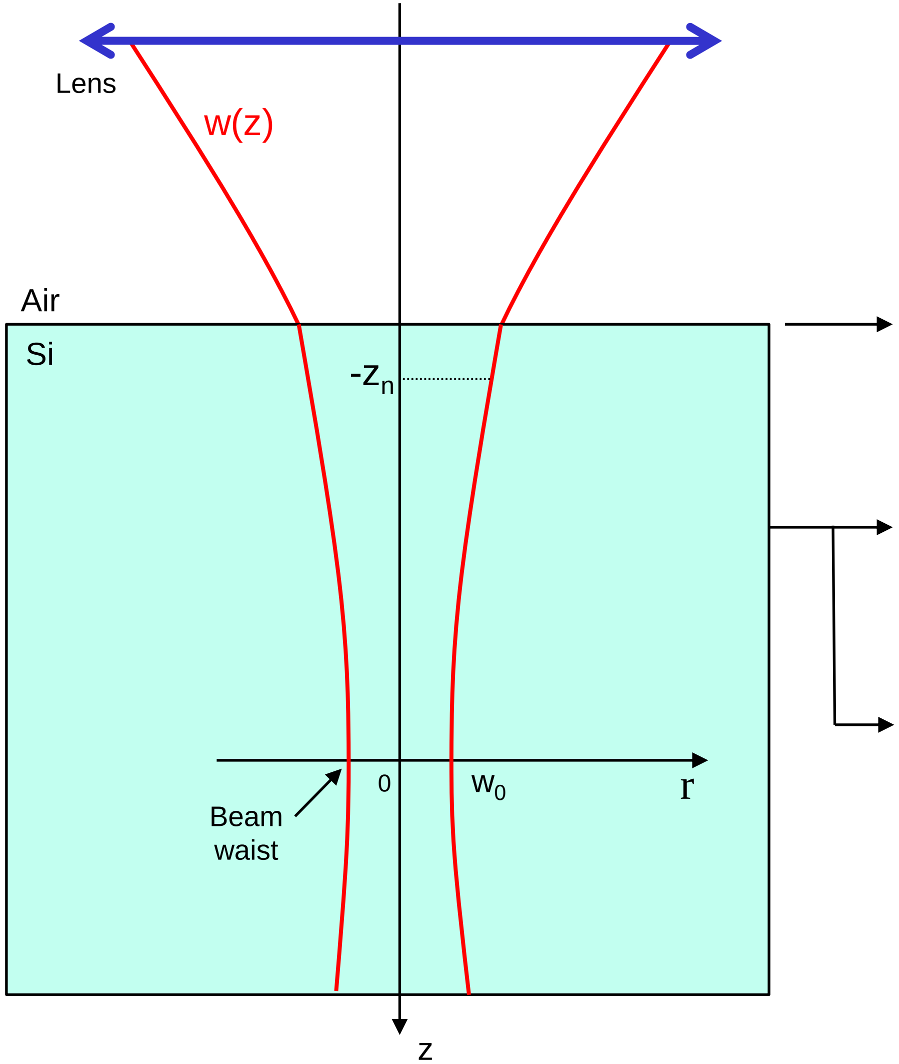
$$\mathrm{I}(r,z,t) = I_0 \frac{w_0^2}{w(z)^2} e^{-\frac{2r^2}{w(z)^2}} e^{-\frac{t^2}{\tau^2}}$$

with $$w(z) = w_0 \sqrt{1 + \left(\frac{z}{z_0}\right)^2}$$

$$z_0 = \frac{\pi w_0^2}{\lambda_0}$$

Confocal (Rayleigh) parameter

… into a Si Substrate



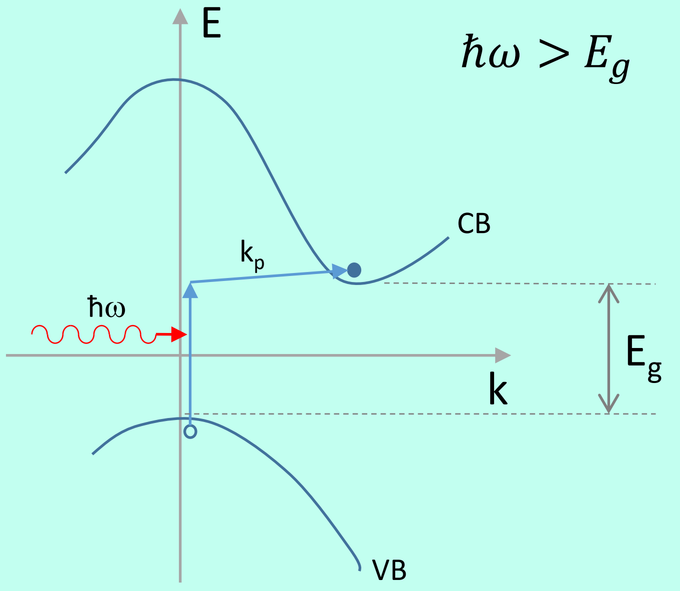
Transmission: $T \approx \dfrac{4n}{(1+n)^2}$ ~ 69% @1064nm

Refraction: $z_0 \rightarrow z_{Si} = n_{Si} z_0$

Absorption ?

Linear optical absorption in Si

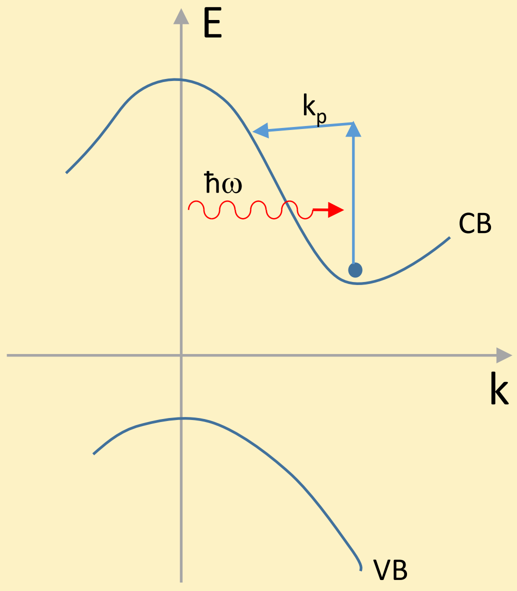
Interband absorption (α_{IB})



⇒ generation of an **electron-hole pair**

+

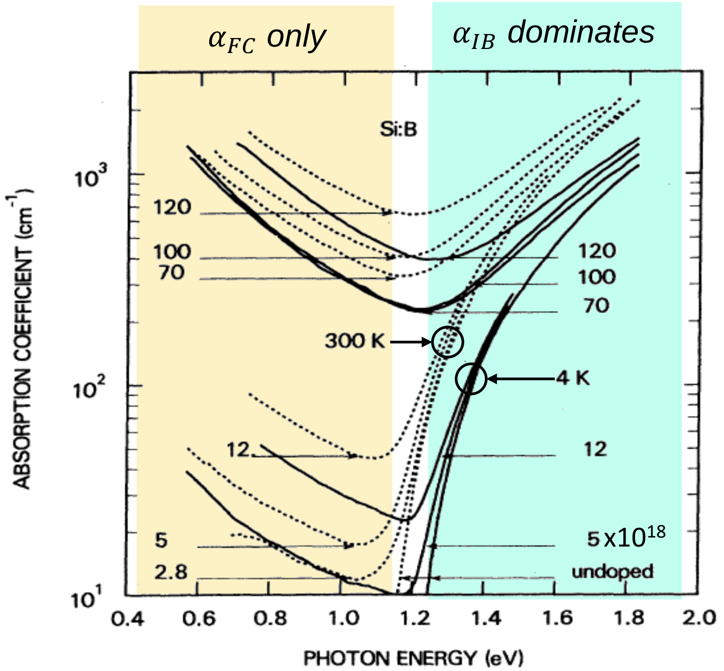
Free carriers absorption (α_{FC})



