U.S. NAVAL RESEARCH LABORATORY

Pulsed-Laser Single-Event Effects in Wide Bandgap Semiconductor Devices

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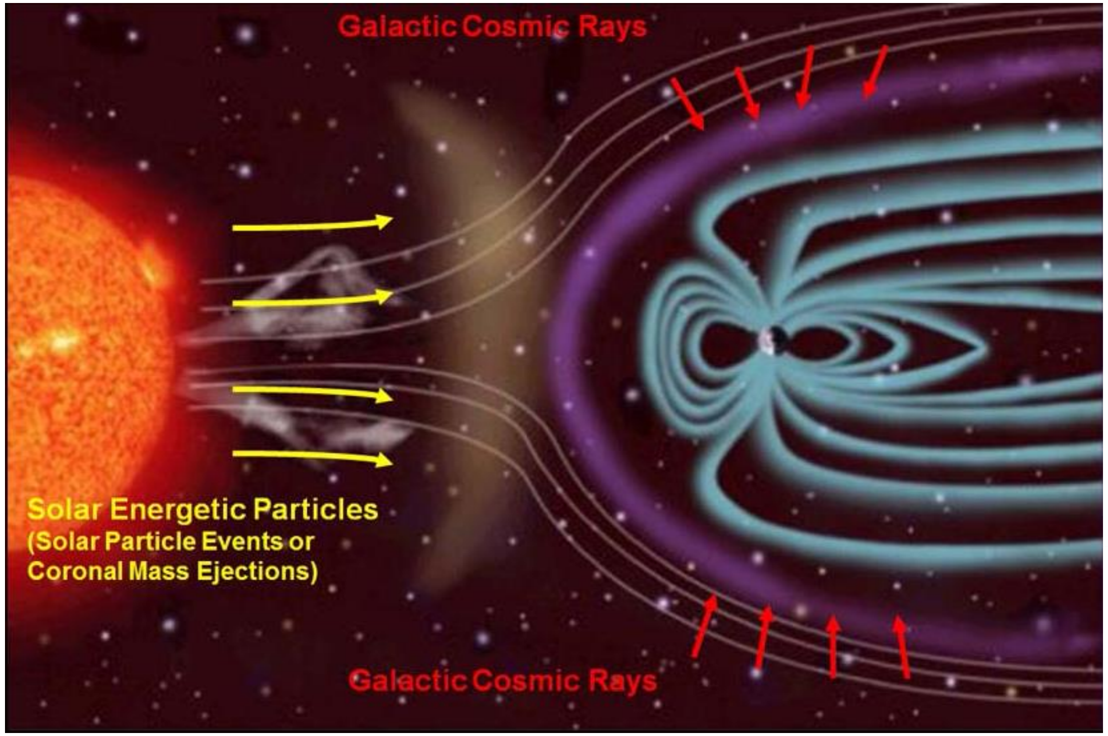
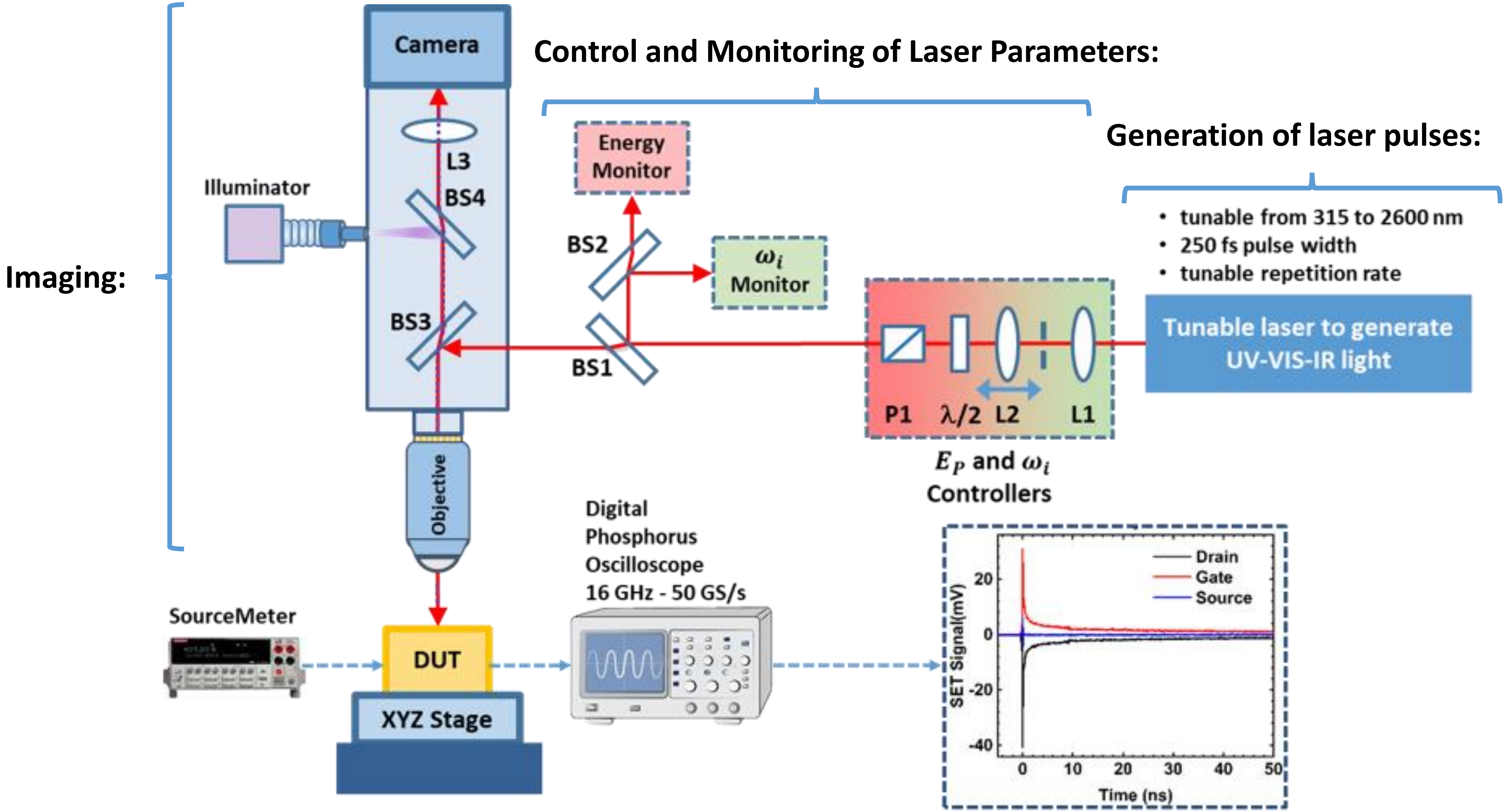
Motivation



- Due to their wide energy bandgaps, high breakdown voltage, ability to withstand high temperatures, wide bandgap material based devices are increasingly used in space environment for high power and high-frequency applications.
- Wide bandgap (WBG) material systems are known to be susceptible to single-event transients (SETs) while operating in the hazardous particle radiation environment in space.
- **The SETs can disrupt the normal operation of a device leading to catastrophic failure events and be a potential reliability issue.**

NRL Pulsed-Laser SEE Experimental Setup



Imaging:

Control and Monitoring of Laser Parameters:

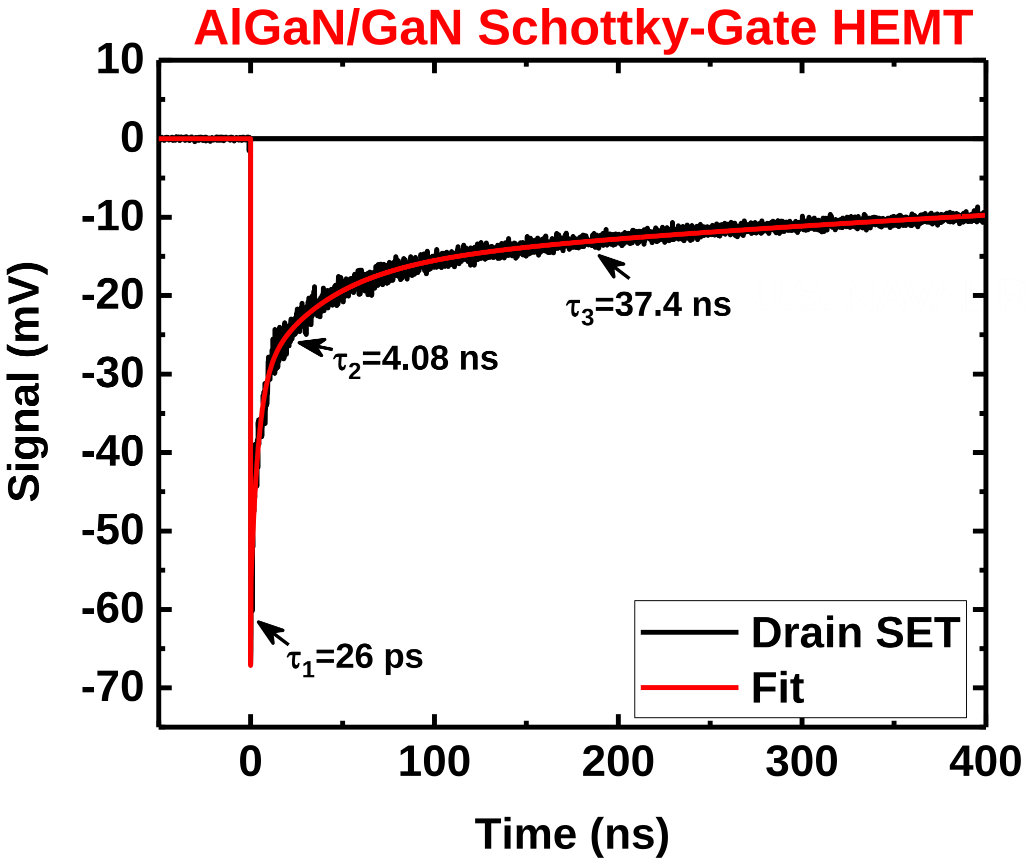
Generation of laser pulses:

