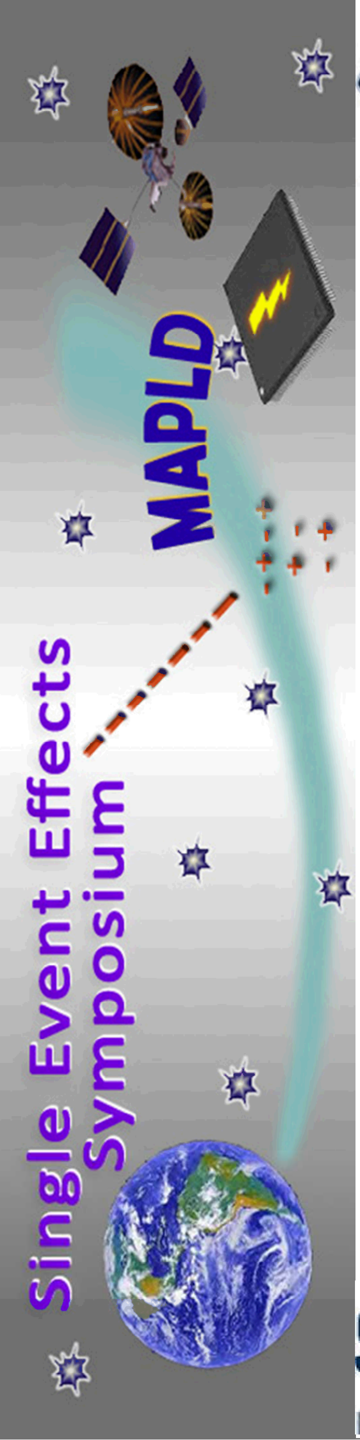


SAND2016-4815C

Generation and Characterization of Two Photon Absorption Pulsed-Laser Single- Event Beam Line for Wide Band-Gap Materials: *Application to Single-Event Transients in a Vertical GaN Diode*

Nicolas J-H. Roche[1], Ani Khachatrian[2], Michael King[3], Stephen P. Buchner[4], Robert Kaplar[3], Andrew Armstrong[3], Isik. C. Kizilyalli[5], Paul D. Cunningham[4], Joseph S. Melinger[4], Dale McMorrow[4]

[1] *The George Washington University, Washington, DC*
[2] *Sotera Defense Solution, Hendon, VA*
[3] *Sandia National Laboratory, Albuquerque, NM*
[4] *Naval Research Laboratory, Washington, DC*
[5] *Avogy, Inc. and is now with Department of Energy*

SEE Symposium + MAPLD Workshop 2016

May 23 – 26, 2016, San Diego, Marriott La Jolla, CA, U.S.A.

PLSEE approach for wide bandgap materials

- Ultrafast pulsed lasers
  - Powerful tools for single-event effects (SEEs) studies,
  - Applied on micro- and nano-electronic devices and integrated circuits (ICs),
  - Works very well for silicon based technologies.

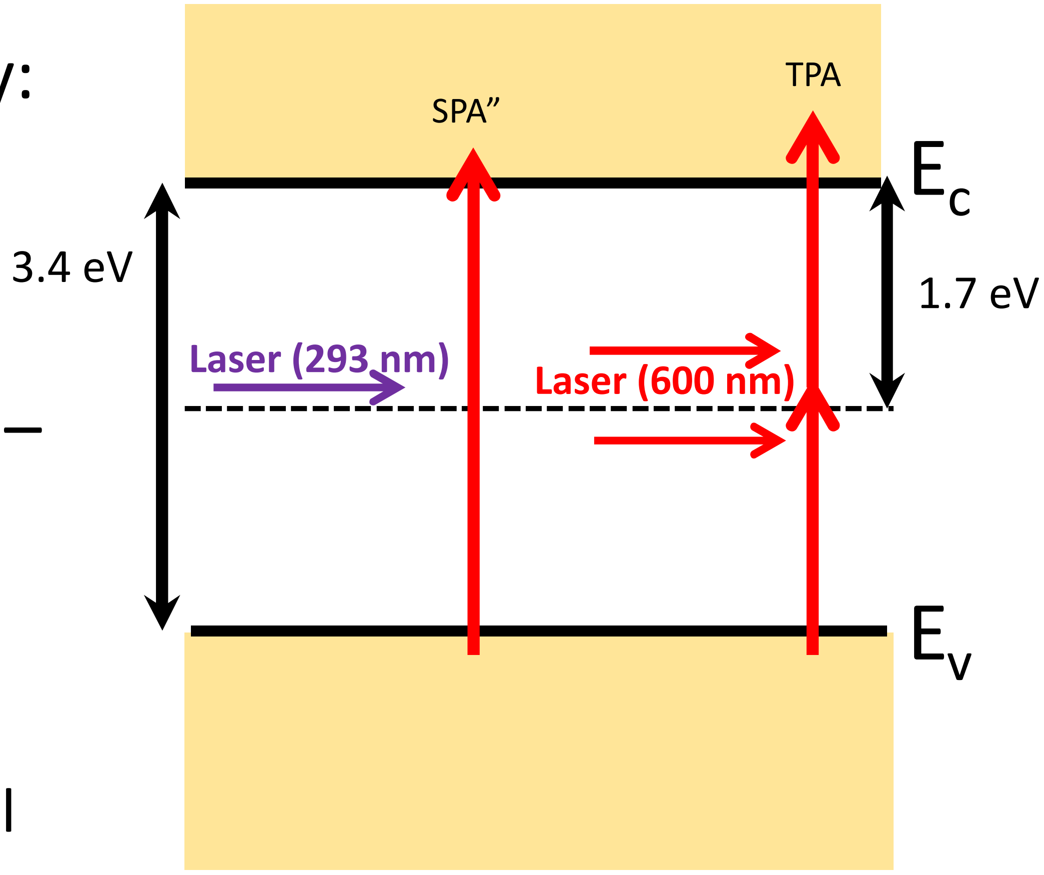
- Challenge
  - Wide bandgap materials, such as GaN and AlGaN alloys,
  - well-known to have deep-level traps.