⇒ heating of carrier, then lattice

=

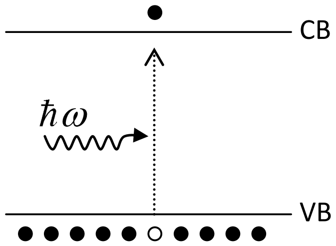
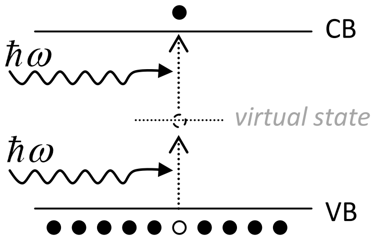
Total absorption ($\alpha = \alpha_{IB} + \alpha_{FC}$)



[P. E. Schmidt, Phys. Rev. B, 1981]

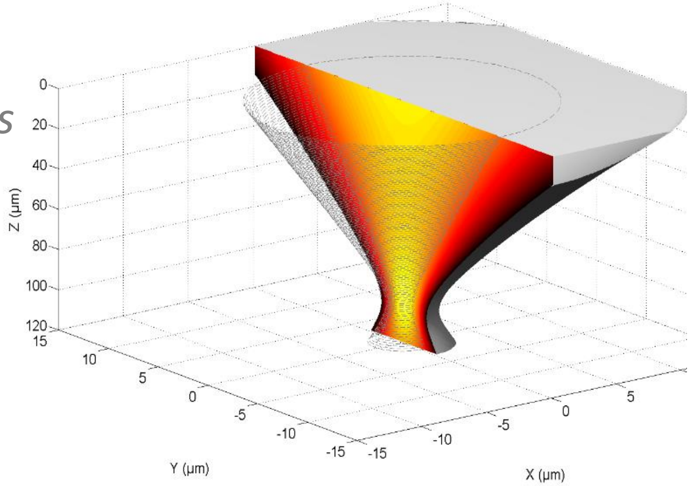
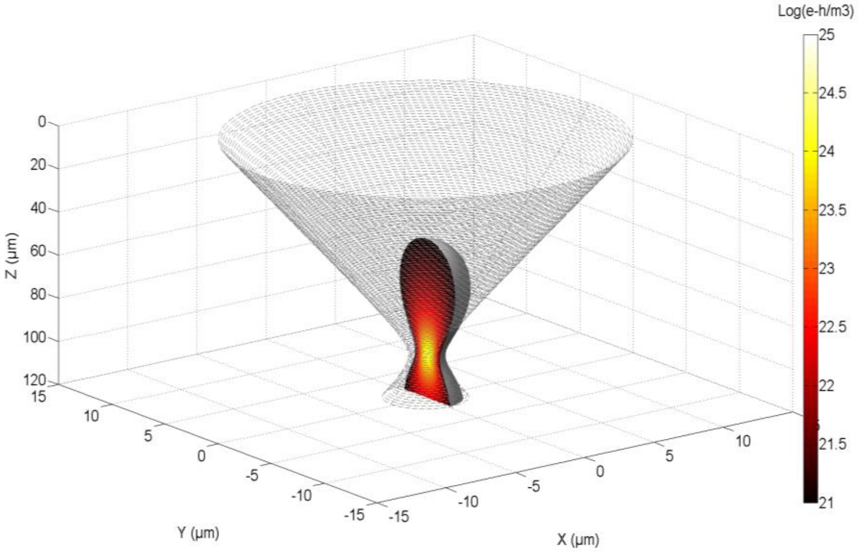
- Phonon-assisted transition ⇒ dependence on T°
- Fermi's golden rule ⇒ transition rate locally proportional to optical intensity

Single-photon vs Two-photon absorption

	Single-Photon Absorption (SPA)	Two-Photon Absorption (TPA)
Principle		
Condition	$\hbar\omega > E_g$ $\lambda_0 < 1100nm$	$E_g > \hbar\omega > \frac{E_g}{2}$ $1100nm < \lambda_0 < 2200nm$

- ☐ Requires higher optical intensity
  - ⇒ Shorter pulse duration

Single-photon vs Two-photon absorption

	Single-Photon Absorption (SPA)	Two-Photon Absorption (TPA)
Charge generation	$G = \frac{\alpha_{IB}}{\hbar\omega} I$	$G = \frac{\beta}{2\hbar\omega} I^2$
Typical induced charge tracks		
Radial profile	Gaussian	Gaussian, $\sqrt{2}$ smaller at same λ
Longitudinal profile	Convergence + exponential attenuation	Complex, limited to focal region

Single-photon vs Two-photon absorption

	Single-Photon Absorption (SPA)	Two-Photon Absorption (TPA)
Charge quantity	Proportional to laser pulse energy	Proportional to (laser pulse energy)^2
Lateral resolution	Reference	Slightly improved [Shao et al, IPFA 2011]
3D resolution	No (> 10µm)	Yes, ~ 3µm [Faraud et al, IEEE TNS 2011]
Focus sensitivity	Low	High
Optimal for	Chip-level testing	Cell-level detailed mapping

Complementary techniques

Typical use cases of laser testing

Research

Charge collection mapping & mechanisms analysis

- Technology characterization
- Dedicated test structures

RHBD

Mapping sensitive areas for specific events

- Usually following an accelerator campaign
- Circuit response analysis, circuit or layout design corrections

RHBD
RHA

Local threshold measurements

- Comparing different layouts, electrical designs or the effect of external parameter values
- Extracting the Safe Operating Area of power devices

RHA
RHBD

Fault injection

- Complex test setup validation
- Firmware, software or system-level impact analysis or mitigation evaluation

Mature applications

RHA

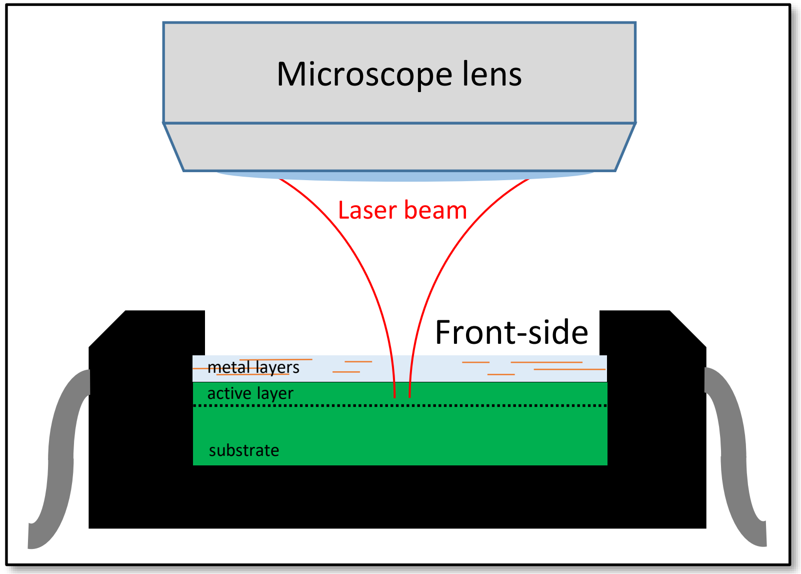
Devices screening

- Reduce the number of candidate parts for a project, before an accelerator test campaign
- Is this COTS SEL-free ?
- RHA with low test budget