- tunable from 315 to 2600 nm
- 250 fs pulse width
- tunable repetition rate

fast transients recorded with DPO

Single Event Transient (SET)

- Laser induced SET



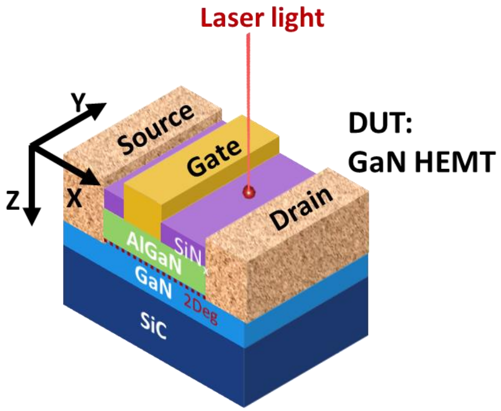
- Transients fitted to multi-exponential decay function to extract time constants and amplitudes:
    - **reveals information about trap density and lifetime**

$$y(t) = \int_{-\infty}^{+\infty} e^{\frac{-(t-t')^2}{2\cdot w^2}} \cdot \sum_{i=1}^{n} A_i \cdot e^{\frac{-t'}{\tau_i}} dt'$$

- The amount of collected charge is calculated by integrating the transient signal considering the 50 Ω input impedance of the scope

Spatial Mapping of GaN HEMTs

- PL SEE allows high precision spatial mapping of defects and traps.
- We were able to identify regions of **enhanced SET signals**, or **“hot spots”** that are attributed to the presence of lattice defects that modify the electric field in the drain at the edge of the gate.



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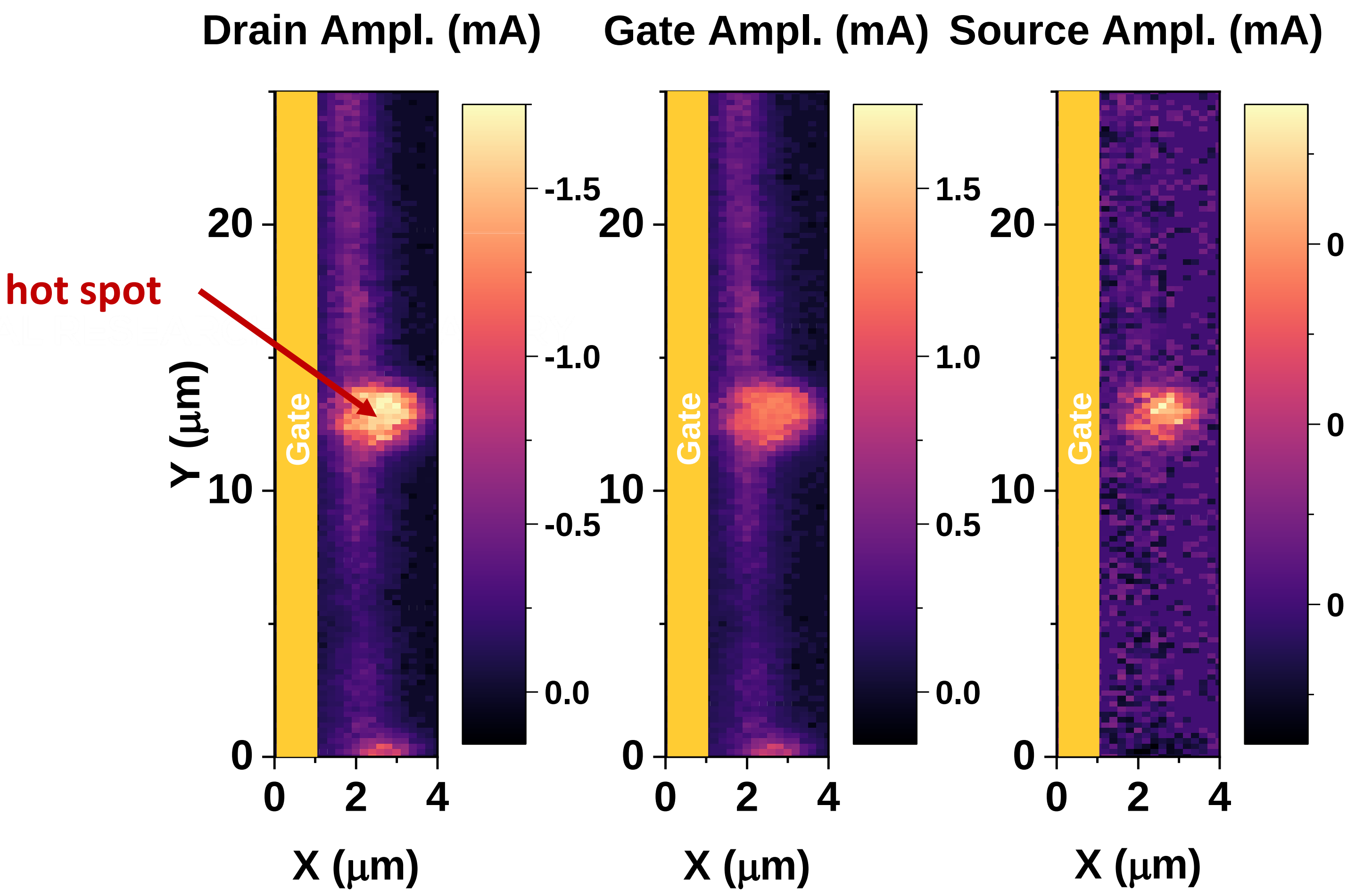
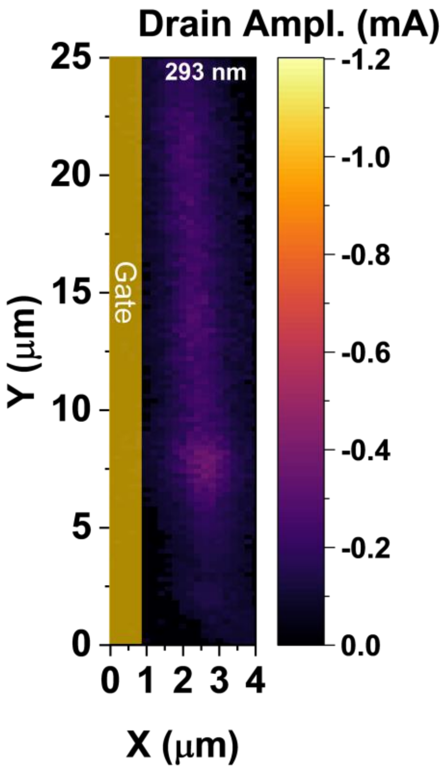
GaN HEMT on Si
Biased OFF (Vds=20V, Vgs= -2V) 293 nm **SPA**