- It is possible to use two-photon absorption (TPA) process by using photons in the visible (VIS) part of the spectrum (around 600 nm)

PLSEE approach for wide bandgap materials

- At sufficiently high light intensities, achieved by:
  - focusing the light
  - using very short pulses of laser light

the material can simultaneously absorb two photons leading to the generation of an electron–hole pair.



- 3D probing of the material is possible
  - By scanning the focal point throughout the material volume

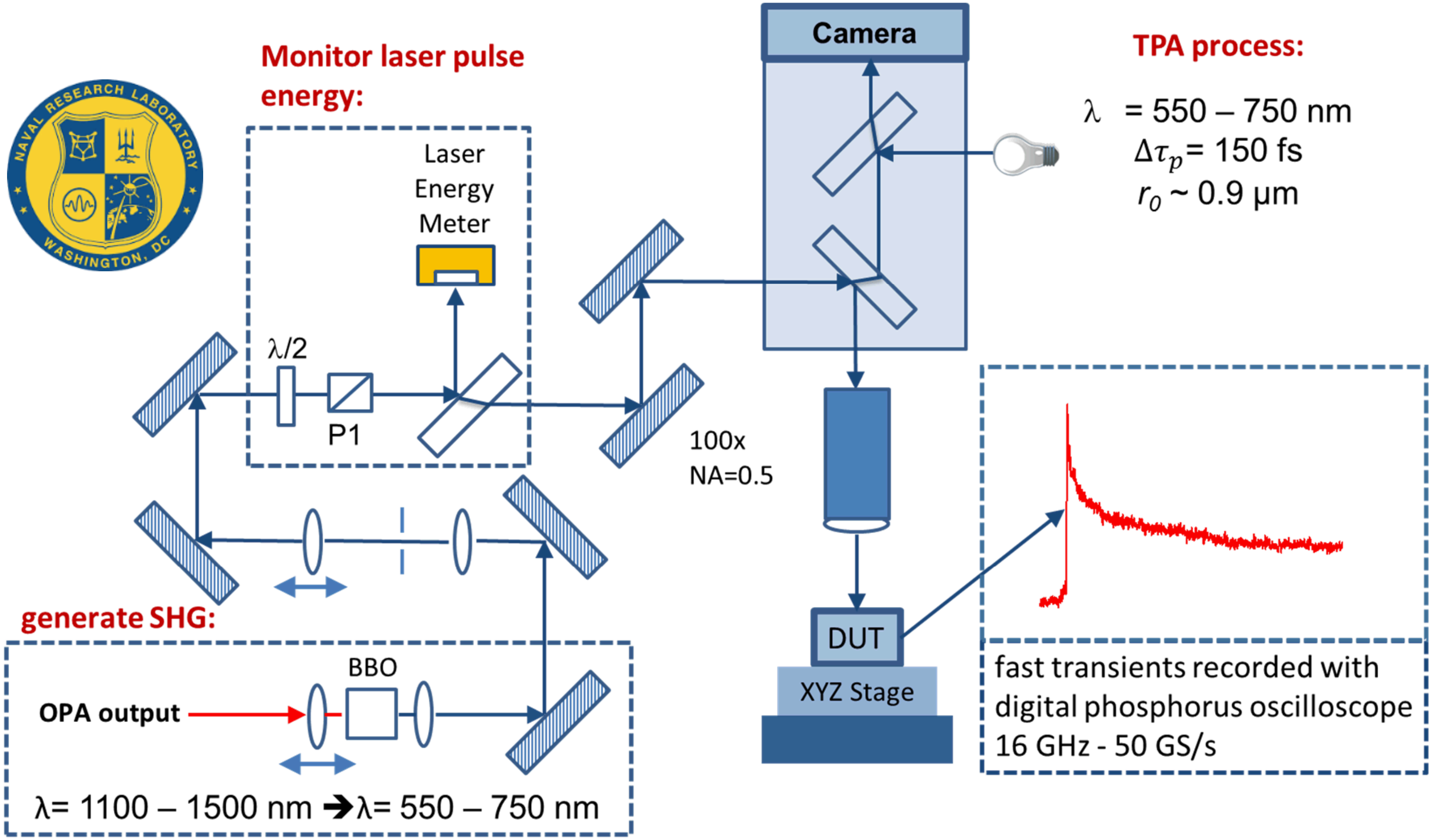
PLSEE approach for wide bandgap materials

- The density of free carriers generated via the TPA process is proportional to:
  - the intensity squared of the light (I^2)
  - the two-photon absorption coefficient (β_2)

$$\frac{dN_{(x,y,z)}}{dt} = \frac{\beta_2 {I_{(x,y,z)}}^2}{2\hbar\omega}$$

  - where $\hbar$ is the reduced Planck constant and ω is the angular frequency.

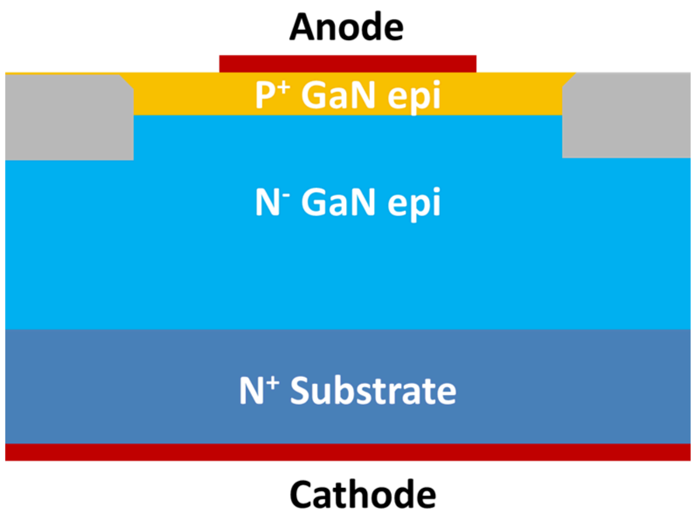
Wide Bandgap Material TPA PLSEE facility at NRL