Growing applications

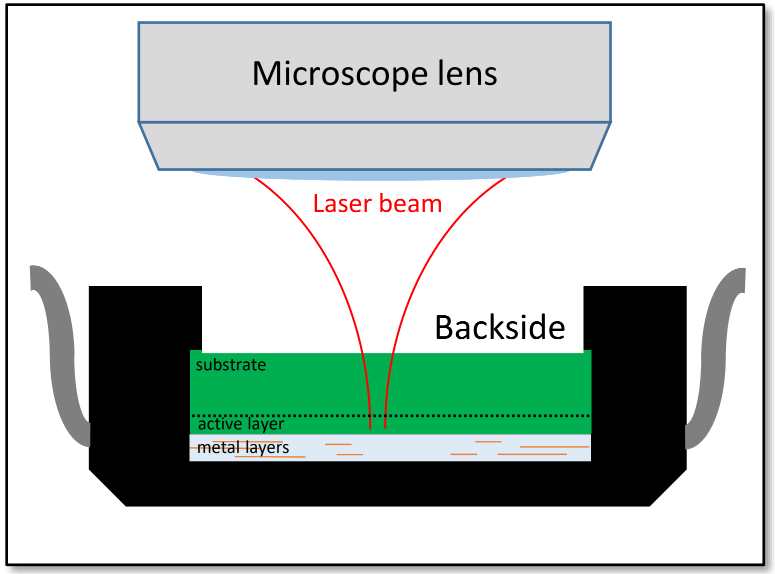
Two practical approaches

Front-side testing



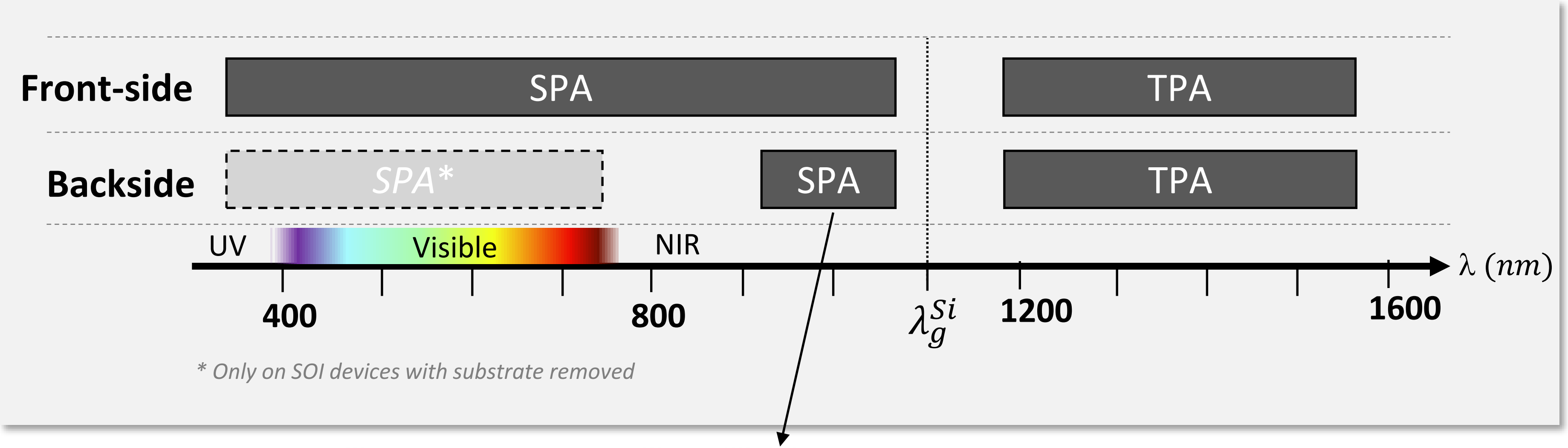
- ❑ The historical approach
- ❑ Beam focused through top dielectric layers
- ❑ **Impossible with modern technologies**: metal layers are too dense and too many
- ❑ Today, front-side testing only useful for
  - ❑ Old linear technologies
  - ❑ Test structures with « dummies » exclusion area

Backside testing

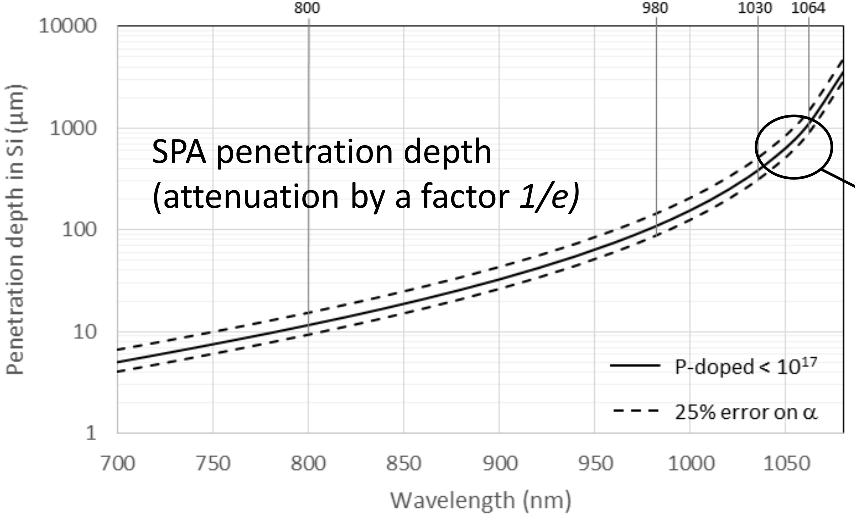


- ❑ Today's common approach
- ❑ Beam focused through the substrate
- ❑ **Mandatory** for all Si technologies < 0.25µm
- ❑ Requires a long penetration depth
- ❑ Requires backside optical access
  - ❑ Sample preparation
  - ❑ PCB hole for non flip-chip ICs

Parameters: **Wavelentgh** (for Si devices)



** Only on SOI devices with substrate removed*



Substrate thinning usually NOT required
for backside SPA@1064nm or TPA

Variations

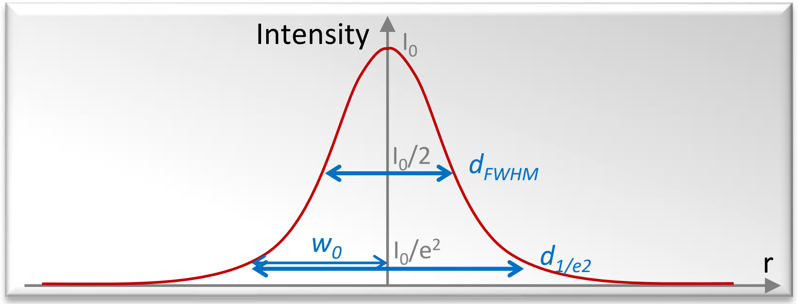
Using different **wavelengths** for testing different technologies
- SPA in GaAs [McMorrow, 1995]
- TPA in SiC devices [Mbaye, 2013] [Johnson, 2019]
- SPA, TPA, 3PA in GaN devices [Khachatrian, 2016], [Ngom, 2021]
- SPA in Black Phosphorus devices [Liang, 2019]

Parameters: **Spot size**

- ❑ Should be as small as possible to get closer from an ion track
- ❑ Spot size always larger than an ion track; may lead to « spot size effects »
- ❑ **Not limiting the achievable mapping resolution nor the dimensions of testable devices**
- ❑ May drift over time in free-space optical setups: <u>periodic monitoring required</u>

- ❑ **Beam spot size vs beam-waist:**

$$d_{1/e^2} = 1.7\, d_{FWHM} = 2w_0$$



- ❑ Smallest possible beam-waist:

$$w_0 = M^2 \frac{\lambda_0}{\pi \ NA}$$

Beam quality factor

Numerical aperture of focusing lens

Example:
with a good optical setup:
$M^2 = 1.2$
$\mathrm{NA} = 0.7$
$\Rightarrow d_{1/e^2} \approx 1.16\mu m\ @1064nm$