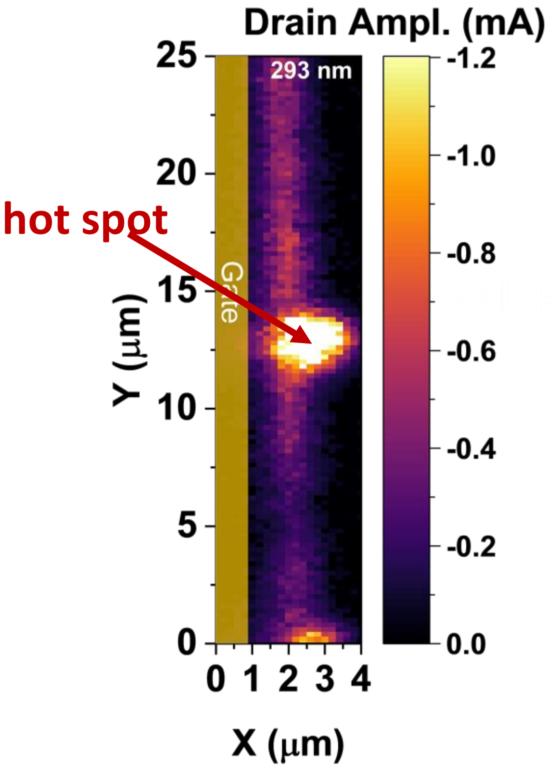


Spatial Mapping of Defects Using PL SEE

- SET mapping of GaN HEMTs
  - Biased OFF (Vds=20V, Vgs= -2V), 293 nm SPA



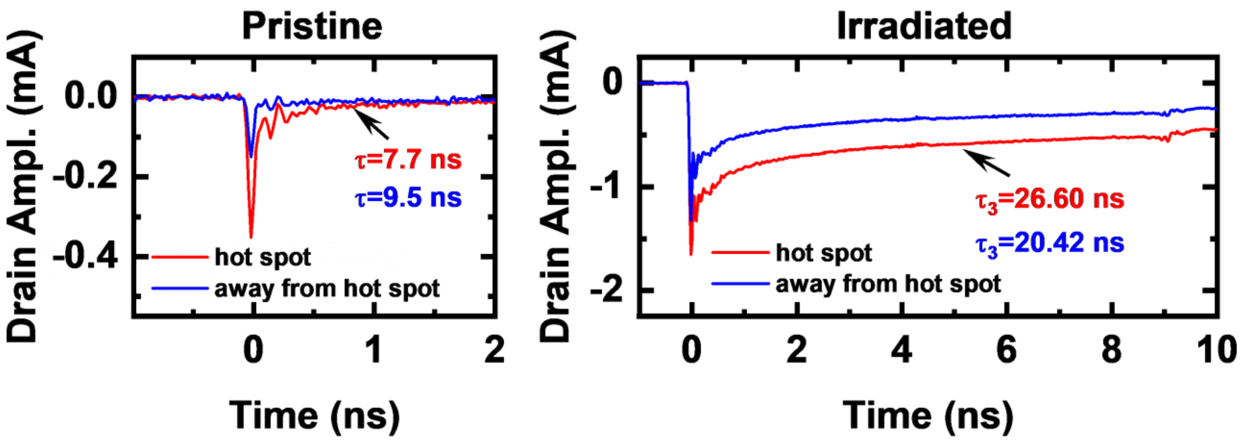
pristine device



proton irradiated device

2 MeV, fluence of 6×10^{14} cm^{-2}

- SET maps identify growth related and radiation induced defects.
- SET shapes are affected by radiation:



- Enhanced SETs in **“hot spots”.**
- “Hot spots” modify electric field.
- **“Hot spots” are areas that most likely will be susceptible to destructive failures.**

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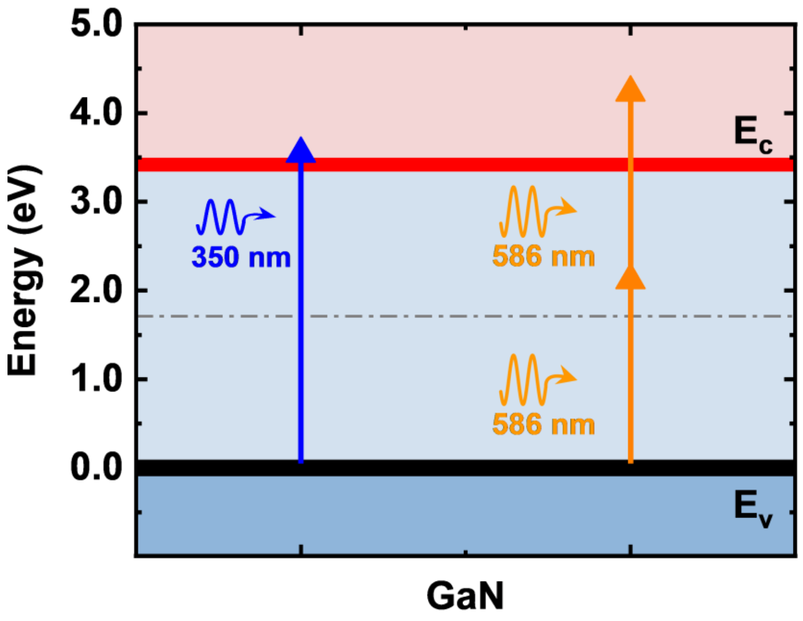
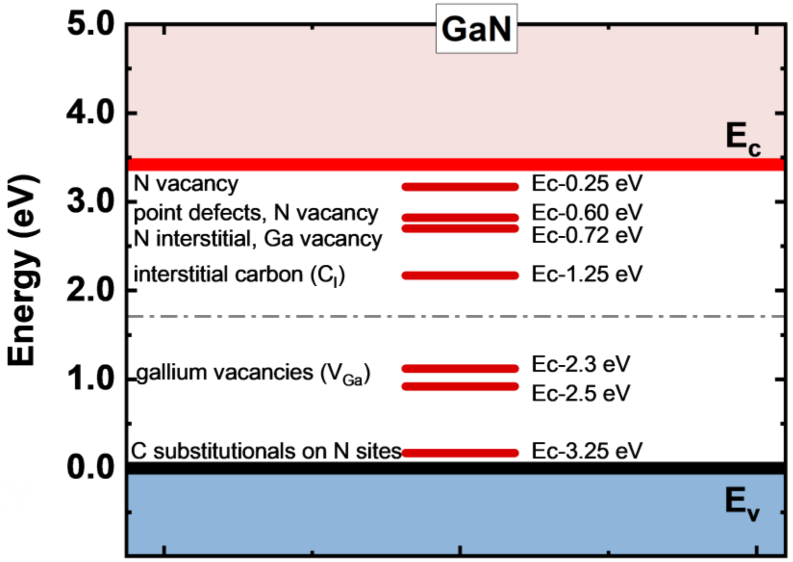
Laser Wavelength Choice



SPA

- The penetration depth changes with wavelength and controls the charge deposition profile.
- For materials like GaN, UV laser light penetration depth is very shallow.



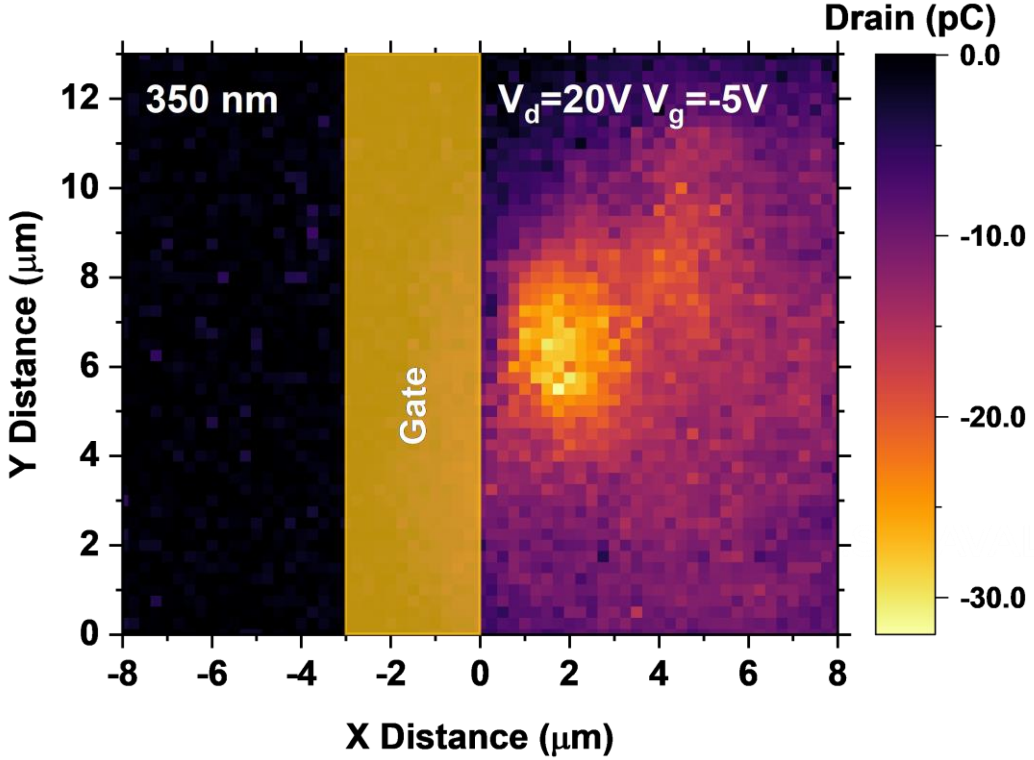
GaN defect energy levels

The choice of laser wavelength depends on several factors, including device geometry, the semiconductor bandgap, and the laser light's penetration depth.

