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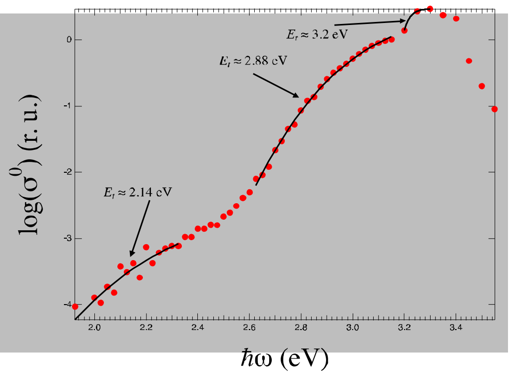

UWBG
ULTRAWIDE BANDGAP
POWER ELECTRONICS

Investigation of deep levels in high-breakdown-voltage, low-threading-dislocation-density vertical GaN P-i-N diodes

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Motivation

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- Wide bandgap (GaN/SiC) devices are desirable for power/RF applications
- Current lateral GaN power devices (HEMTs) suffer from parametric drift and catastrophic breakdown
- Vertical devices benefit from higher yield, higher breakdown voltage, higher forward current and smaller area per device
- Understanding defect-related limitations of vertical GaN devices will enable better electrical performance in future devices

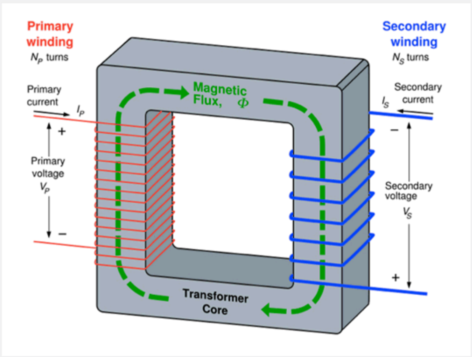
Outline

- Introduction
- Advantage of GaN for power electronics
- Device performance metrics
  - Forward *I-V*
  - Reverse *I-V*
  - Temperature dependence
  - Figure of merit
- Deep level optical spectroscopy
- Lighted C-V profiling of defects
- Conclusions

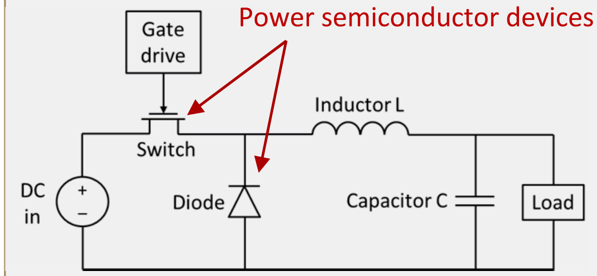
What Are Power Electronics?

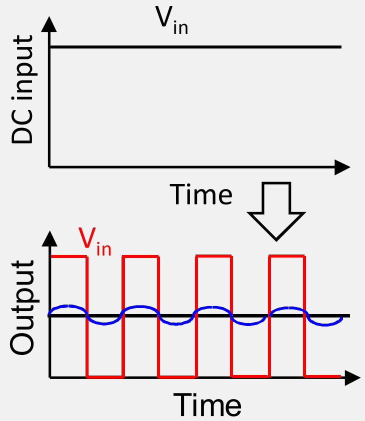
- *Power electronics*: Application of solid-state electronics for routing, control, and conversion of electrical power

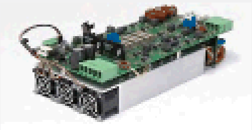
Passive transformers (dumb)



Power Electronics – Active switching (smart)





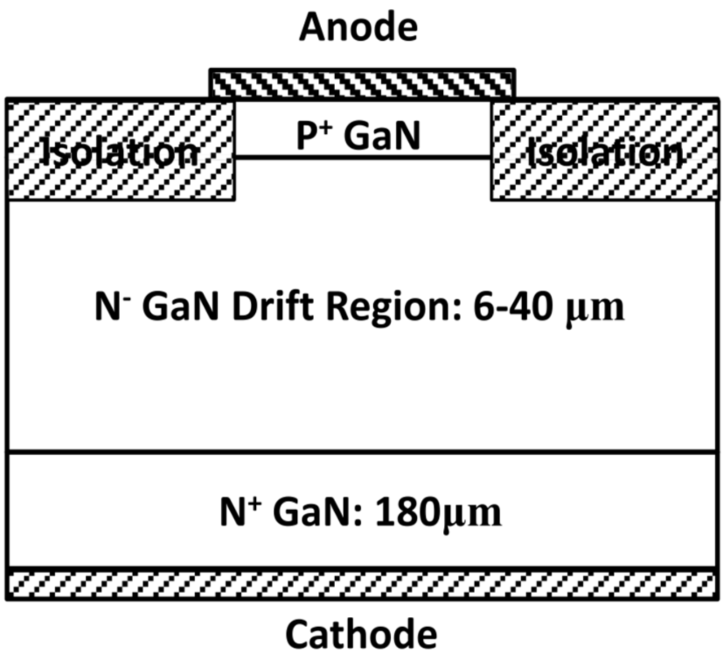


- Current power electronics are limited by the properties of Silicon semiconductor devices
- New system capabilities are enabled by:
  - Higher switching frequency (enables better SWaP)
  - Lower power loss
  - Higher temperature operation