- ❑ SPA: charge track spot size = optical beam spot size
- ❑ TPA: charge track spot size = optical beam spot size / $\sqrt{2}$

Variations

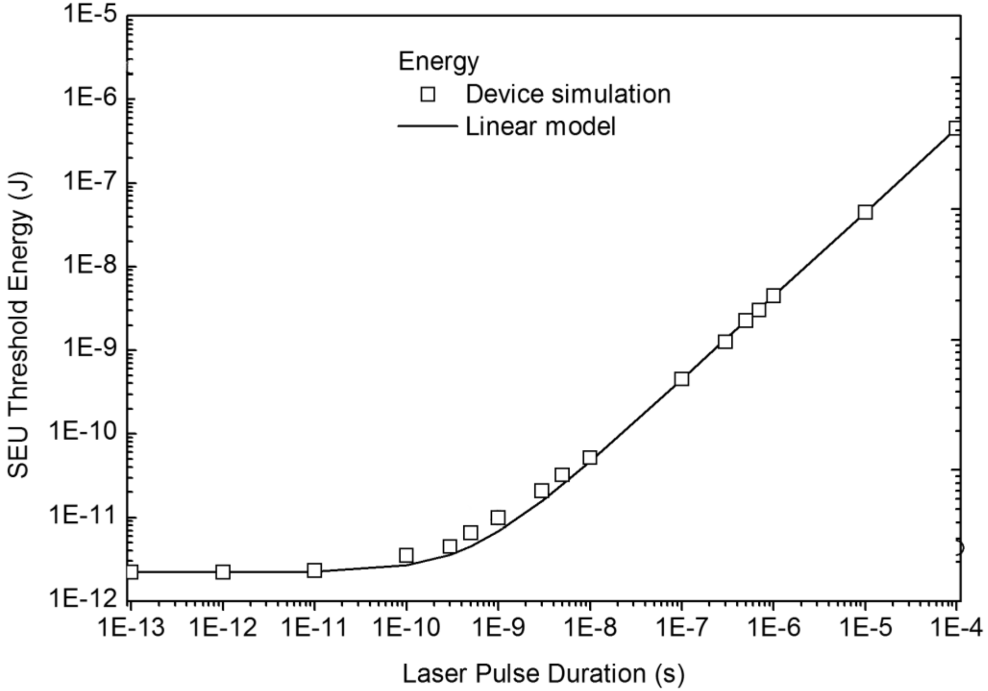
Using larger **spot sizes**
"Local" irradiation for quicker screening [Chumakov, 2011]
Using specific **beam structure**
Bessel beam for longer TPA spot [Hales, 2020]

Parameters: **Pulse duration**

- Laser pulse duration must be short enough to reproduce the real dynamics of an SEE
  - Particle time-of-flight, e-h pairs generation and thermalization: ~1ps
  - Device response (charge collection, circuit feedback): from a few ps to ns
  - Laser pulse time-of-flight in Si (12fs/µm) is negligible

⇒Laser pulse duration should be shorter than the device electrical reaction time

- Longer pulse durations may lead to:
  - Erroneous threshold measurements
  - Activation of different failure mechanisms



[Douin et al, IEEE TNS 2006]

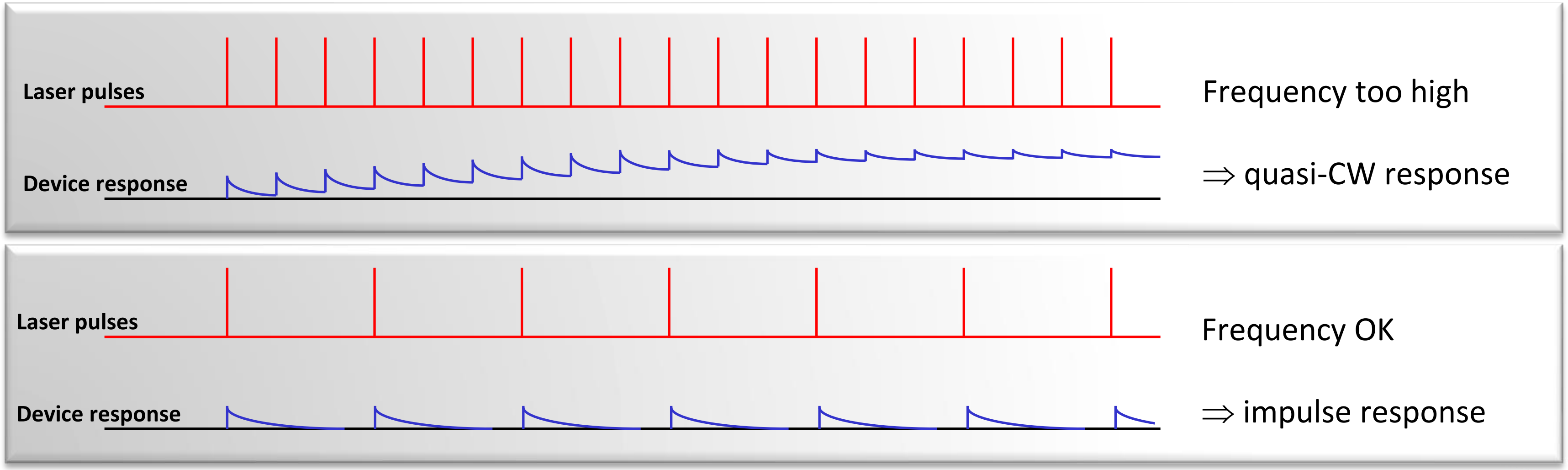
- Useful ranges
  - SPA
    - [1 , 50] ps
  - TPA
    - [100 , 500] fs

Parameters: **Pulse Frequency**

- Pulse frequency (repetition rate) may be controlled directly within the laser source or by external modulators
- Using a high pulse frequency is tempting to rapidly increase the pulse fluence and reduce scanning time

BUT

- Pulse period should be long enough to enable the device to return to a steady state (including charge transport + circuit effect + **local temperature**) between two consecutive pulses



Frequency too high

⇒ quasi-CW response

Frequency OK

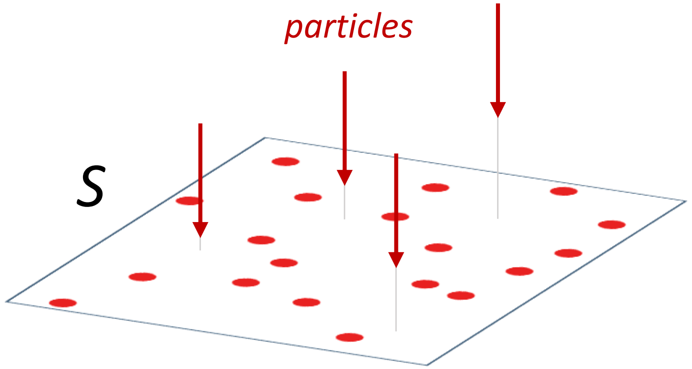
⇒ impulse response

increased risk of laser-induced damage

- Max usable frequency depends on DUT technology, scanning motion speed…
  - Should be < 1kHZ in most cases

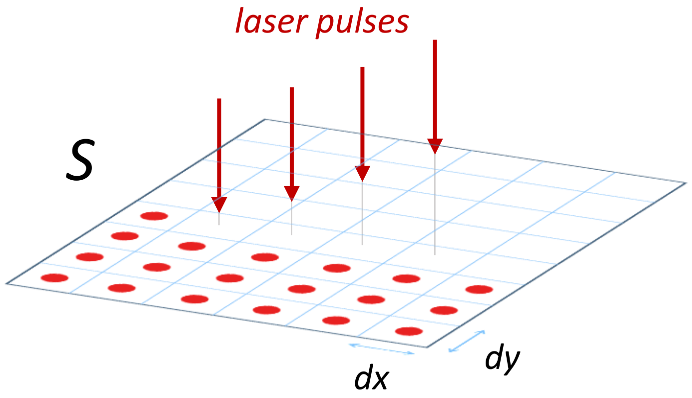
Parameters: **Scan Resolution** or **Pulse Fluence**

PARTICLE BROAD-BEAM TESTING



Particle fluence: $\Phi = \frac{n_{particles}}{S}$

LASER TESTING



dx, dy = scanning **resolution** (or steps)

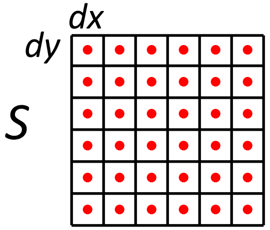
Laser pulse fluence: $\Phi = \frac{n_{pulses}}{S} = \frac{1}{d_x d_y}$

Resolution (dx=dy)	**Fluence**
1 µm	10^8 cm^{-2}
3 µm	10^7 cm^{-2}
10 µm	10^6 cm^{-2}
31 µm	10^5 cm^{-2}

The choice of the scanning steps should be done independently of any consideration on the laser spot size.