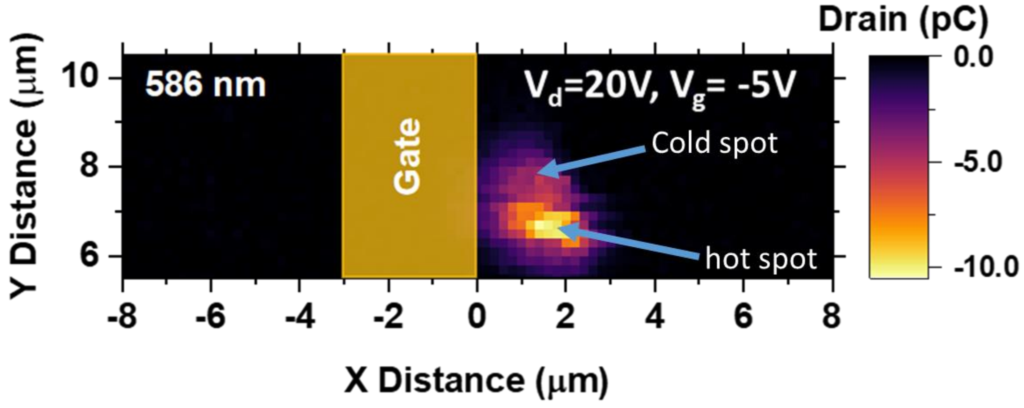
TPA

- TPA allows access to regions below the surface.
- More localized charge deposition allows mapping of 3D charge collection response.

Charge Collection Mapping of GaN HEMTs

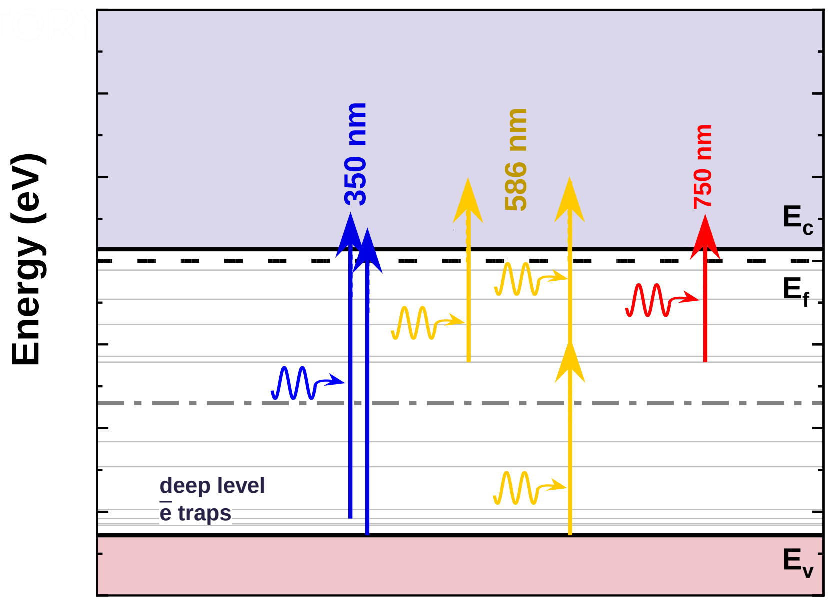


SPA @ 350 nm
(V_{ds}=20V, V_{gs}= -5V)



TPA @ 586 nm
(V_{ds}=20V, V_{gs}= -5V)

- Wavelength tunability
  - can aid in determining the origin of defects
  - allows probing of band-to-band transitions or defect-to-band transitions.



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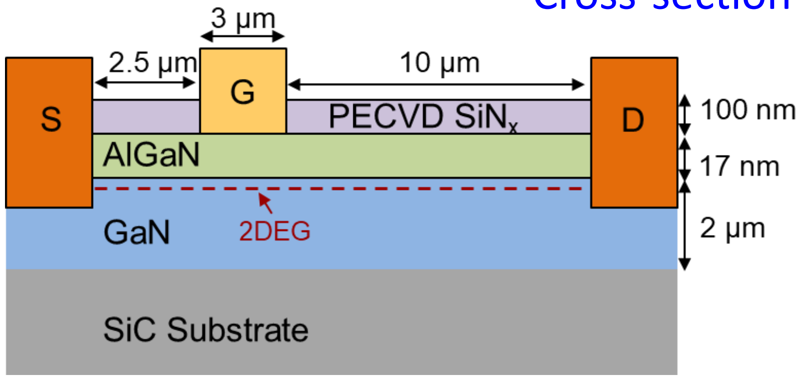
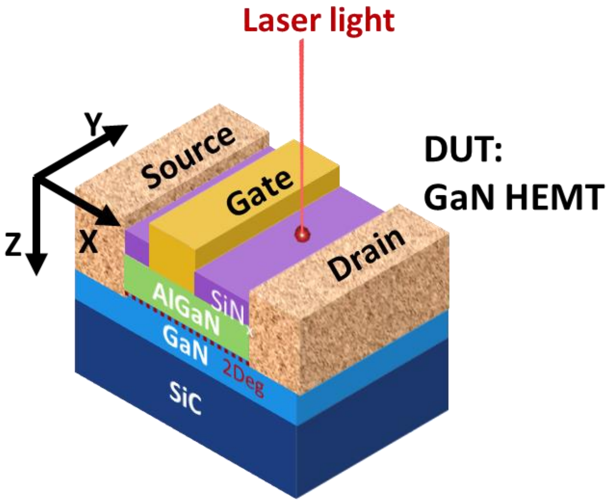
GaN HEMT PL SEE

- GaN HEMT

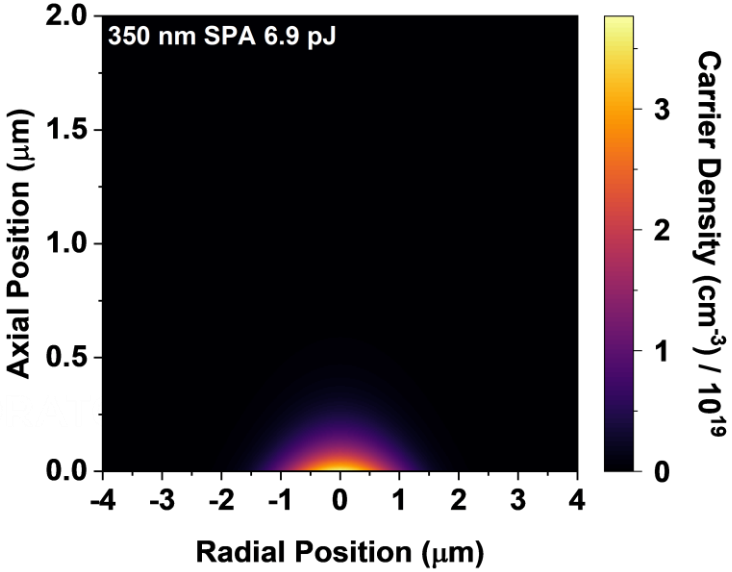
Cross-section



Top view



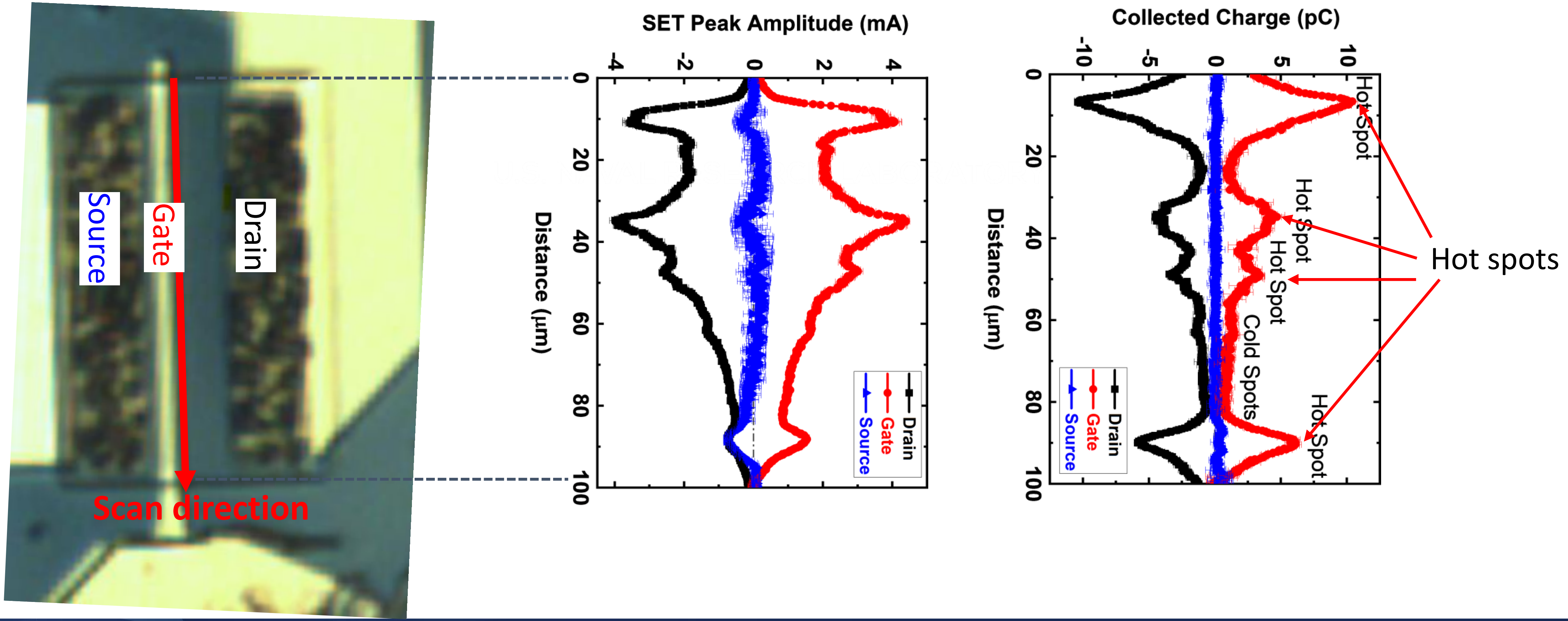
- Laser-induced charge distribution profile