➢ ***Motivation for WBG semiconductors***

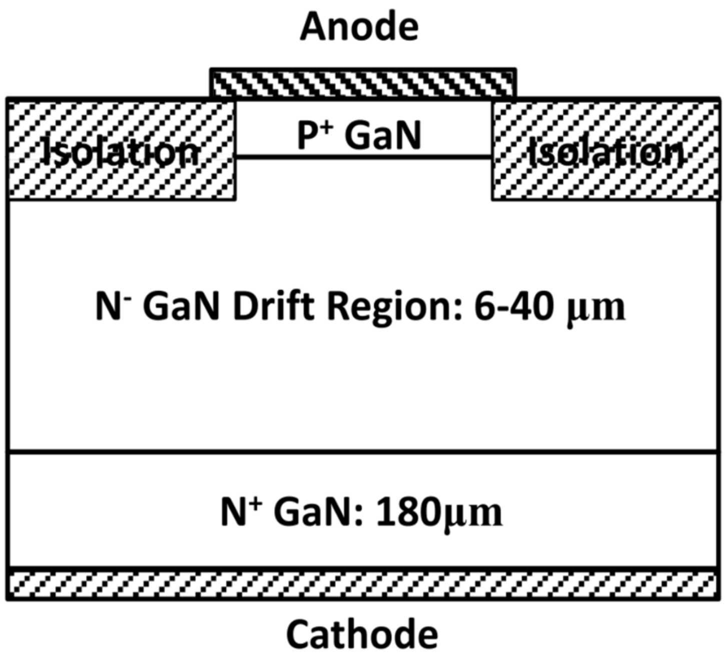
Vertical GaN Devices for Power

SiC is 10% the volume and weight of Si for equivalent capability (10 kV, 100 A)

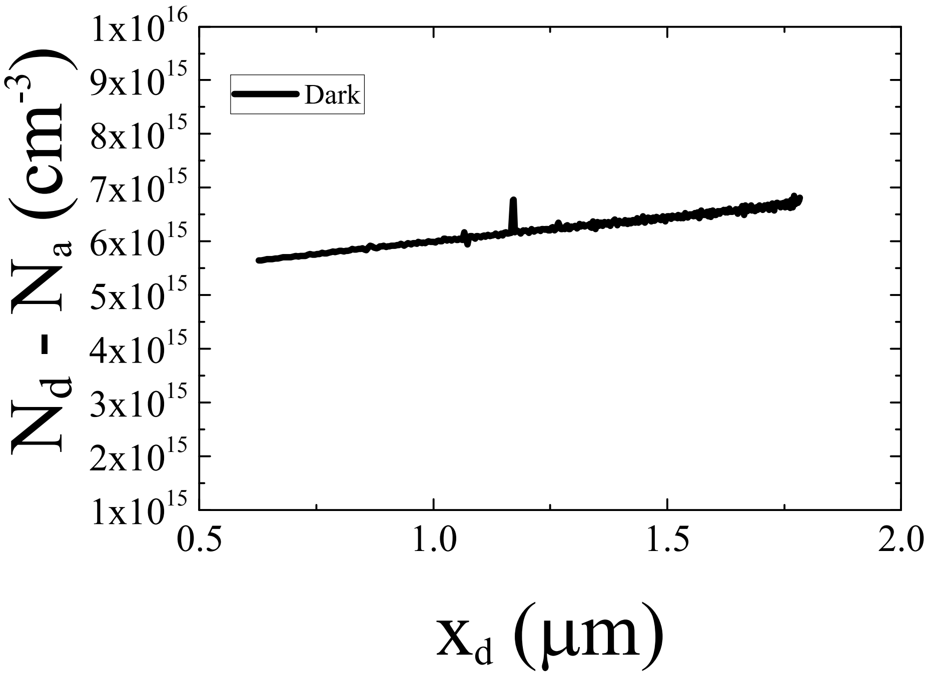


Vertical devices have smaller area per device, higher device yield, increased breakdown voltage, and larger current drive in comparison to lateral device structures.