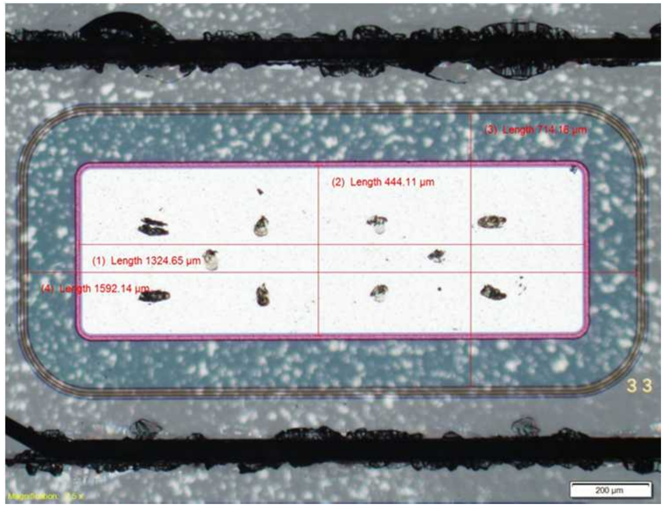


- Wavelength-tunable OPA
- Near Infra-Red (NIR)
- Ultrafast laser
- (λ= 1100 – 1500):
  - Frequency doubling
    - λ= 550 – 750 nm
  - Repetition rate of 1 kHz
  - 100X / NA 0.5 objective lens
  - Spot size of ~ 0.9 µm (FWHM)

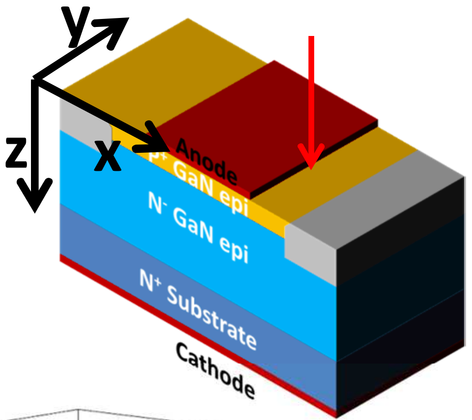
Test Structure

- The test structure is a high-breakdown voltage vertical GaN diode grown on native substrates from Avogy Inc.
  - This is a P^+N diode
  - Fabricated by in-situ growth of a **Mg-doped P^+ GaN** epitaxial layer on top of the N-type GaN epitaxial drift region
    - Deposition and patterning of palladium to contact the P-type GaN.
    - Backside contacts formed by evaporating aluminum onto the back surface of the N-type GaN substrate.