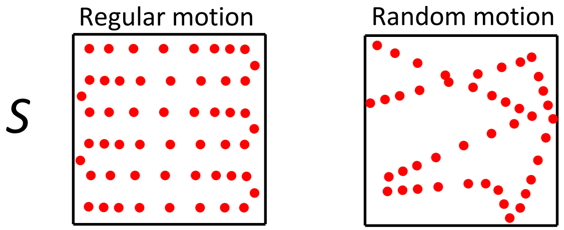
Parameters: **Scan Resolution** or **Pulse Fluence**

- For **mapping**:
  - Define the required X and Y resolution
  - Pulses usually delivered over a regular grid in synchronous mode (1 laser pulse & 1 DUT measurement per grid pixel)



$$\Phi = \frac{n_{pulses}}{S} = \frac{1}{d_x d_y}$$

- For **screening** or **counting** events:
  - Define the required target fluence
  - Pulses can be delivered at constant frequency *f* (asynchronous mode) while scanning
  - *f* defined to stay in the impulse response regime and to prevent events pile-up according to the tester loop



Tester dead-time

$$\Phi = \frac{f \times \left(t_{scan} - t_{off}\right)}{S}$$

Variations

Using specific **scanning method**

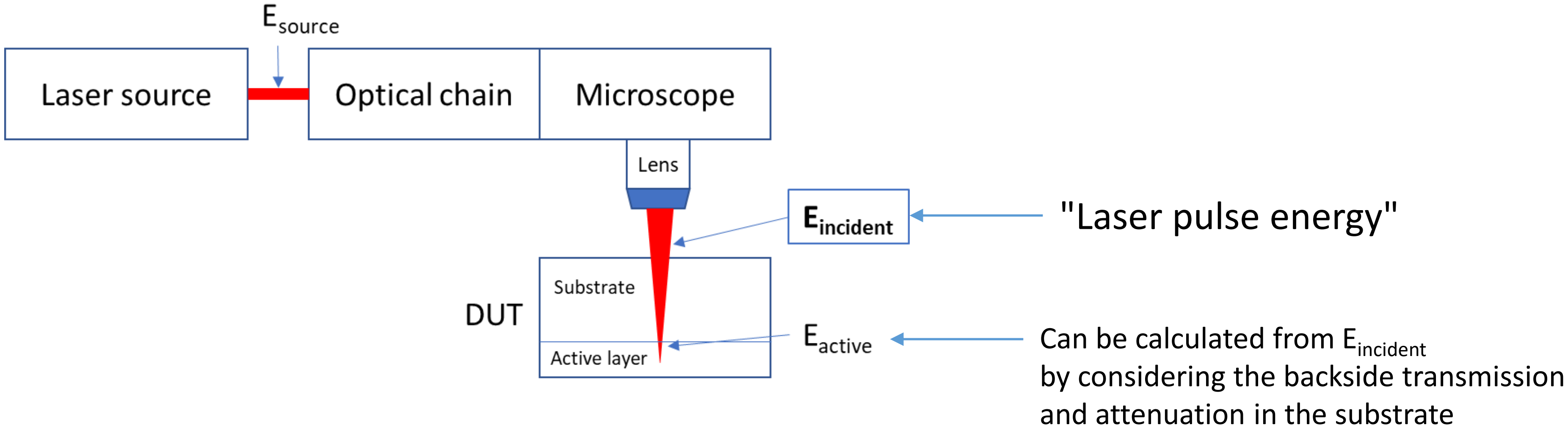
Spiral scanning motion [Chugg, 2011]

Fast scanning the beam using galvanometer-based mirrors [Cannon, 2017]

Parameters: **Pulse Energy**

- Main variable parameter during a laser test
  - Controls the amount of generated charge
  - Can be varied almost continuously and rapidly
  - In-line measurement required

- Useful range: from fJ to 10s of nJ depending on wavelength, DUT substrate…
  - Easily accessible equivalent LET range with SPA: 10^{-3} to 10^{3} MeV.mg^{-1}.cm²