Vertical GaN *P-i-Ns*

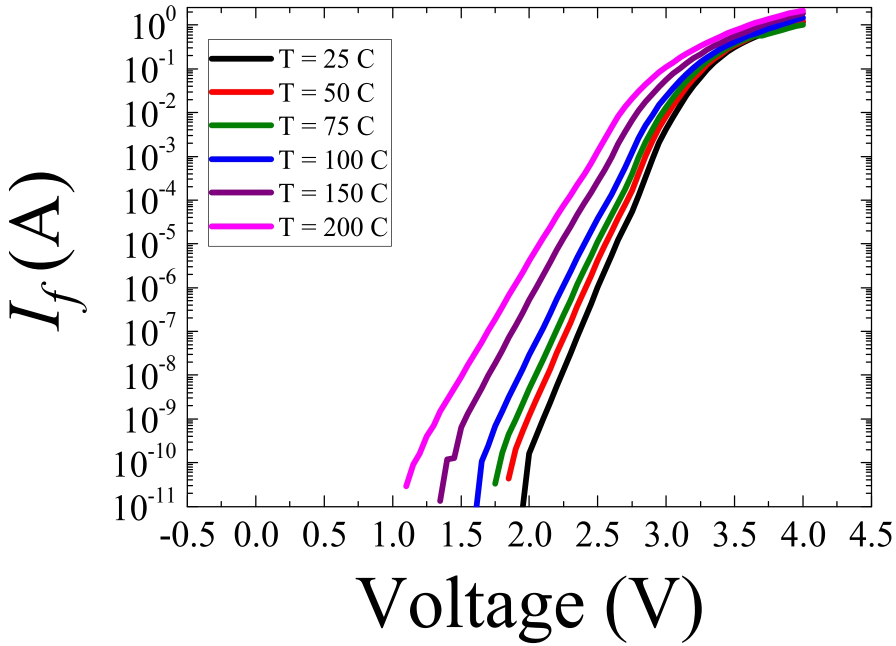


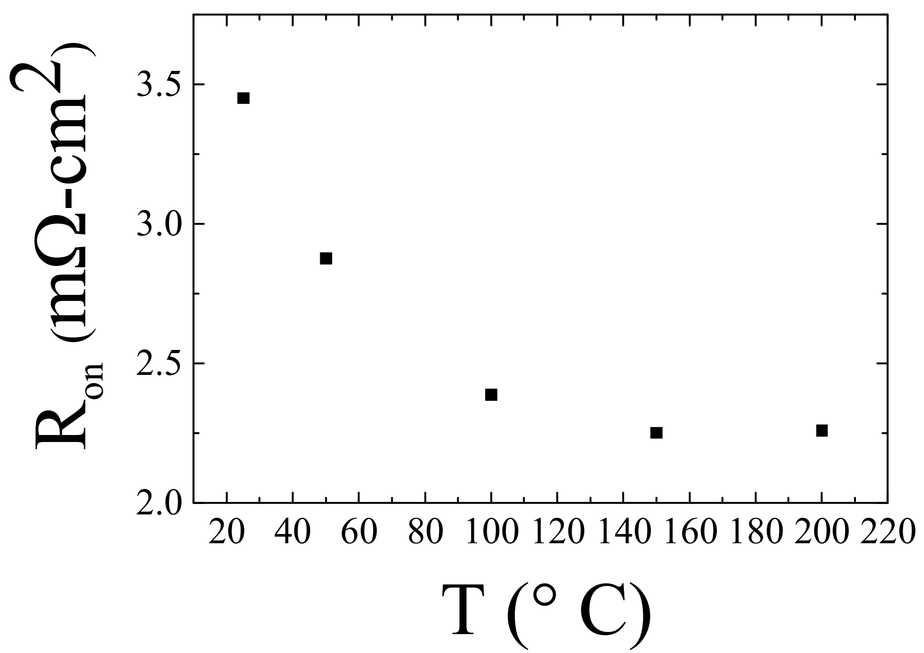
- Devices are vertical p^+-n^--n^+
- Epi (~10 µm) is grown by MOCVD on HVPE GaN substrates
- Edge termination formed by ion implantation of p^+ GaN region



- Devices exhibit low-epi doping over thick *n*-drift region
- Enables a vertical *P-i-N* device in GaN