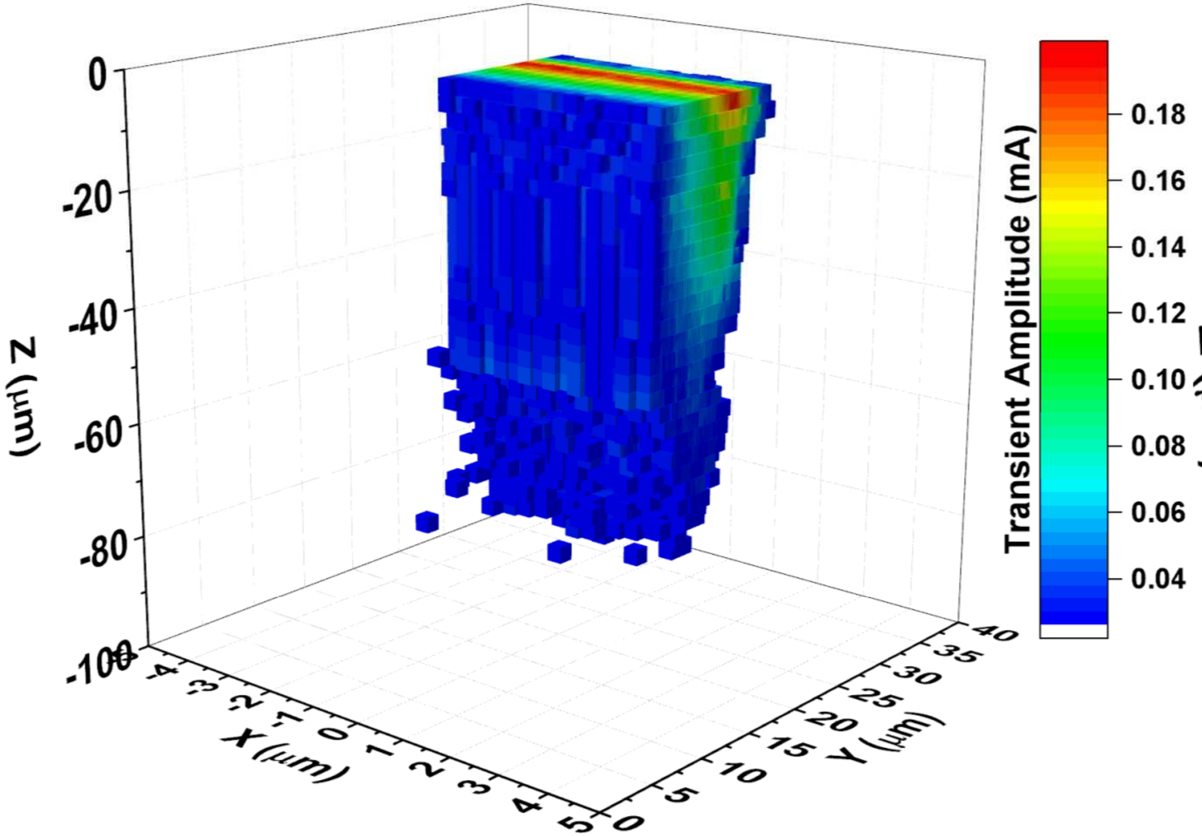


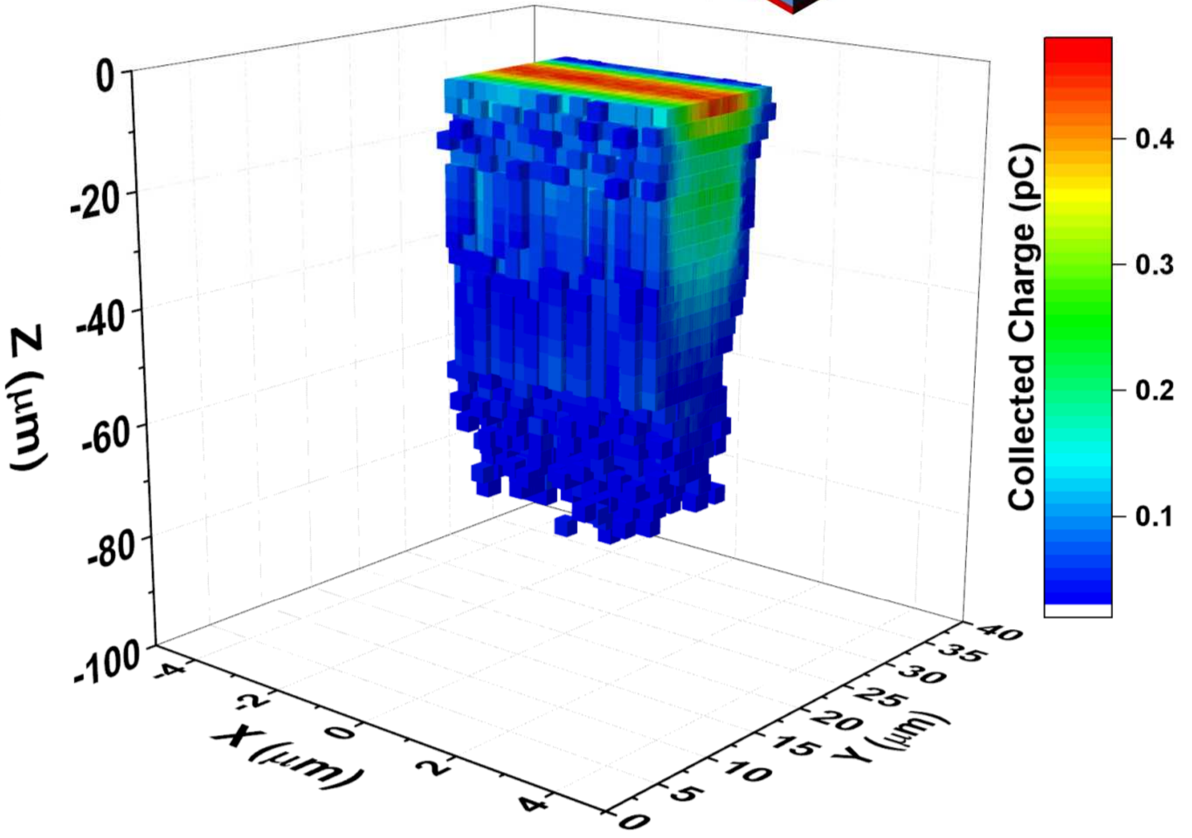


3D mappings



- 3D current peak amplitude & Charge Collection volume
  - (area of 4 x 25 µm (XY)):





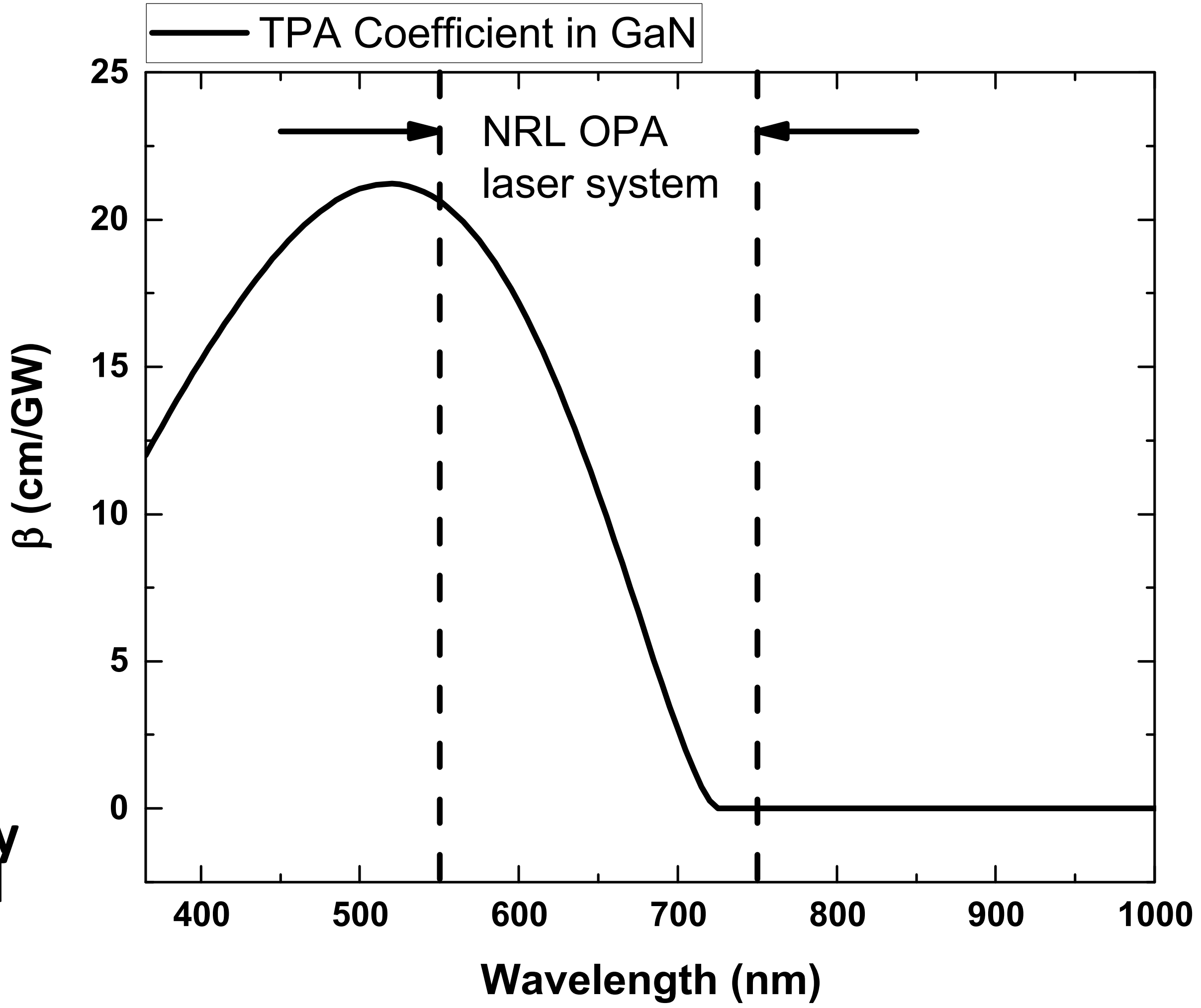
N. J-H. Roche, SEE Symposium & MAPLD Workshop 2016 - May 23rd–26th, 2016
San Diego, Marriott La Jolla, CA, U.S.A.