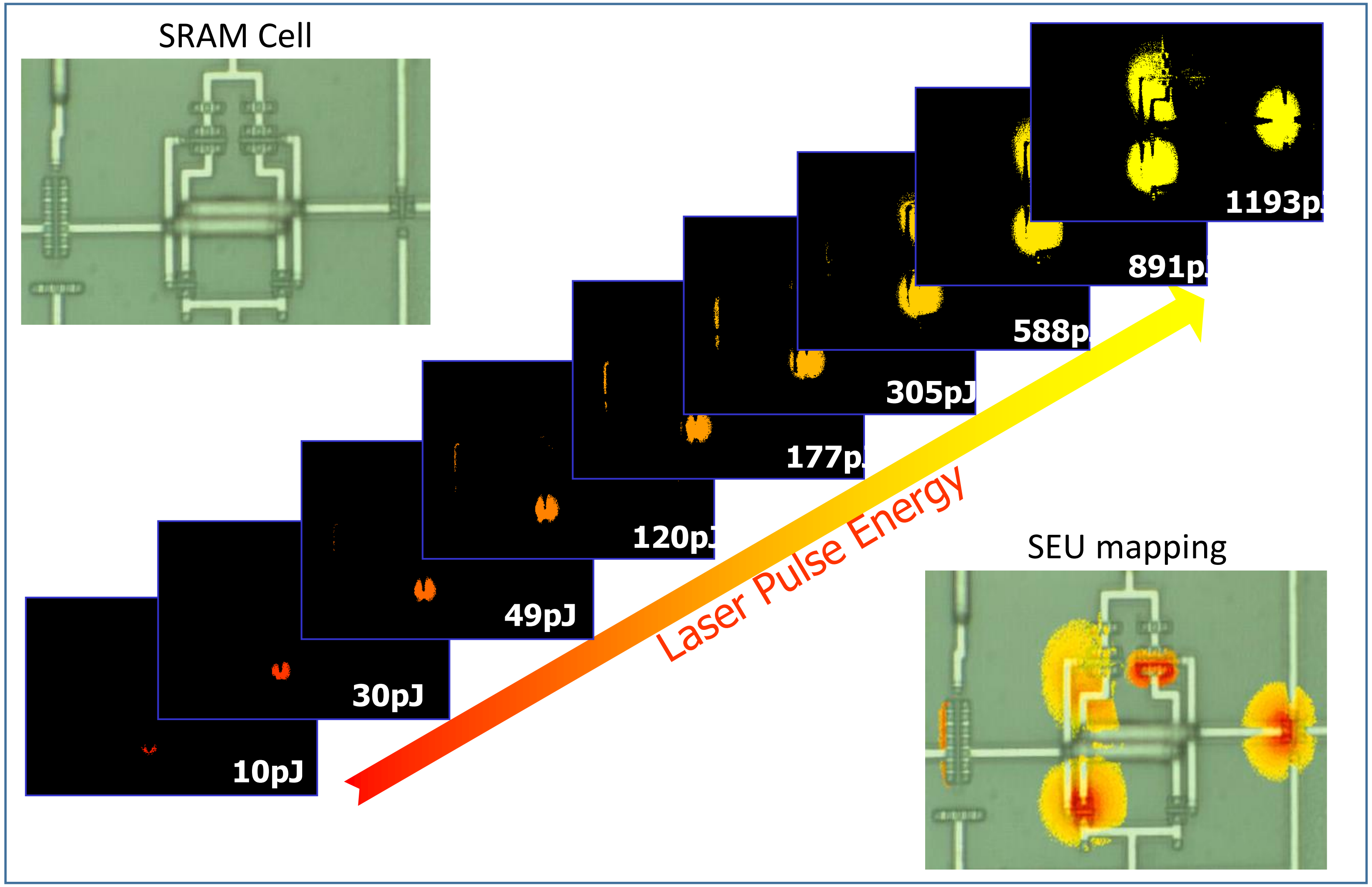


"Laser pulse energy"

Can be calculated from $E_{incident}$ by considering the backside transmission and attenuation in the substrate

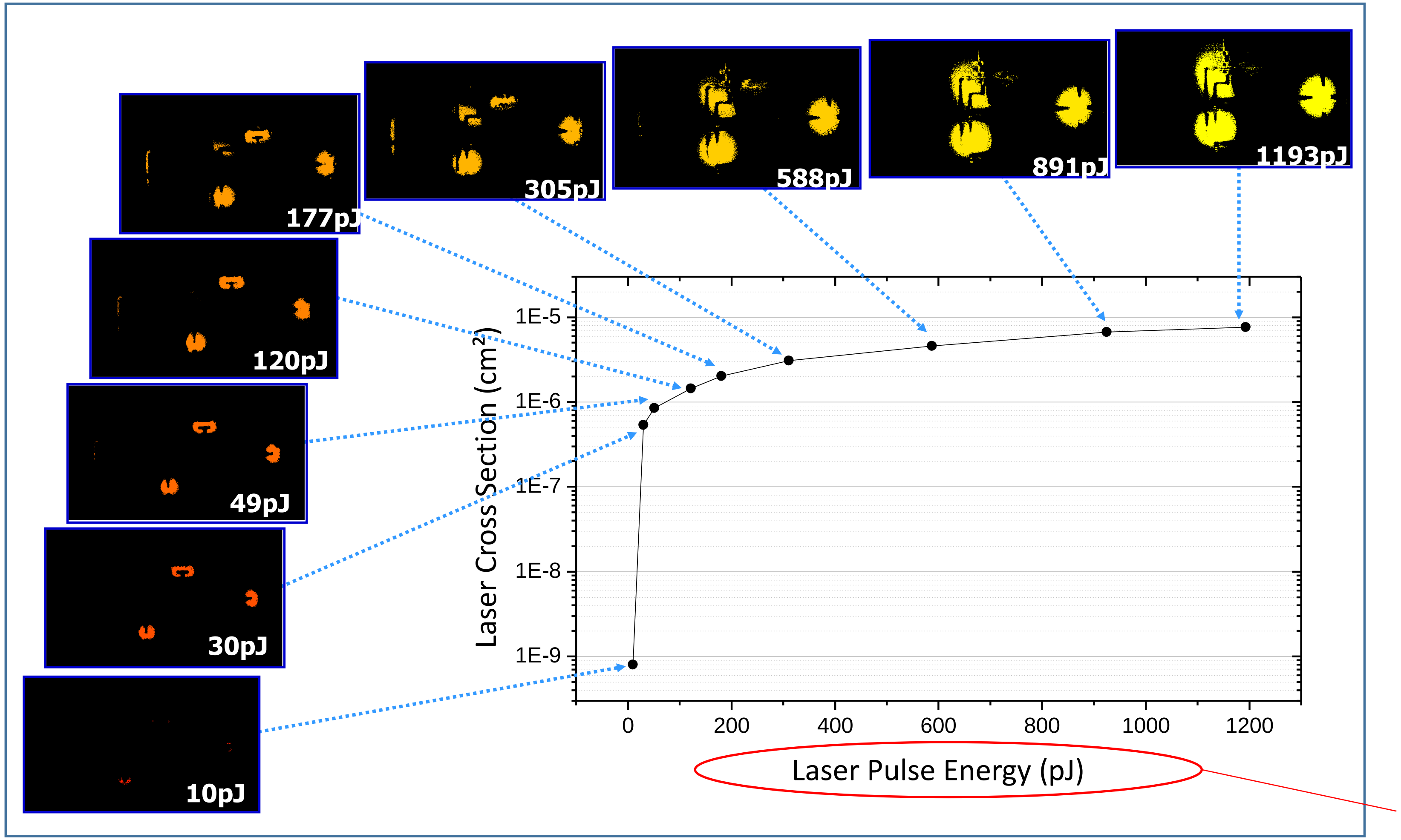
Laser Mapping

SEU mapping in a test structure



Laser Cross Section

At Cell level

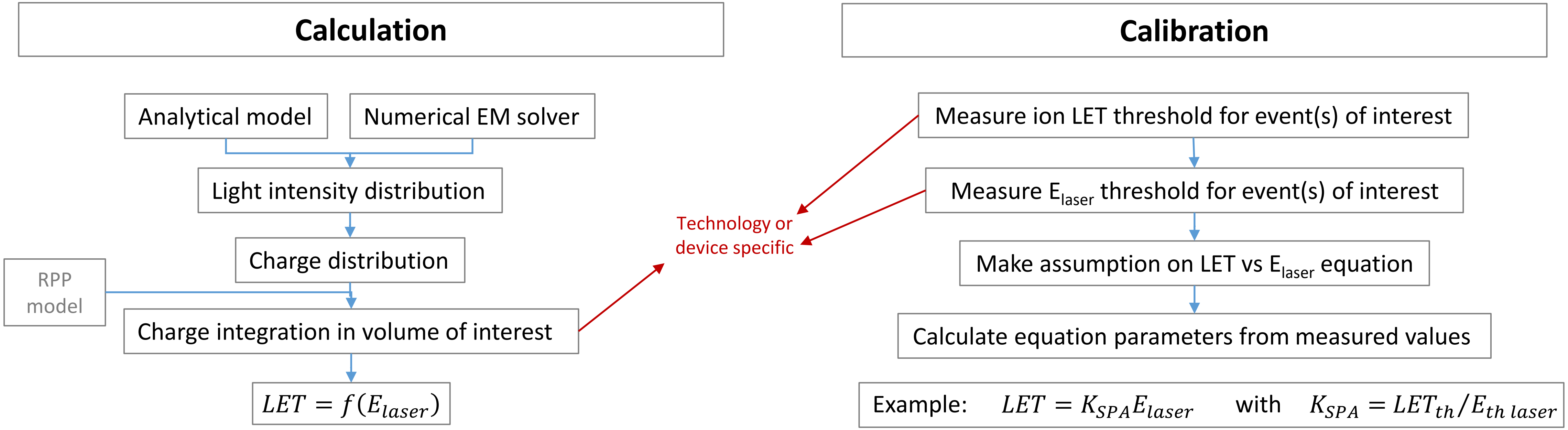


Can we convert this into an LET scale?