- 350 nm SPA process ω_{1/e^2}=1.35 µm $\tau_{1/e}$=150 fs 1kHz
- Deposited Charge is 1.5 pC
- Laser equivalent LET$_L$ is 80 MeV·cm^2·mg^{-1}

Hot Spot Identification

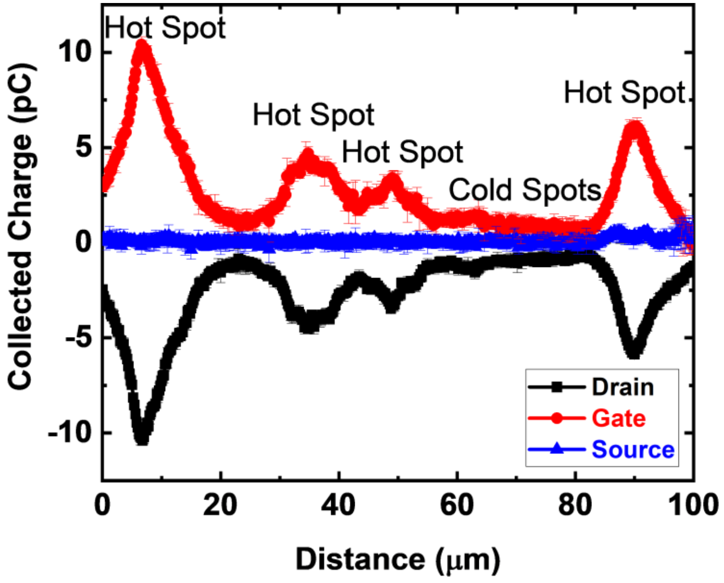
- GaN HEMT on SiC V_d=20V V_g=-5V device is biased OFF
- 350 nm SPA process ω_{1/e^2}=1.35 µm $\tau_{1/e}$=150 fs 1kHz
- Deposited Charge is 1.5 pC and laser equivalent LET_L is 80 $MeV \cdot cm^2 \cdot mg^{-1}$



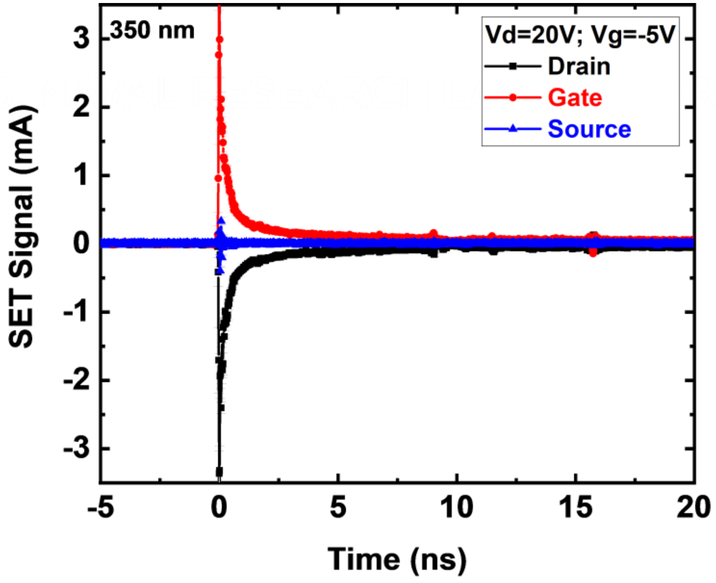
SETs: Hot Spot vs Cold Spot

- Transients extracted from the line scans along the gate of GaN HEMT
- 350 nm SPA process ω_{1/e^2}=1.35 µm $\tau_{1/e}$=150 fs 1kHz
- Deposited charge is 1.5 pC and laser equivalent LET$_L$ is 80 MeV·cm^2·mg^{-1}