Calculated λ TPA Coefficient Dependence

- TPA coefficient (β_2) of a direct bandgap semiconductor at a photon energy $h\nu$

$$\boldsymbol{\beta}_{2(h\nu)} = \boldsymbol{a} \times \boldsymbol{K} \times \sqrt{\frac{\boldsymbol{E_p}}{\boldsymbol{n_0^2 E_g^3}}} \times \boldsymbol{F_2}\left(\frac{\boldsymbol{h\nu}}{\boldsymbol{E_g}}\right), \mathrm{Ep} = \frac{2|\rho_{vc}|}{m_0}, F_{2(x)} = \frac{(2x-1)^{1.5}}{(2x)^5}$$

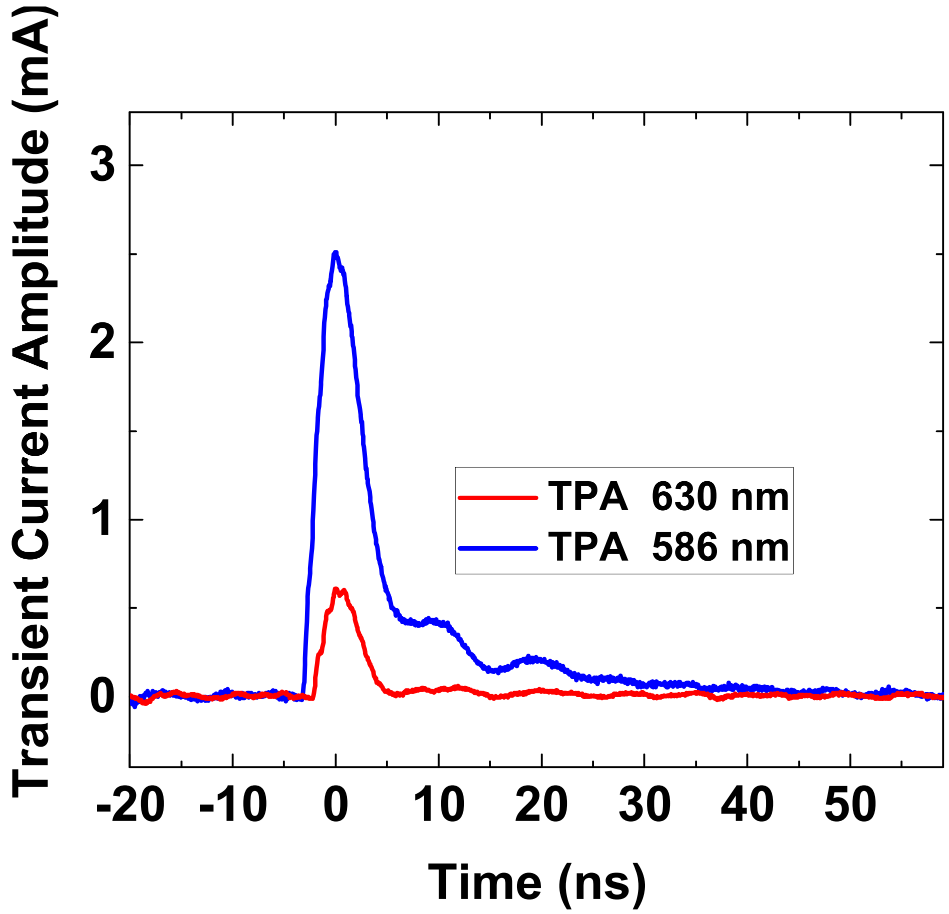
  - a is an **empirical parameter** equal to 12
  - K is a **material-independent constant**, equal to 1940
  - $\mathrm{E_p}$ is **nearly material independent**, equal to 21
  - n_0 is **wavelength dependent refractive index**
  - Eg is the **GaN bandgap energy**,
  - $\mathrm{F_2}$ is a function of the **ratio** of the **photon energy** to the **bandgap energy** and reflects the assumed **band structure** and the **intermediate states** considered in calculating the TPA transition rate.



Transient Response @ 586 & 630 nm

- transients obtained by exposing the GaN diode to a laser light pulse with an energy of **1.4 nJ** and a wavelength of **586 nm** (blue trace) and **630 nm** (red).

- Even though the laser **pulse energies are identical**, the curves are **very different**, as is evident by the large differences in **transient current amplitude** and area (**collected charge**).