Estimating the equivalent LET of a laser pulse

- Objectives
  - Given an LET, estimate the laser energy required to produce the same effect (with same cross-section)
  - Given a laser energy, estimate the ion LET that would produce the same effect (with same cross-section)

- Two complementary paths for equivalent LET estimation



Calculation

Analytical model

Numerical EM solver

Light intensity distribution

Charge distribution

RPP model

Charge integration in volume of interest

$LET = f(E_{laser})$

Technology or device specific

Calibration

Measure ion LET threshold for event(s) of interest

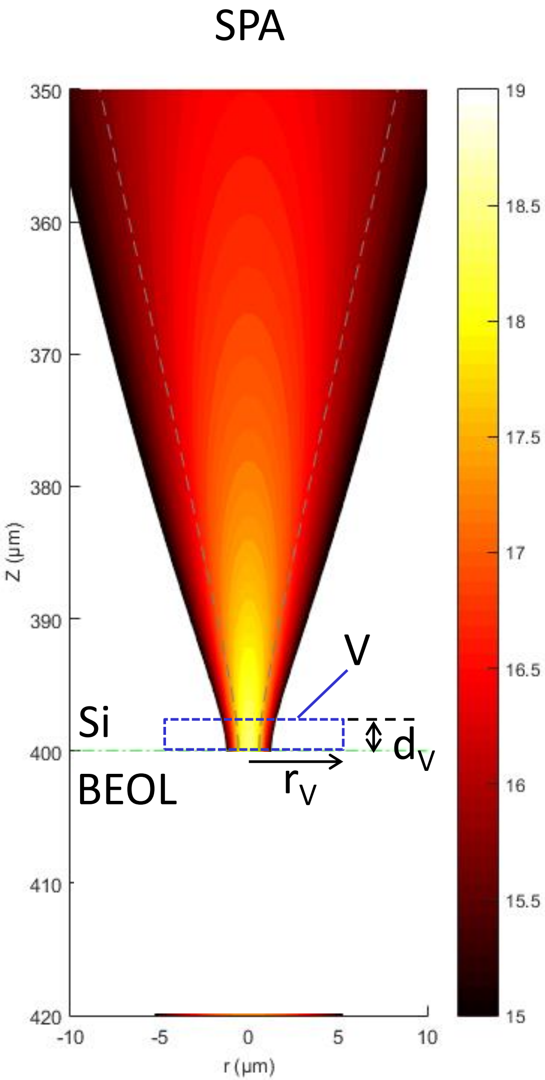
Measure E_{laser} threshold for event(s) of interest

Make assumption on LET vs E_{laser} equation

Calculate equation parameters from measured values

Example: $LET = K_{SPA}E_{laser}$ with $K_{SPA} = LET_{th}/E_{th\ laser}$

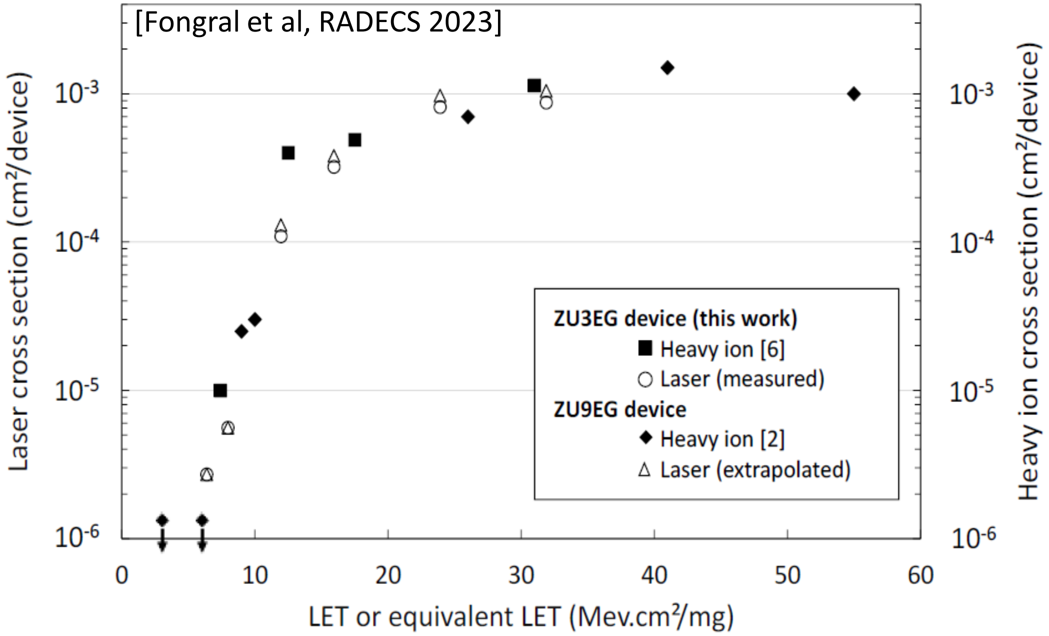
Equivalent LET calculation



- Example
  - Backside SPA testing through 400µm substrate
  - Laser propagation and induced carriers density $N_{las}(\boldsymbol{r})$ calculated by numerical method
- **Define the volume of interest V**
  - With limited information on the technology, a rectangular parallelepiped (RPP), a cylinder, or an infinite slab (depth of 1µm, infinite radius) can be used
  - Possible refinements with more information on the technology
    - Use a set of volumes with weights representing collection efficiency
    - Use a finite radius smaller than the spot size if the collection efficiency drops rapidly when moving away from the sensitive structure
- $$LET_{las} = \frac{E_{pair}}{d_V} \iiint_V N_{las}(\boldsymbol{r})\, d\boldsymbol{r}$$

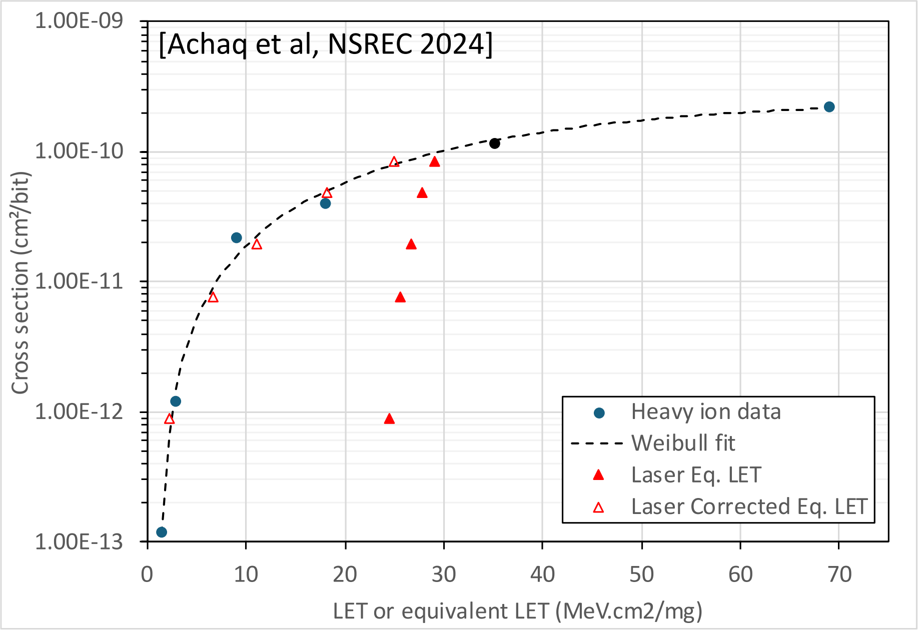
Equivalent LET calculation – Recent results

SEL in **16nm** FinFET



- Using infinite radius works well (for SEL)