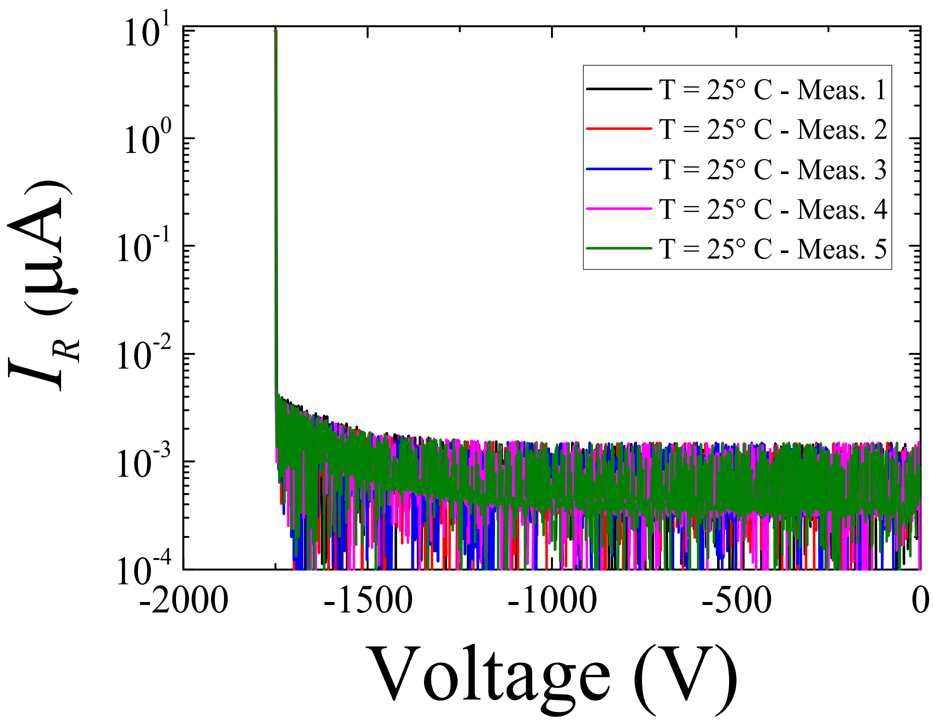
Forward Current vs Temperature





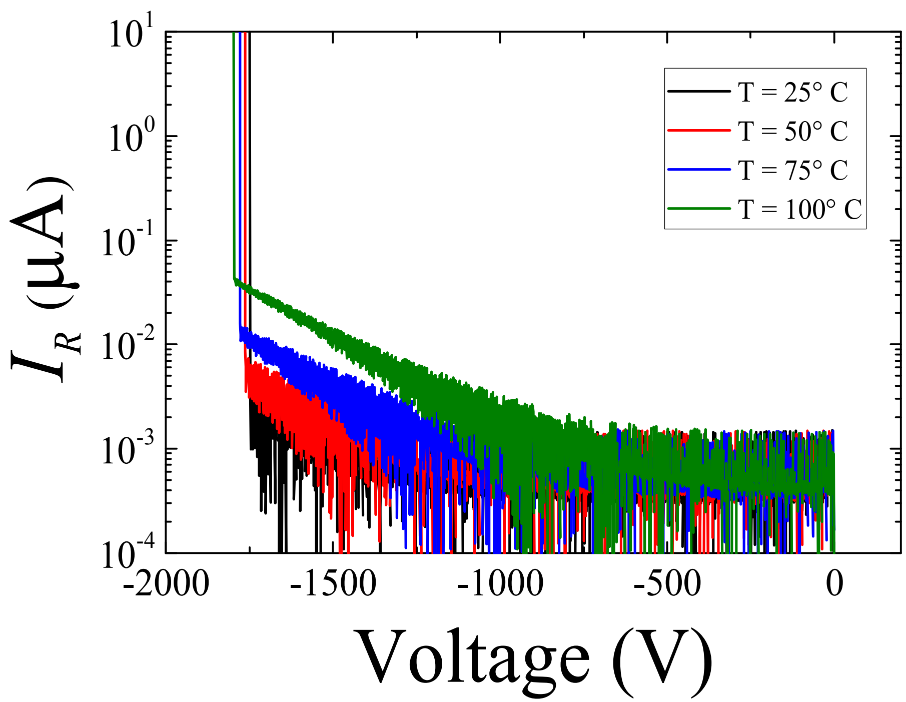
- Increasing temperature leads increased drive and leakage current
- R_{on} vs T shows decreasing on-state resistance for increasing temperature
- Indicates strong current handling capabilities for high temperature operation