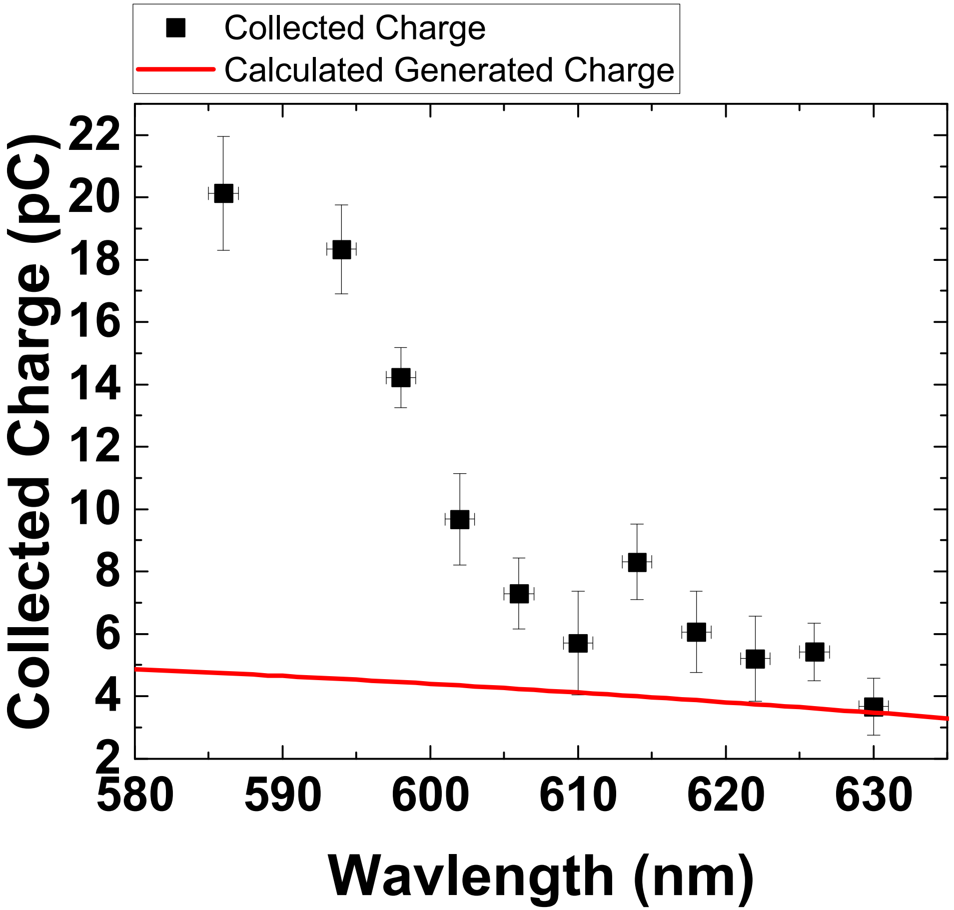


Collected charge as a function of λ

$$Cc_{Tot} = \frac{\sqrt{\pi}}{2\sqrt{2}} \times \frac{\beta_{2(h\nu)} P_E n_0}{\tau h c} \times q$$

- strong wavelength dependence of charge generation processes in bulk GaN.

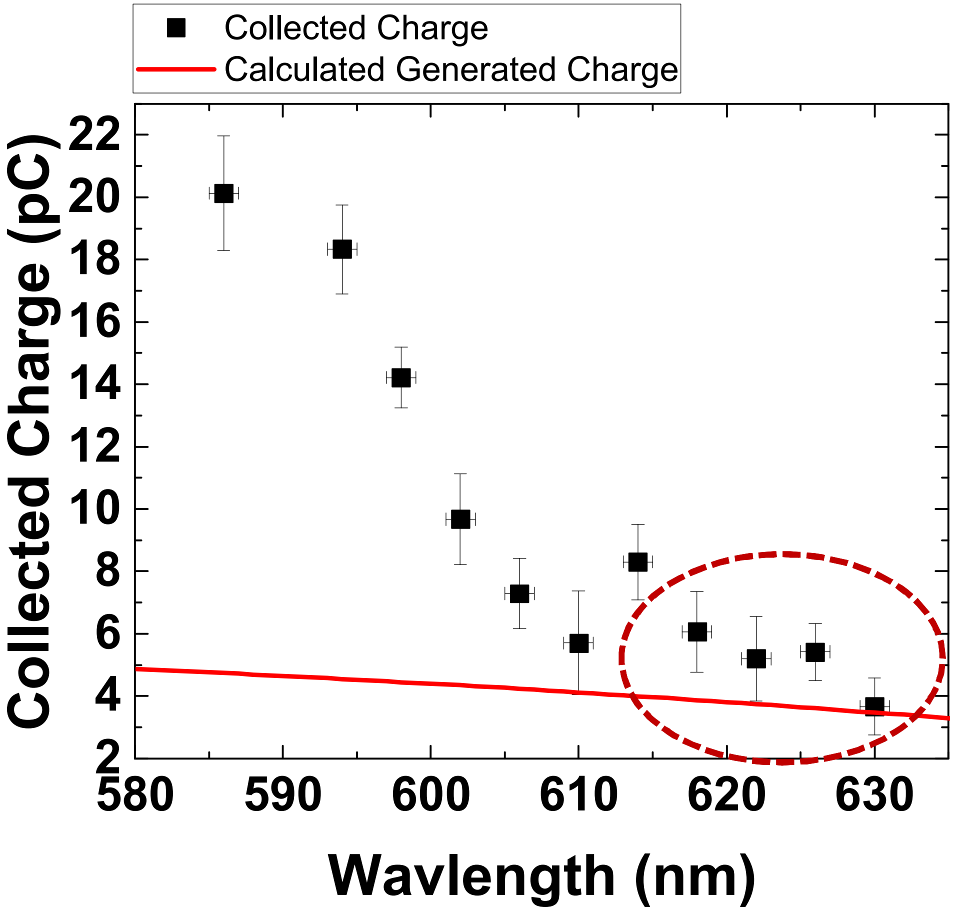
- It has to be noted that:
  - the calculated generated charge in bulk GaN through TPA process at 630 nm is of the same order of magnitude as the measured value,
  - but for shorter wavelengths there is a large discrepancy (x 4.5).