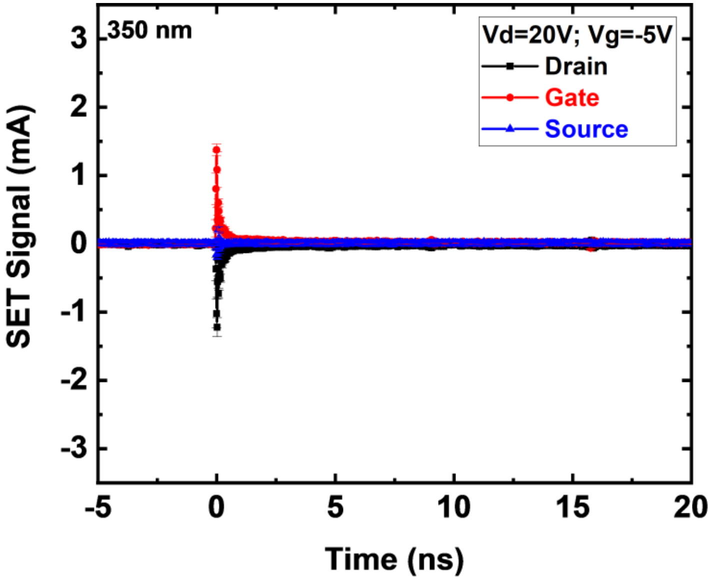
Collected Charge



Hot spot SET



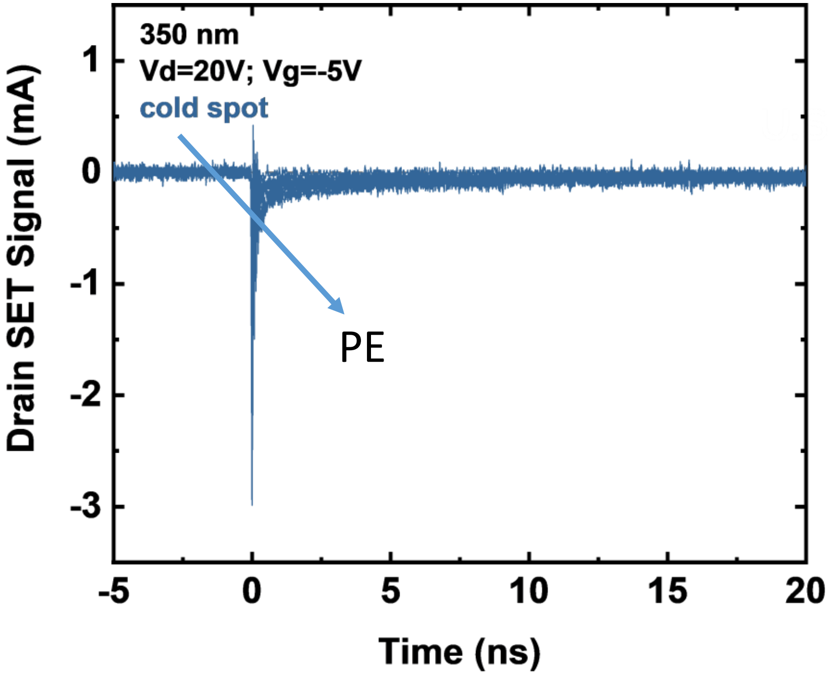
Cold spot SET



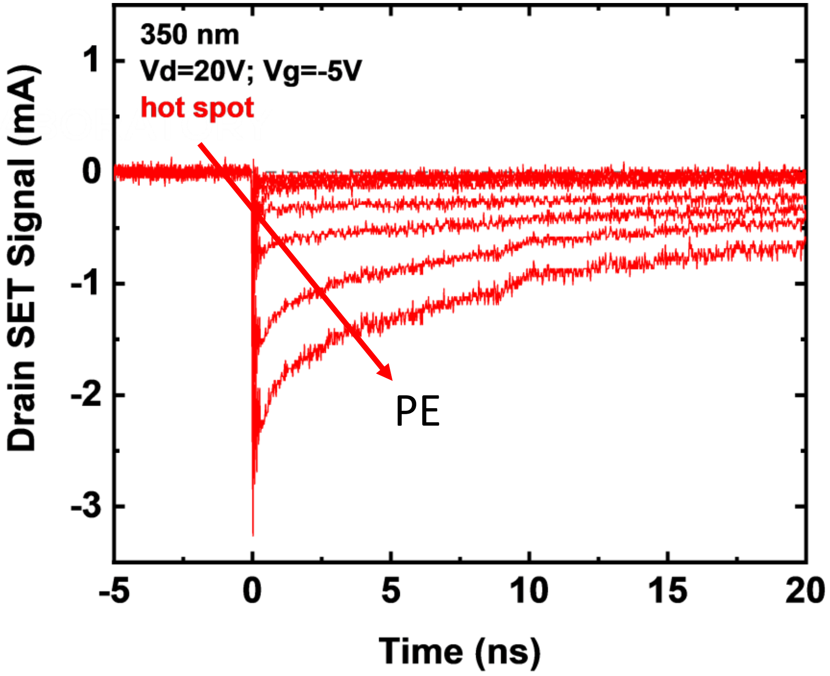
Laser Induced Burnout in GaN HEMT

- **Fixed bias conditions**
  - V_d=20V V_g=-5V
- **Varied laser pulse energy (LET)**
- Single-event burnout at a laser pulse energy (PE) of 8 pJ (LET_L ~ 90 $MeV \cdot cm^2 \cdot mg^{-1}$)

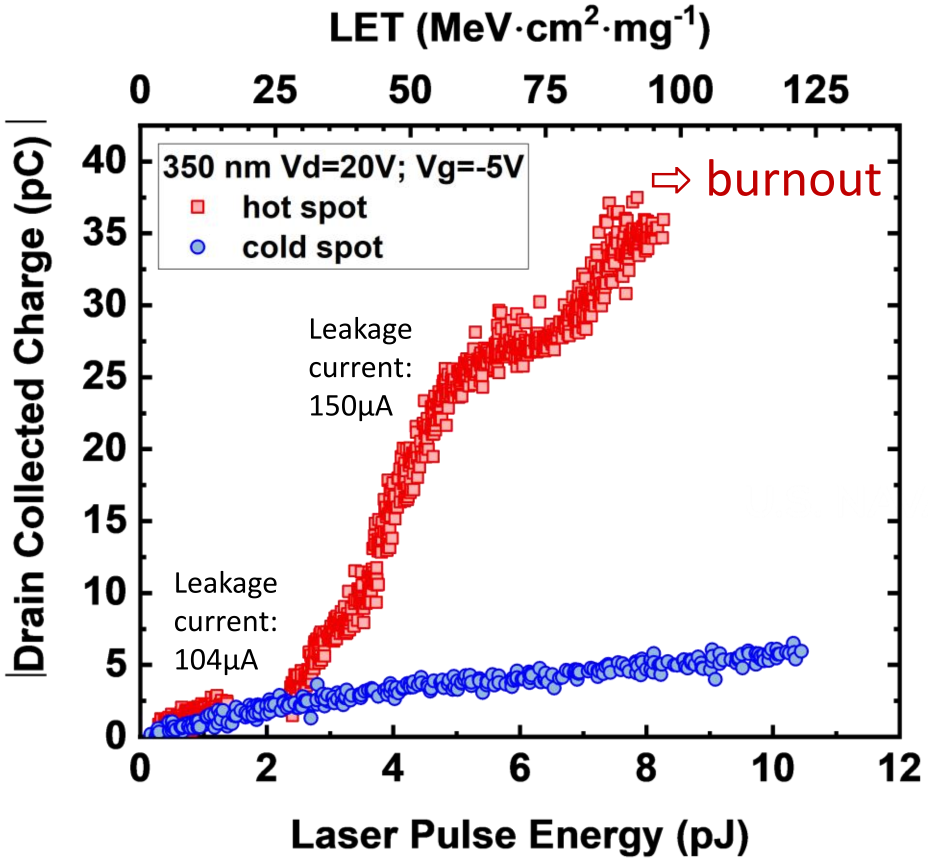
Cold spot SETs at PE 0 to 10.4 pJ



Hot spot SETs

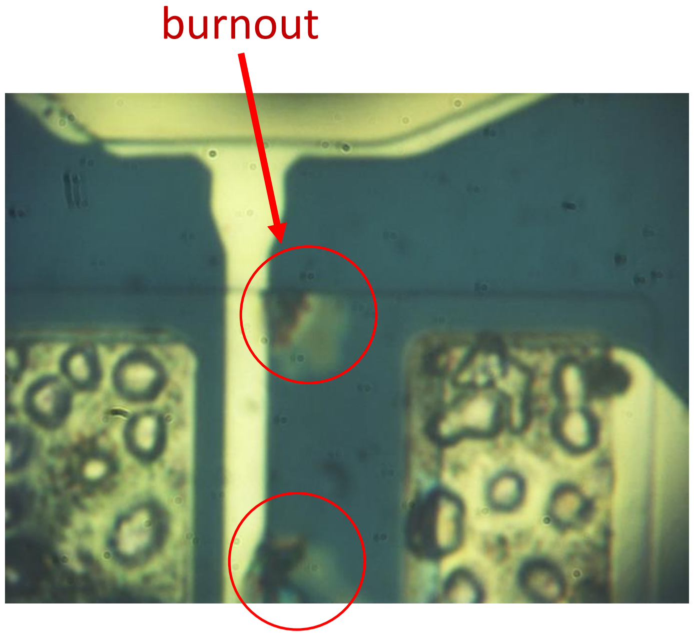


Laser Induced Burnout in GaN HEMT



- Single-event burnout at laser pulse energy (PE) of 8 pJ (LET$_L$ ~90 MeV·cm^2·mg^{-1})

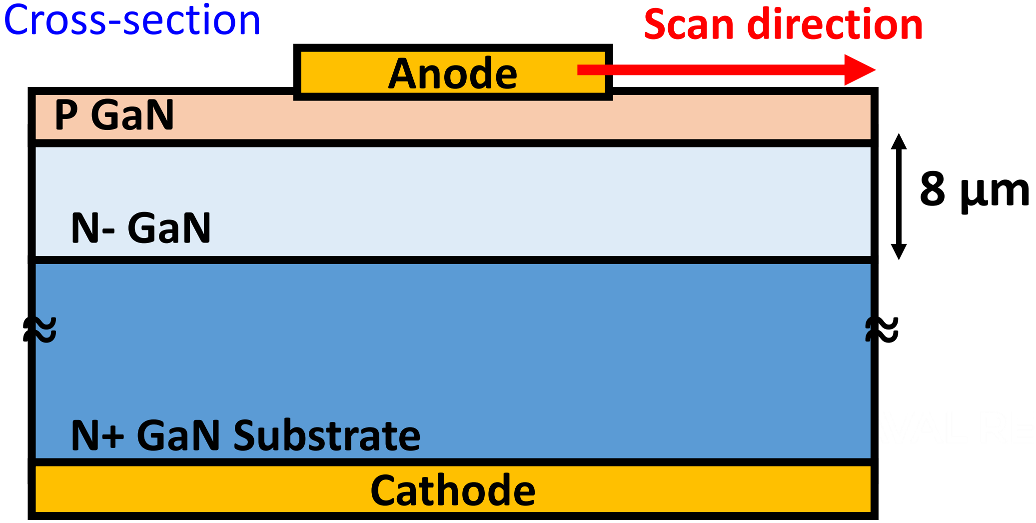
- OFF state (V_g=-5V) GaN HEMT is **rated for V_d=650 V**.
- Pulsed-laser-induced burnout at V_d =20 V is **well below operational voltage**.