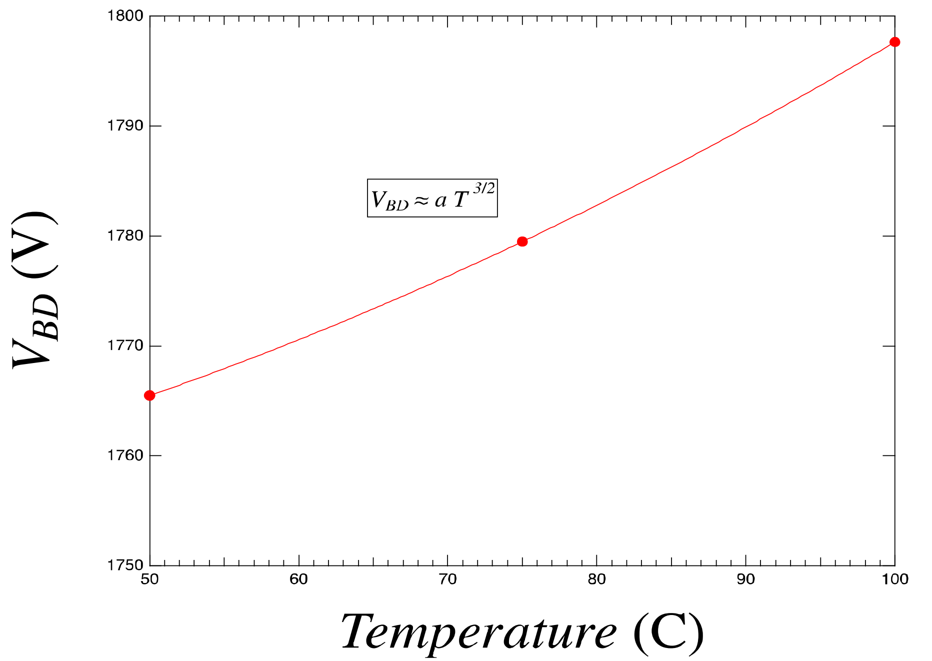
Reverse Breakdown



- Repeated reverse I-V measurements show low leakage (< 1 nA @ >1500 V)
- Non-destructive consistent V_{BD} > 1750 V
- Sharp breakdown characteristics suggest impact ionization

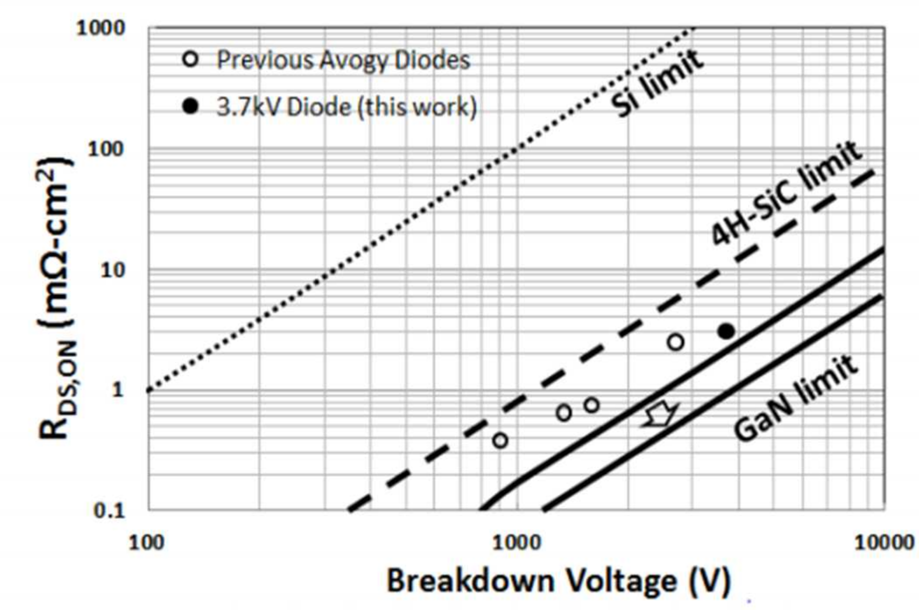
Reverse Breakdown vs Temperature





- Increasing temperature leads to increased leakage current
- Increasing temperature causes higher V_{BD}
- V_{BD} vs T exhibits $T^{3/2}$ dependence
- Consistent with avalanche processes impeded by phonon scattering