Collected charge as a function of λ

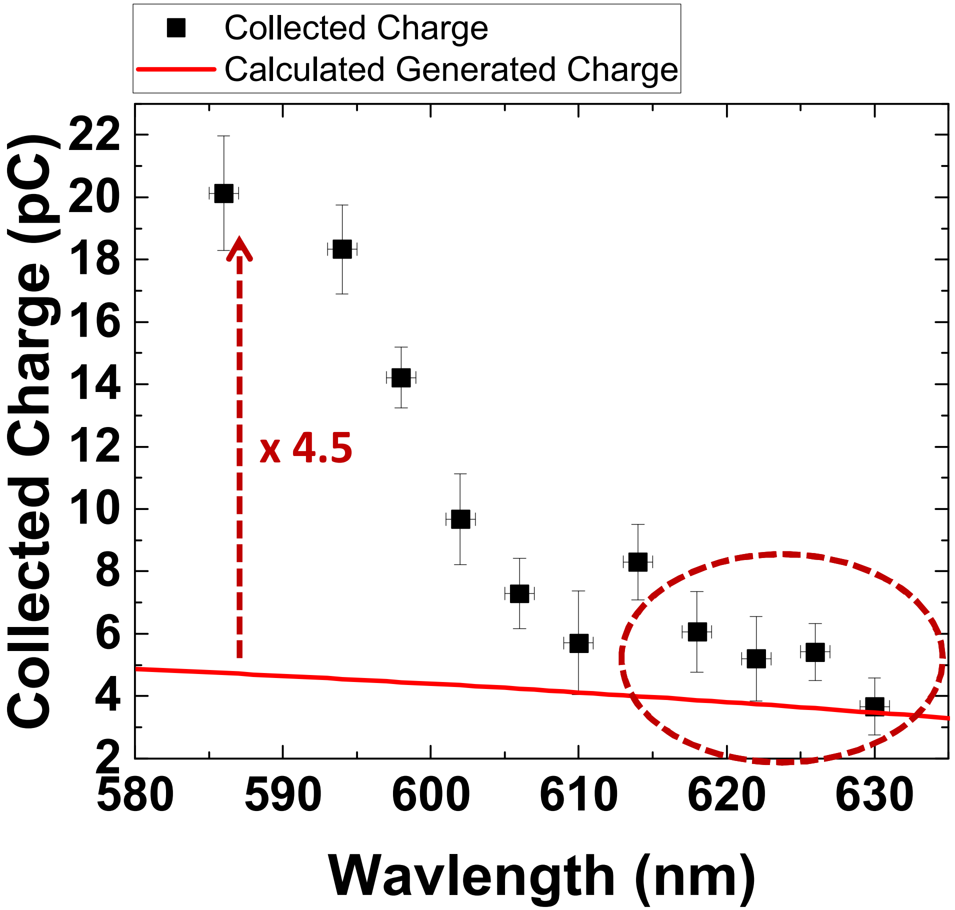
$$Cc_{Tot} = \frac{\sqrt{\pi}}{2\sqrt{2}} \times \frac{\beta_{2(h\nu)} P_E n_0}{\tau h c} \times q$$

- strong wavelength dependence of charge generation processes in bulk GaN.
- It has to be noted that:
  - the calculated generated charge in bulk GaN through TPA process at 630 nm is of the same order of magnitude as the measured value,
  - but for shorter wavelengths there is a large discrepancy (x 4.5).



Collected charge as a function of λ

$$Cc_{Tot} = \frac{\sqrt{\pi}}{2\sqrt{2}} \times \frac{\beta_{2(h\nu)} P_E n_0}{\tau h c} \times q$$