Vertical GaN Diode PL SEE

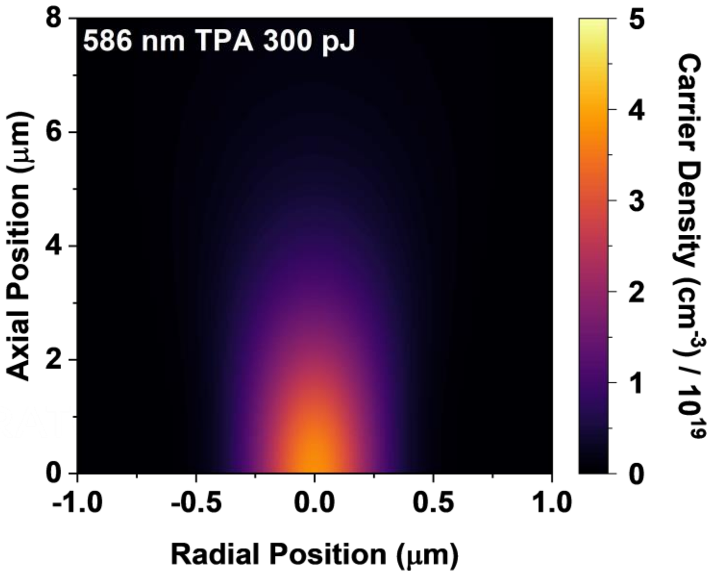
- Vertical GaN Diode

Cross-section



Top view

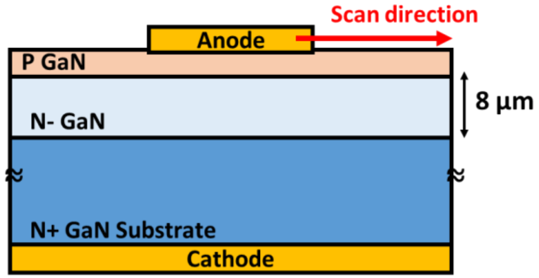
- Laser-induced charge distribution profile

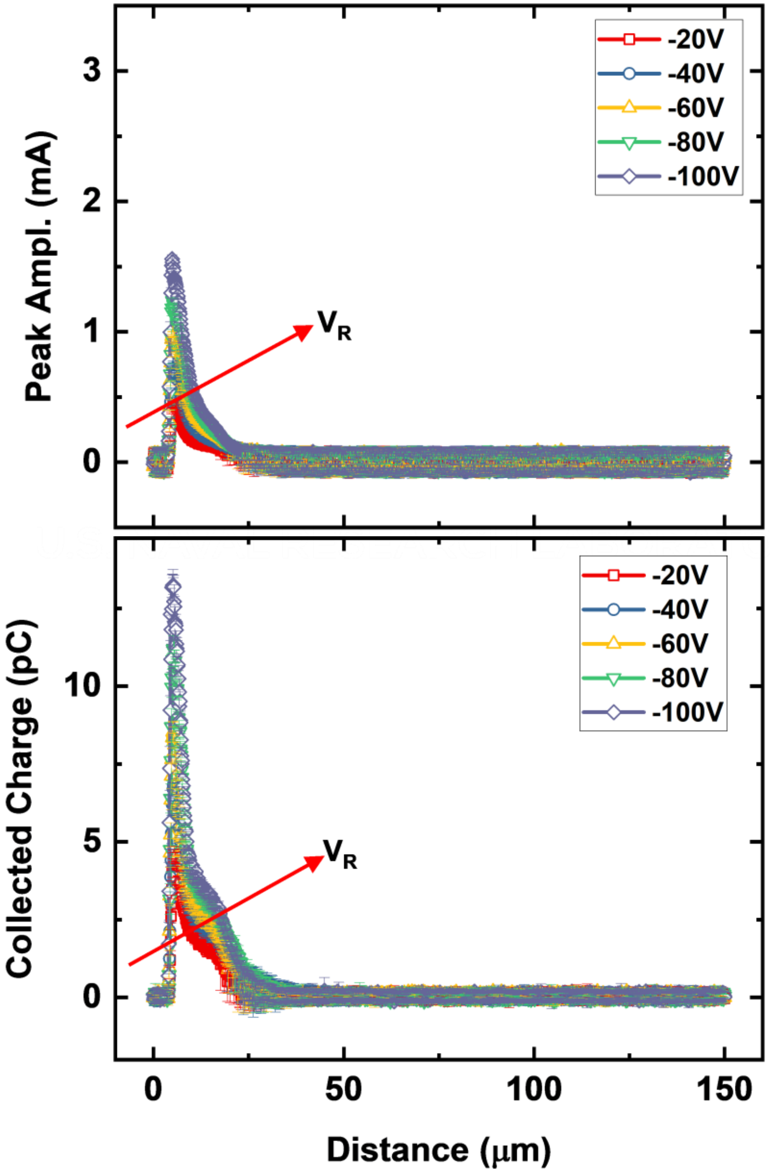


- 586 nm TPA process ω_{1/e^2}=0.54 µm $\tau_{1/e}$=150 fs 1kHz
- Deposited Charge is 11.2 pC
- Laser equivalent LET_L is 17.8 MeV·cm^2·mg^{-1}

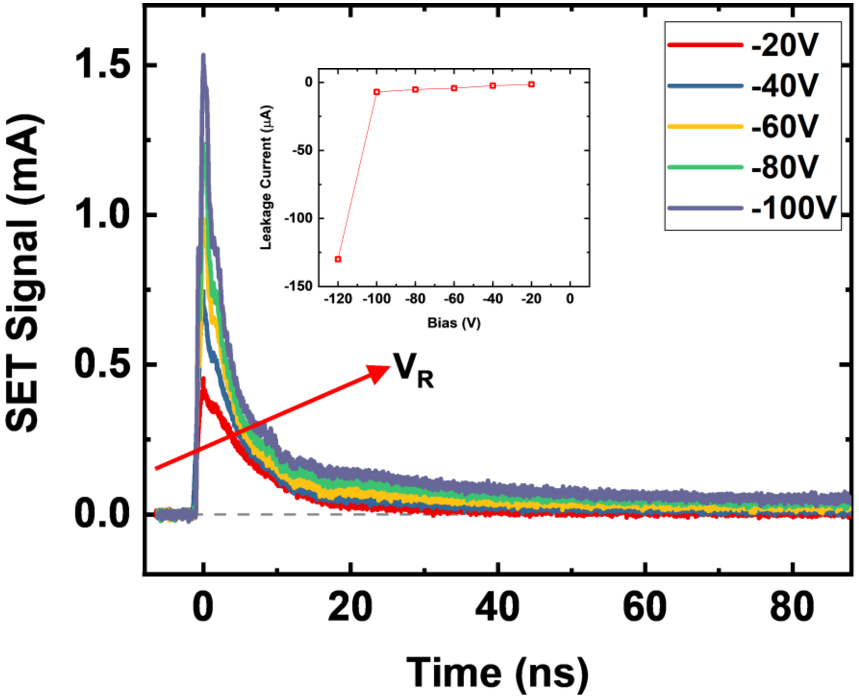
Vertical GaN Diode PL SEE

- Fixed laser pulse energy
  - 586 nm TPA process
  - Deposited charge is 11.2 pC
  - LET_L is ~18 $MeV \cdot cm^2 \cdot mg^{-1}$





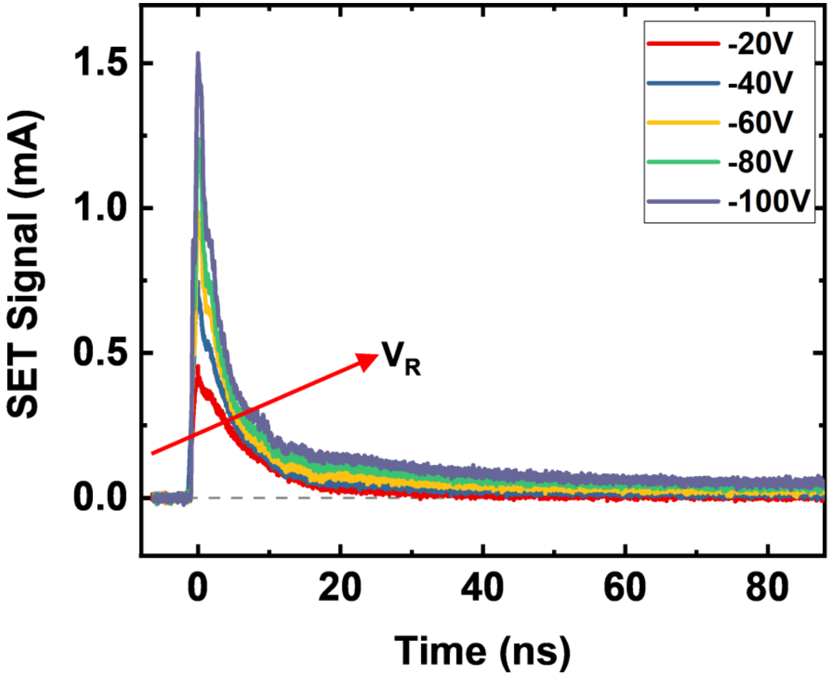
- Varied reverse bias



SETs extracted from the peak collected charge location near the edge of the anode.