SEU in **7nm** FinFET



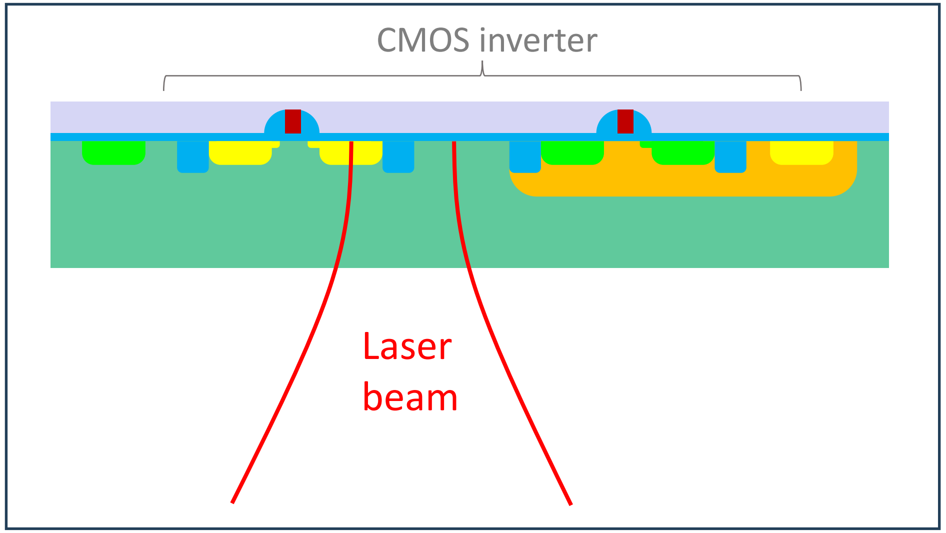
- Using infinite radius doesn't work (for SEU)
- Energy dependent correction introduced

See later talks by M. Fongral and S. Achaq for more details on these results

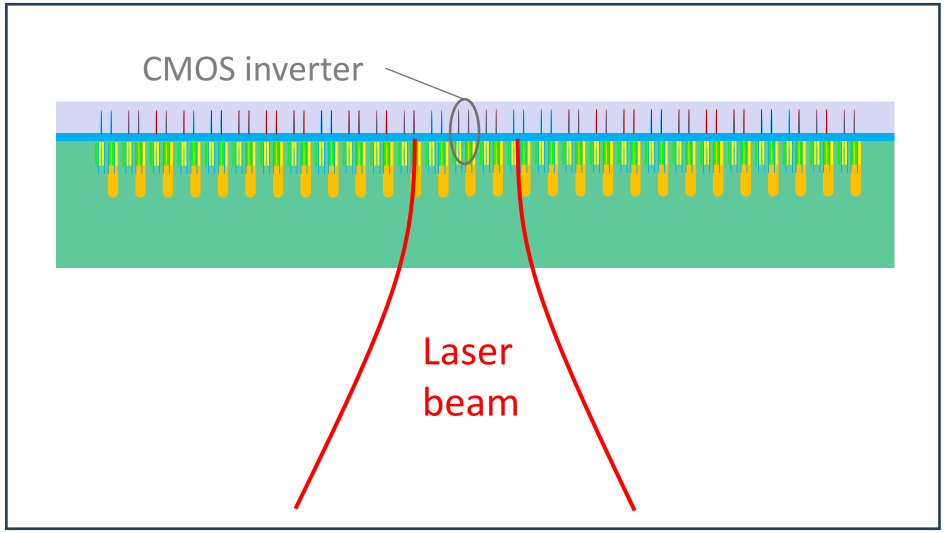
CMOS Scaling

- CMOS scales have changed, while laws of diffraction have not

A not so long time ago…



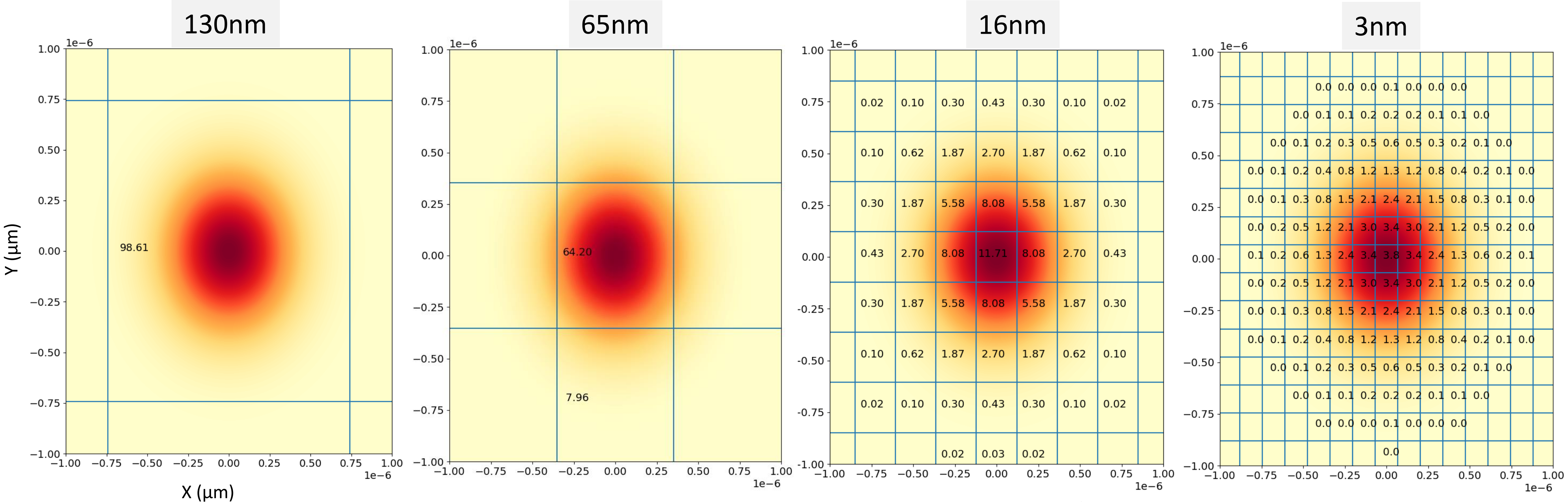
Now



- Laser-generated charge spread over multiple adjacent logic cells
  - Charge generated on the sides does not contribute to SEU in the target cell in the center of the beam

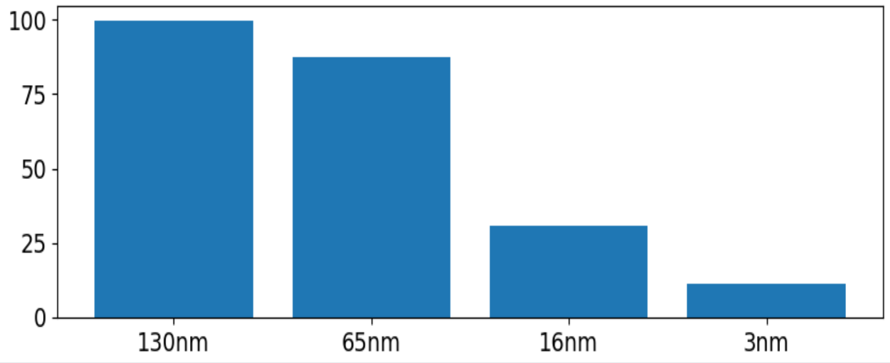
⇒ We need to adjust the **width** of the volume used for equivalent LET calculation

Laser spot in an SRAM array



Grid = SRAM cells
Numbers in cells = % of total generated charge

SEU/MCU Energy threshold relative margin (%)



Summary

- Laser testing for Single-Event Effects: a useful tool for in-lab testing and analysis of various SEE
- A complement to other techniques: heavy ion testing, modelling, focused X-rays…
- SPA and TPA: complementary techniques with a lot of background for Si technologies
- Commonly used today for SEE mechanisms analysis and RHBD
- Growing interest for RHA of COTS
- Laser-ion equivalence:
  - Some fundamental differences to be kept in mind
  - Equivalent LET estimation is possible, with some margins
- Guidelines for SEE laser testing available