Performance - Figure of Merit

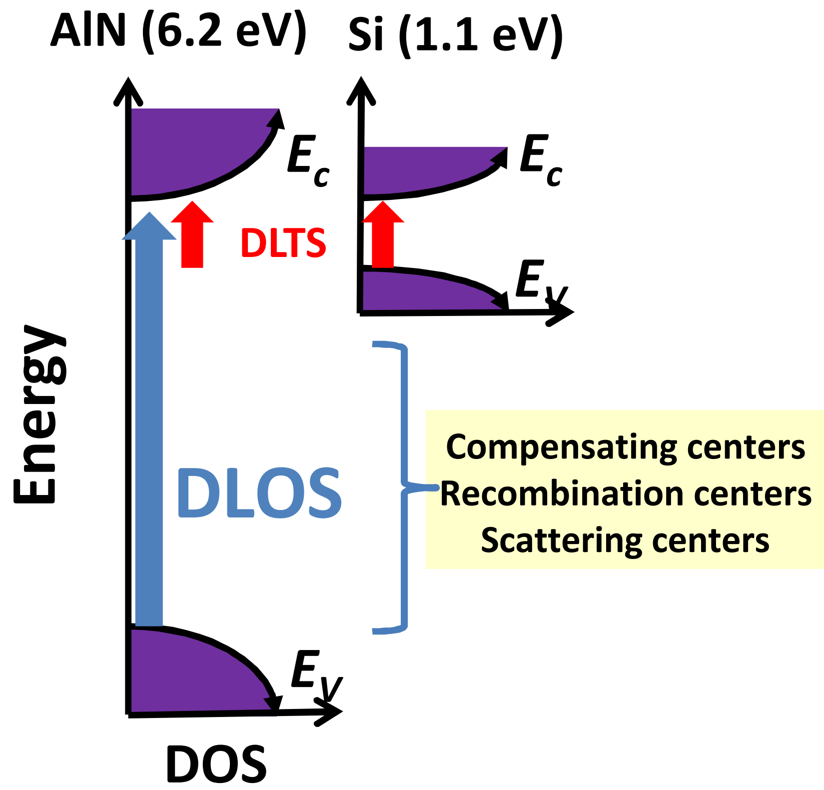


$$4\frac{{V_{BD}}^2}{R_{on,sp}} = \epsilon\mu_n {E_C}^3$$

Challenges to studying defects in III-Nitrides

Quantitative defect spectroscopy is difficult for wide bandgap semiconductors

- **Thermal emission techniques limited to ~ 1 eV of band edge**
- **Luminescence insensitive to non-radiative centers and not usually quantitative**

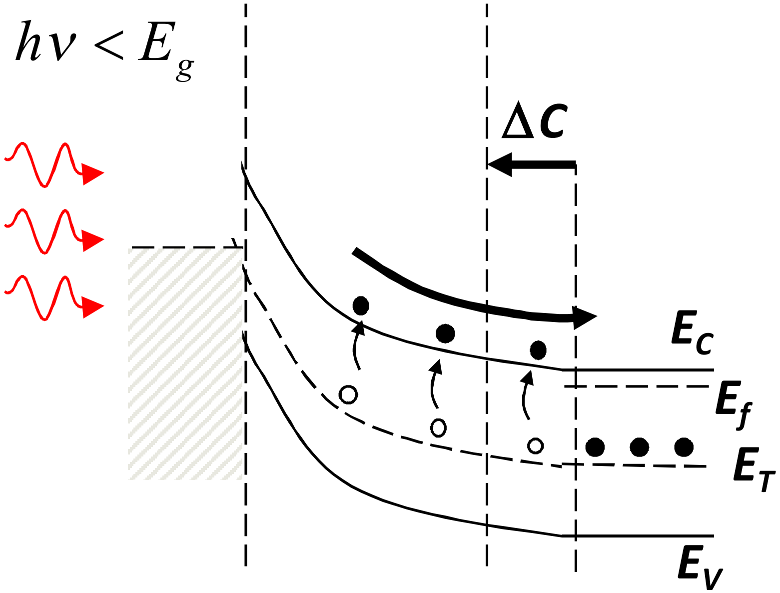


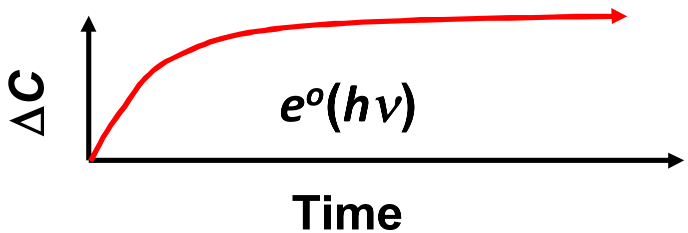
Solution: Deep Level Optical Spectroscopy (DLOS)

Deep Level Optical Spectroscopy

Deep Level Optical Spectroscopy (DLOS)[1]

- ***Electrical measurement*** **of** ***optical absorption*** **by deep level defects**
- **Photocapacitance technique**
- **Sub-band gap optical stimulation to photoionize defect levels**





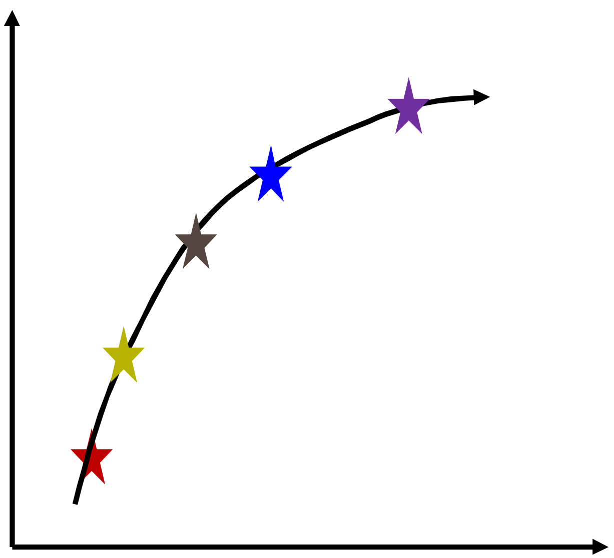
1. Chantre *et al.* PRB 23, 5335 (1981).