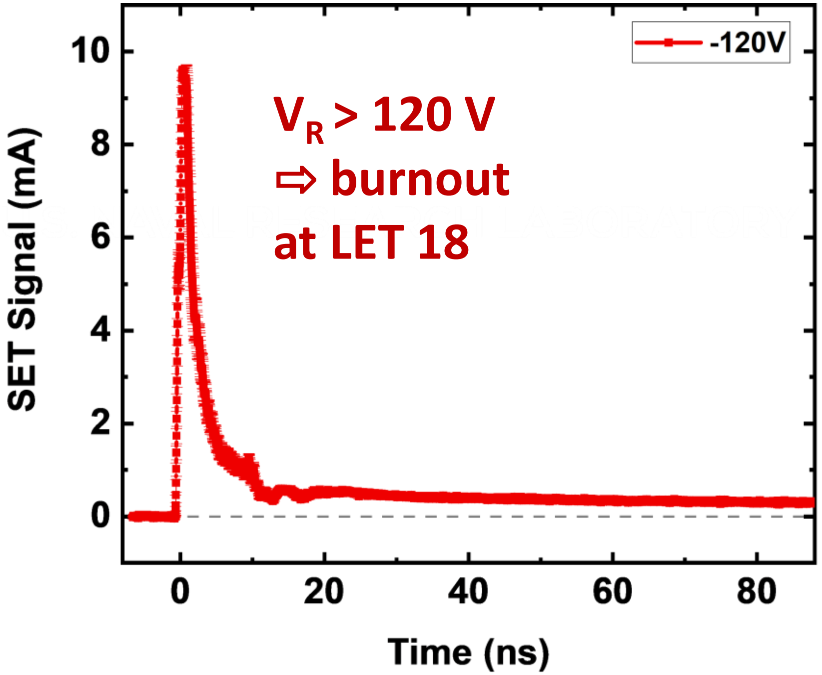
Laser-Induced Burnout in GaN Vertical Diode

- Fixed laser pulse energy (LET ~18 MeV·cm^2·mg^{-1}) varied bias

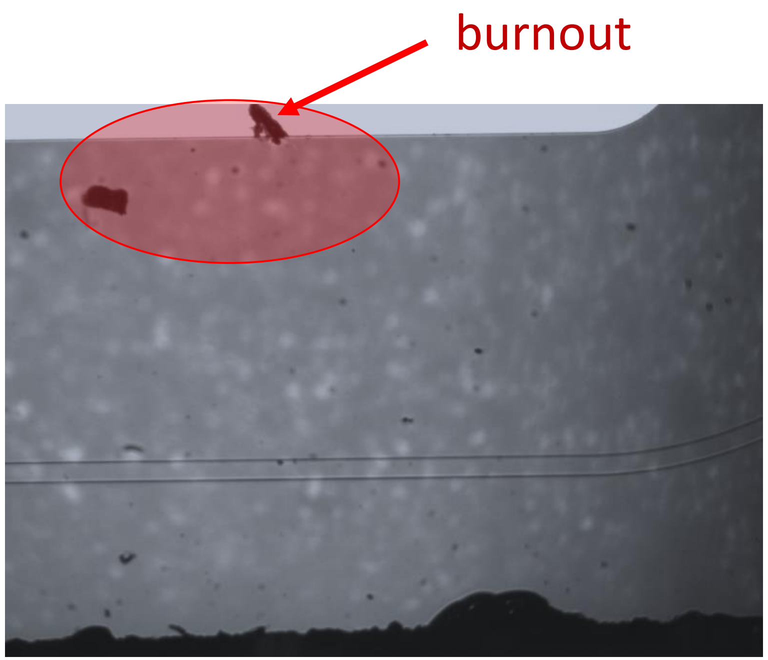


- GaN vertical diode is **rated V_R = 1200 V**.
- Pulsed-laser-induced burnout at $V_R \geq 120$ V is **well below operational voltage**.

Burnout precursor SET



V_R > 120 V
⇨ burnout
at LET 18

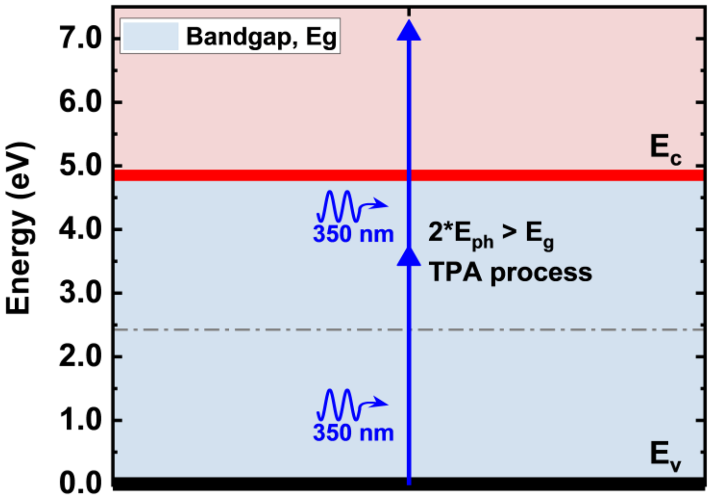


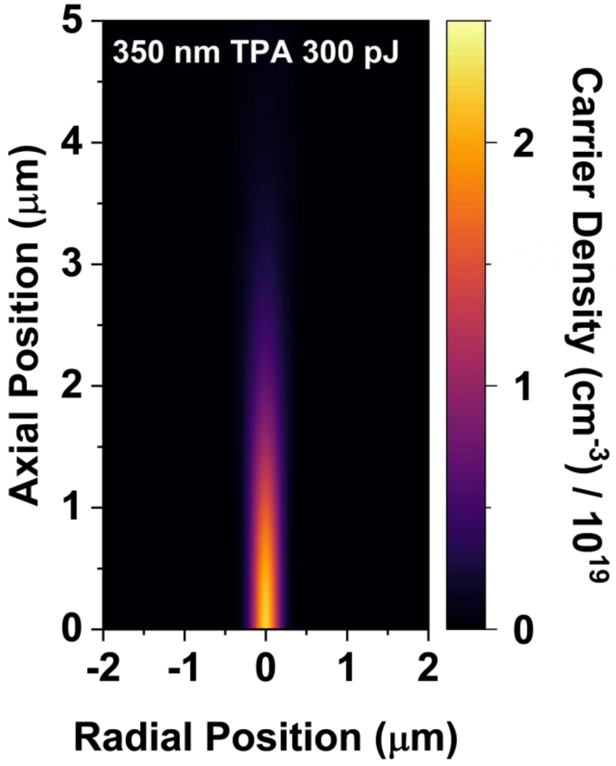
Precursor SET :

- Significant increase in peak amplitude
- $Q_{coll}(V_R = 120V)/Q_{coll}(V_R = 100V) \sim 10$

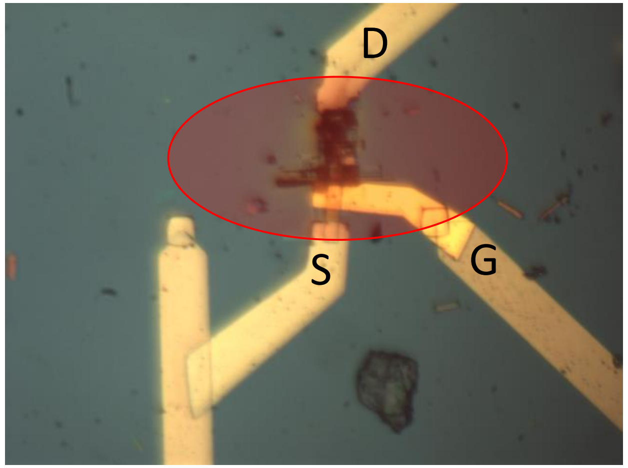
Single-Event Burnout in Ga_2O_3 FET

- PL SEE study of Ga_2O_3 FETs
- 350 nm TPA process ω_{1/e^2}=0.35 µm $\tau_{1/e}$=150 fs 1kHz
- Hot spot is in the drain access area (near gate edge)





- OFF state (V_g=-3V) Ga_2O_3 FET is **rated for V_d = 650 V**.
- Catastrophic SEB when exposed to laser energy of >300 pJ (LET_L~49).
- Pulsed-laser-induced burnout at V_d = 35V is **well below operational voltage**.



- **Single-event burnout at LET_L > 49**

Collaboration with Univ. of Florida (F. Ren and S. Pearton)

Summary

- A pulsed-laser SEE study was conducted on wide-bandgap semiconductor devices, employing both single-photon and two-photon absorption processes.
- PL SEE was utilized to locate and characterize defects.
- It was demonstrated that "hot spots" with large electric fields are most susceptible to destructive failure events.
- An increase in material quality can improve the hardness of wide bandgap devices.
- **Future work:**
  - Develop a methodology by varying bias and laser pulse energy to determine laser-induced SEB threshold in wide-bandgap semiconductor devices.

Thank you!