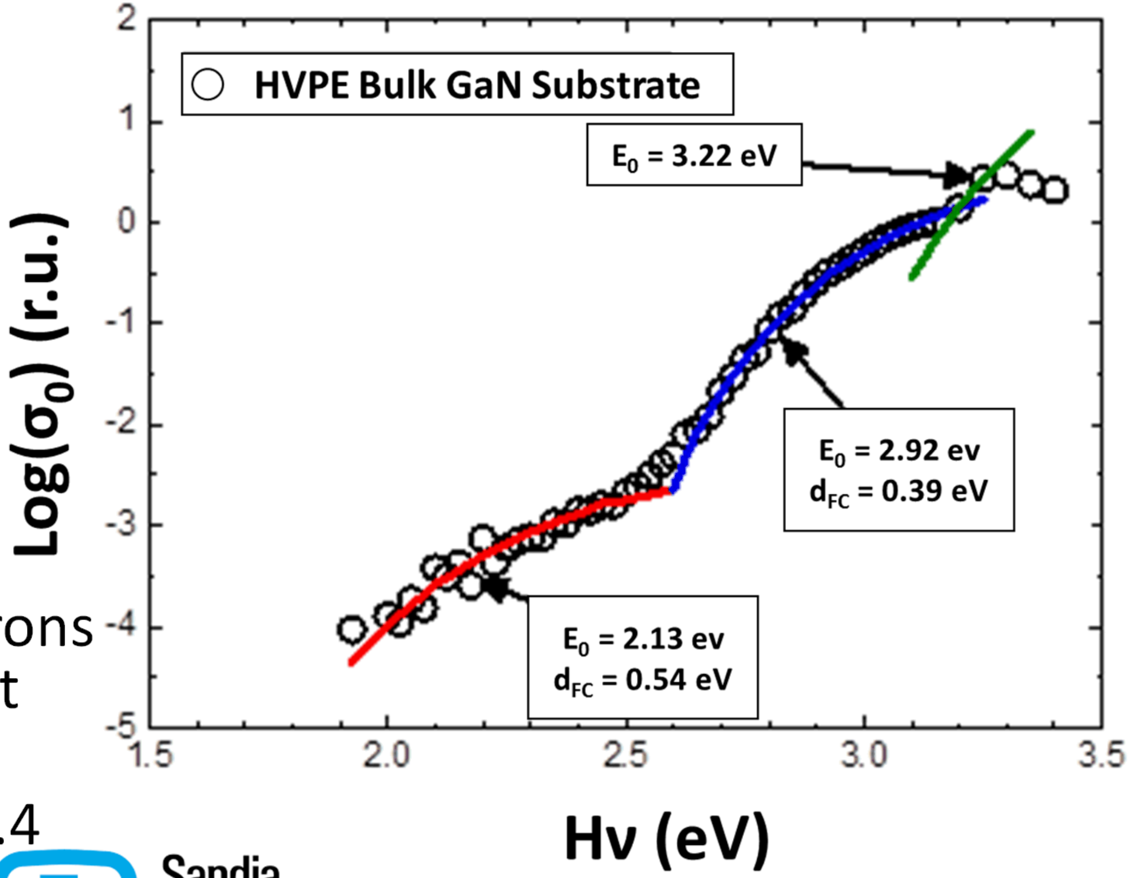


- strong wavelength dependence of charge generation processes in bulk GaN.
- It has to be noted that:
  - the calculated generated charge in bulk GaN through TPA process at 630 nm is of the same order of magnitude as the measured value,
  - but for shorter wavelengths there is a large discrepancy (x 4.5).

Deep level optical spectroscopy (DLOS)

- DLOS reveals the presence of two bandgap states close to the valence band
  - E1 = 2.13 eV (582 nm)
  - E2 = 2.92 eV (425 nm)

  - At low photon energy (<1.7 eV) no absorptior
  - When photon energy > 1.7 eV get TPA
  - When photon energy sufficient to excite electrons from traps to conduction band and >1.7 eV, get SPA from traps and TPA
  - When photon energy greater than bandgap (3.4 eV) get SPA from valence to conduction band which is dominant.

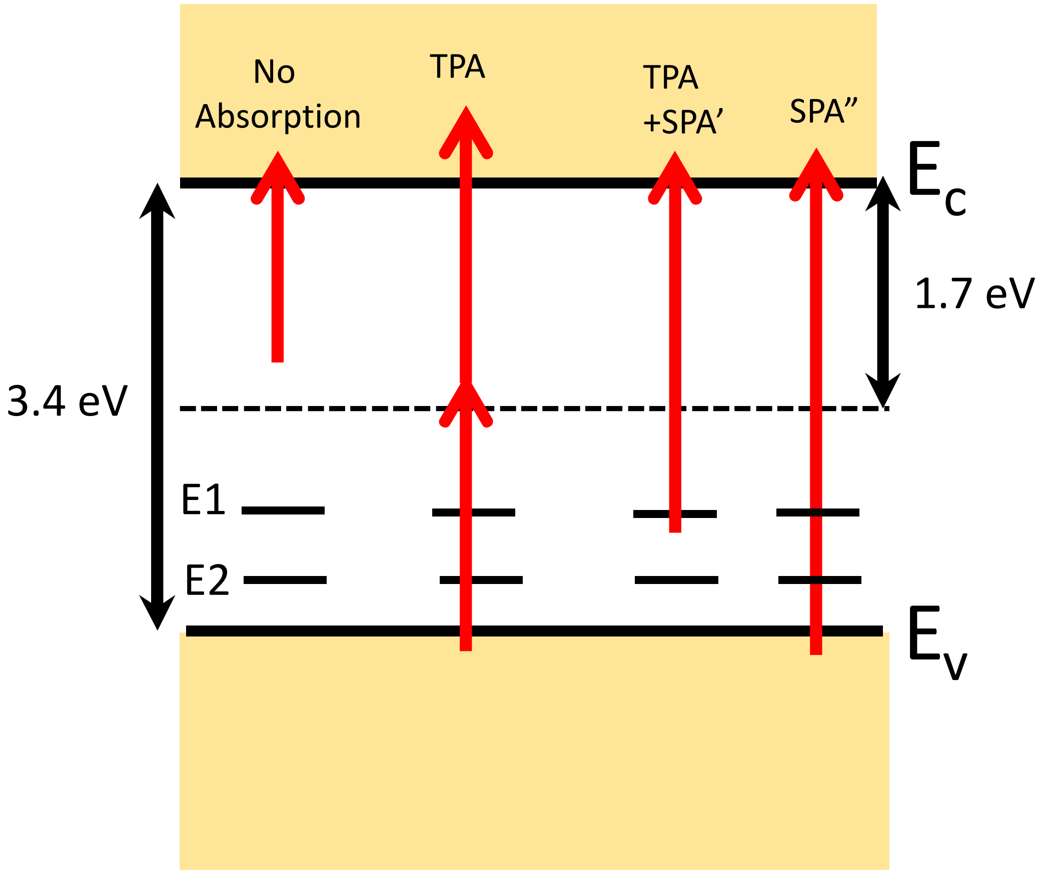


Sandia National Laboratories

Deep Level Trap & SPA excitation

- DLOS reveals the presence of two bandgap states close to the valence band
  - E1 = 2.13 eV (582 nm)
  - E2 = 2.92 eV (425 nm)

  - At low photon energy (<1.7 eV) no absorption
  - When photon energy > 1.7 eV get TPA
  - When photon energy sufficient to excite electrons from traps to conduction band and >1.7 eV, get SPA from traps and TPA
  - When photon energy greater than bandgap (3.4 eV) get SPA from valence to conduction band which is dominant.



Conclusion

- We presented first results for generating SETs in bulk wide bandgap material (GaN) using a TPA PLSEE approach:
  - 3D VIS TPA PLSEE measurements were performed on high-breakdown voltage vertical GaN diodes grown on native substrates.
- It is the first time the impact of wavelength on TPA-PLSEE approach is reported:
  - Possible excitation of electrons from deep level traps to the conduction band in GaN is reported (V_N),
  - It is very important to choose a laser light wavelength that allows TPA to occur while limiting the excitation of electrons in deep traps through SPA ($\lambda > 610$ nm).
- This technique allows time-resolved 3D probing of GaN and other wide bandgap materials:
  - Generating 3D plots of SETs in bulk wide bandgap material,
  - Map out the charge collection paths which can provide useful information when trying to understand SETs generation.