Deep Level Optical Spectroscopy

Deep Level Optical Spectroscopy (DLOS)[1]

- **Fundamental physics from optical cross-section: $\sigma^o(h\nu) = e^o(h\nu)/\phi(h\nu) = \alpha/N_t$**
- **Determine deep level energy E_o from lineshape of $\sigma^o(h\nu)$**
- **Discuss defect density later…**

Optical analog of Arrhenius plot

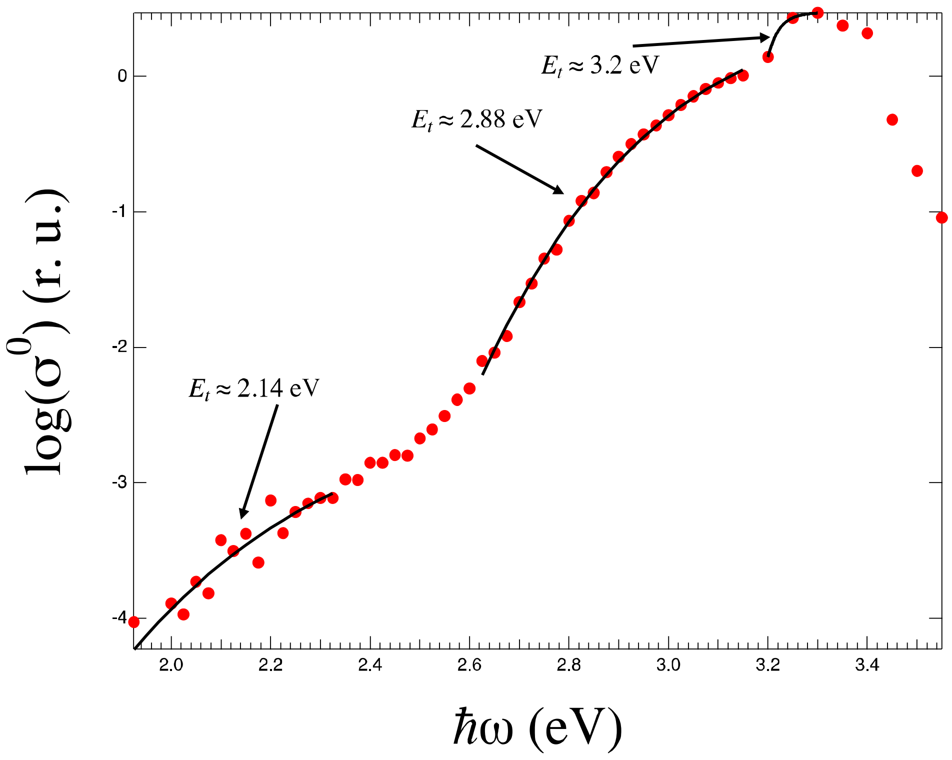


$$\sigma^o(h\nu) \propto \frac{1}{E_0}\left\{\left(\frac{E_0}{h\nu}\right)\cdot\left(1-\frac{E_0}{h\nu}\right)\right\}^{3/2}$$

$$\sigma^o(h\nu,T) \propto \frac{E_o^2}{h\nu\sqrt{4k_BT\pi d_{FC}}}\int_1^\infty dx\sqrt{\frac{x-1}{E_o}}\frac{1}{[(x-1)/E_o+m]^2} \times\exp\left[-\frac{E_o^2(h\nu/E_o-x)^2}{4k_BTd_{FC}}\right], \quad (4)$$

1. Chantre *et al.* PRB 23, 5335 (1981).

DLOS Results



- DLOS studies show three prominent defect levels at
  - E_C - 2.14 eV
  - E_C - 2.88 eV
  - E_C - 3.2 eV
- States at E_C - 2.14 eV and E_C - 2.88 eV are broad, indicating strong lattice relaxation following carrier emission
- Levels at E_C - 2.88 eV and E_C - 3.2 eV are observed to be large in magnitude and likely are primary compensating defects

Steady State Photocap. Response

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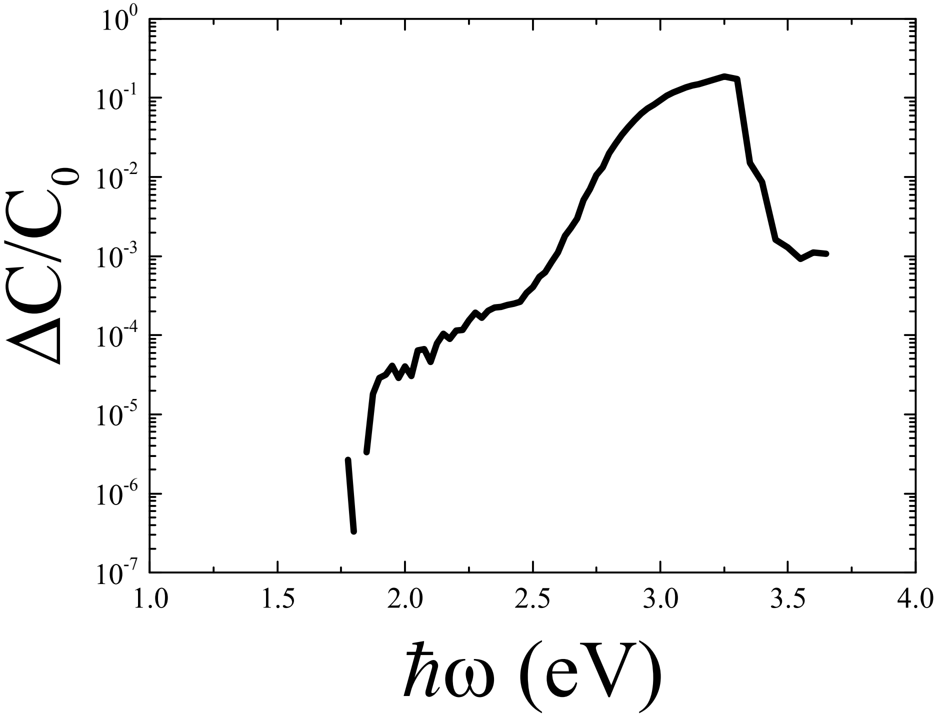
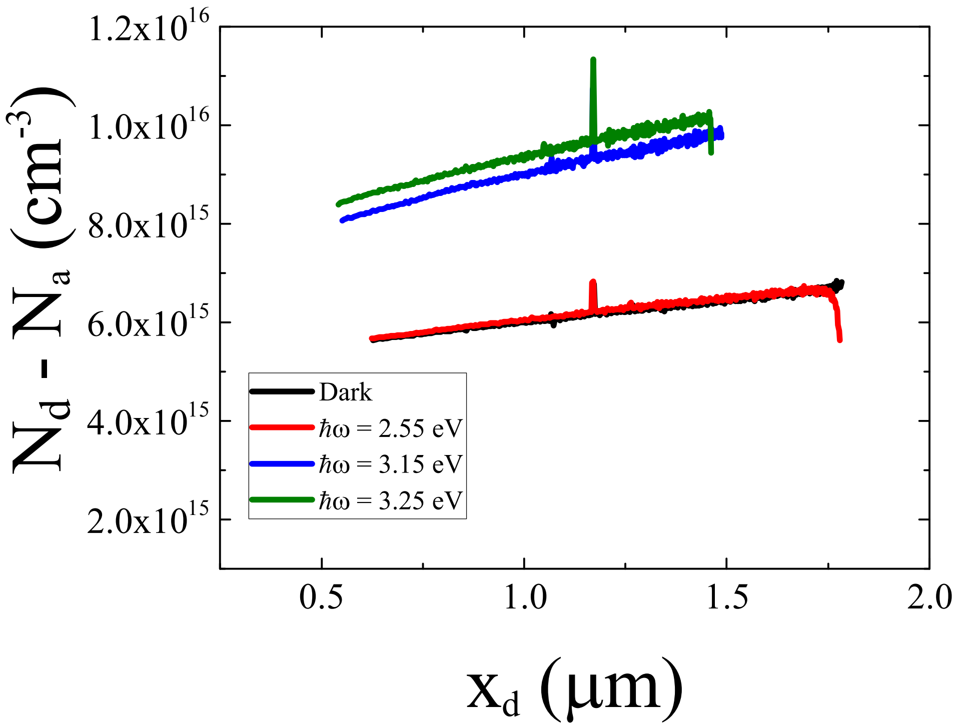


- Change in steady-state photocapacitance shows three primary defects
- States at E_C - 2.14 eV and E_C - 2.88 eV are again broad
- Defect level at E_C-2.14 eV shows small impact on photocapacitance response, $N_t \approx 3\times10^{13}$ cm^{-3}
- Levels at E_C-2.88 eV and E_C-3.2 eV are observed to be large in magnitude – need more sensitive technique to determine concentration

Lighted C-V Results



- Lighted C-V measurements show net carrier concentration is highly compensated by deep levels
- The E_C - 2.88 eV level is observed to be the primary compensating defect with $N_t \approx 2\times10^{15}$ cm^{-3}
- The E_C-3.2 eV level present is on order of the free carrier concentration with $N_t \approx 2.5 \times 10^{15}$ cm^{-3}

Conclusions

- State of the art commercial devices were evaluated for electrical performance with the results indicating excellent performance for power devices in the BFOM
- Consistently low-doped epitaxial material enables high-quality vertical devices grown on GaN native substrates
- Deep levels present in as-grown material are observed to heavily compensate the free carrier concentration
- Controlling point defects is important for maximizing performance and high-reliability applications of vertical GaN power electronics, even when grown homoepitaxially on bulk substrates